CENTRO E. PIAGGIO
Bioengineering and Robotics Research Center

Additive manufacturing

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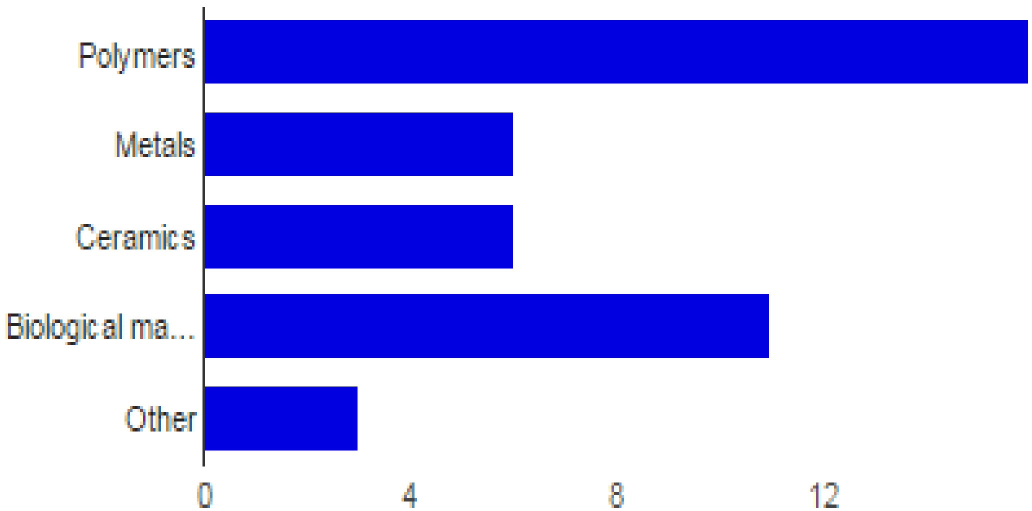
Question #1 07/10/2015

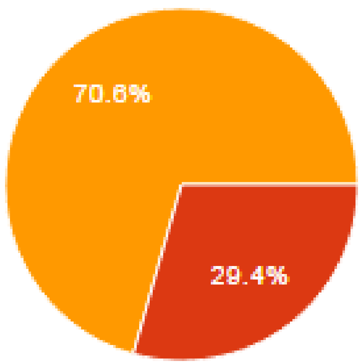
Which classes of materials can be processed with additive manufacturing technologies



Polymers	16	80%
Metals	6	30%
Ceramics	6	30%
Biological materials	11	55%
Other	3	15%

Question #2 07/10/2015

When Stereolithography (an additive manufacturing technology) was invented?

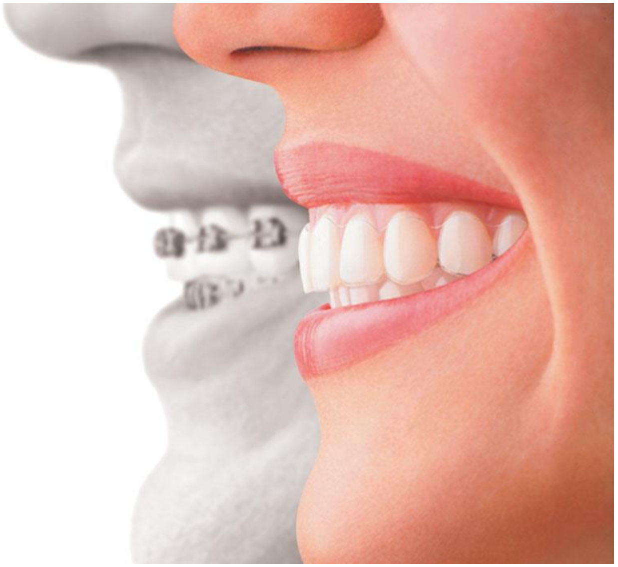


less than 10 years ago	0	0%
between 10 and 20 years ago	5	29.4%
more than 20 years ago	12	70.6%
Other	0	0%

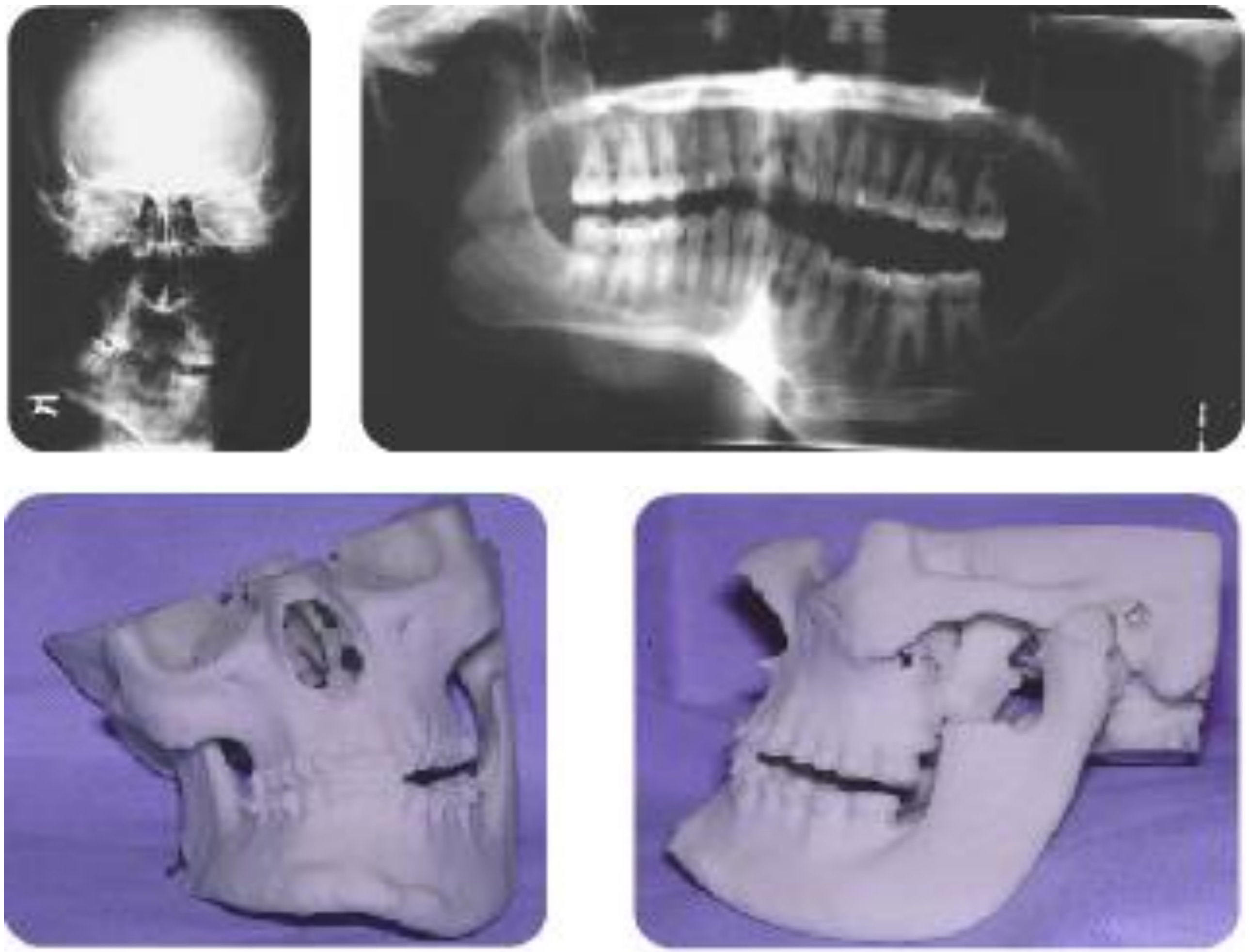
MEDICAL APPLICATION OF RAPID PROTOTYPING

Invisalign Orthodontic Aligners

- An aligner for orthodontic use manufactured using a combination of rapid tooling and thermoforming.



Surgery



Surgery

Surgery

Surgery

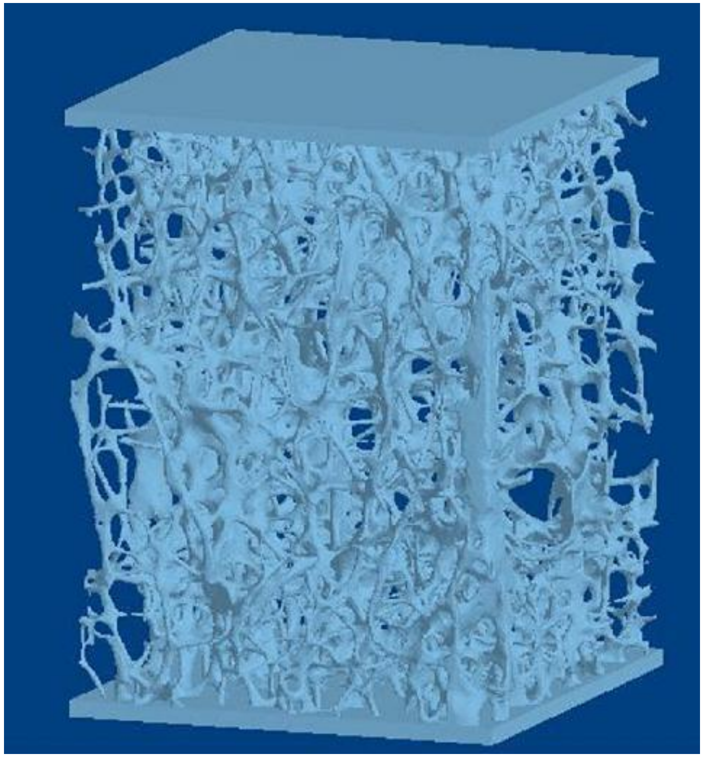



Tissue Engineering - Biofabrication

- Living cells are extracted from patients and seeded onto a carrier (scaffold) which accomodates and guides the growth of new cells in 3D within laboratory environment.

+ Tissue Engineering - Biofabrication

- STL Data produced from Micro-CT scan data
- Multiple specimens of identical structure can be made, reducing samples variations.



OPEN QUESTION

Open questions

- Which are the Intellectual Property Implications of
Low-Cost 3D Printing?

- Is the Open Source 3-d printing an enabling technology for self-directed sustainable development?

- Can a 3D printed organ be patented?

Software for Additive manufacturing

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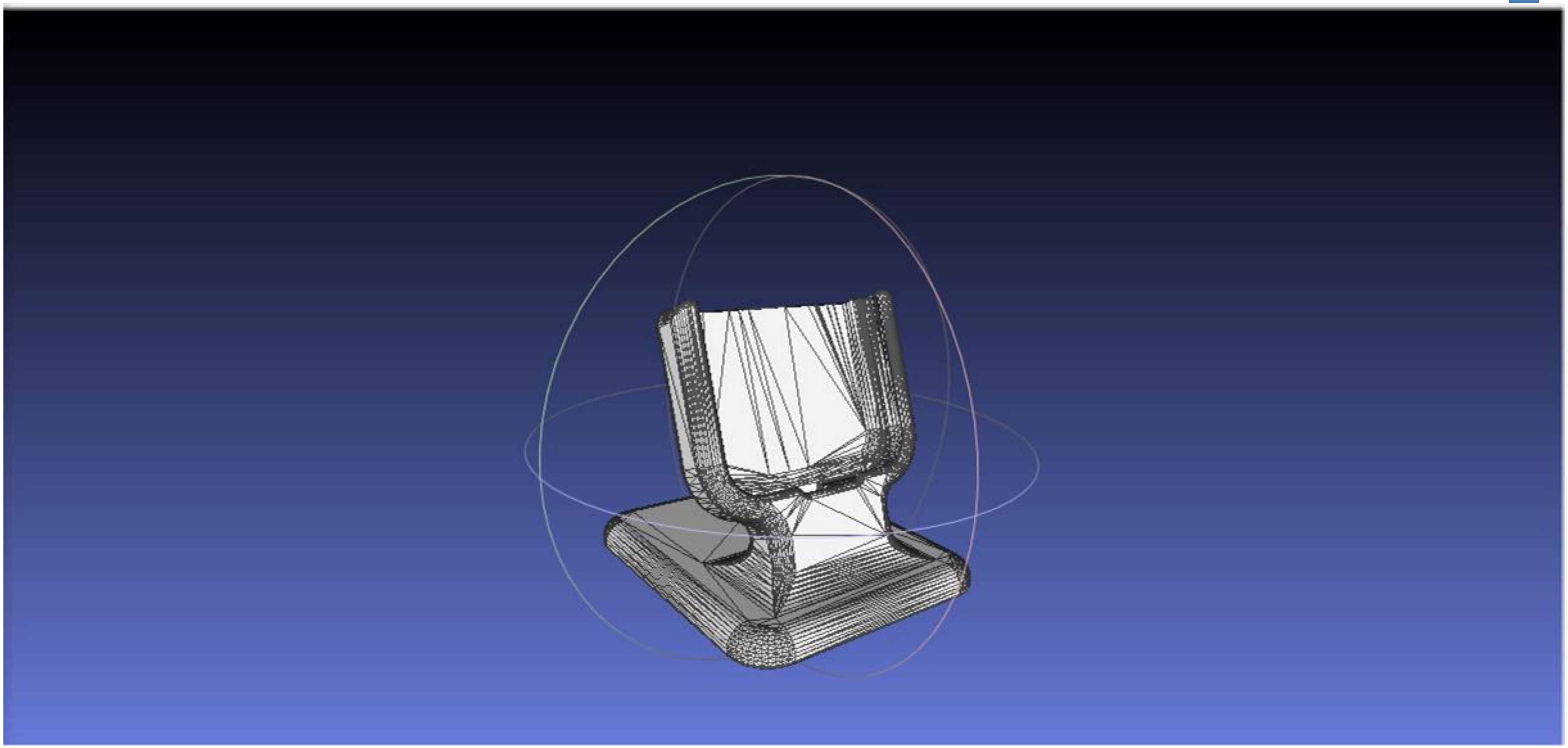
Additive manufacturing Process Flow

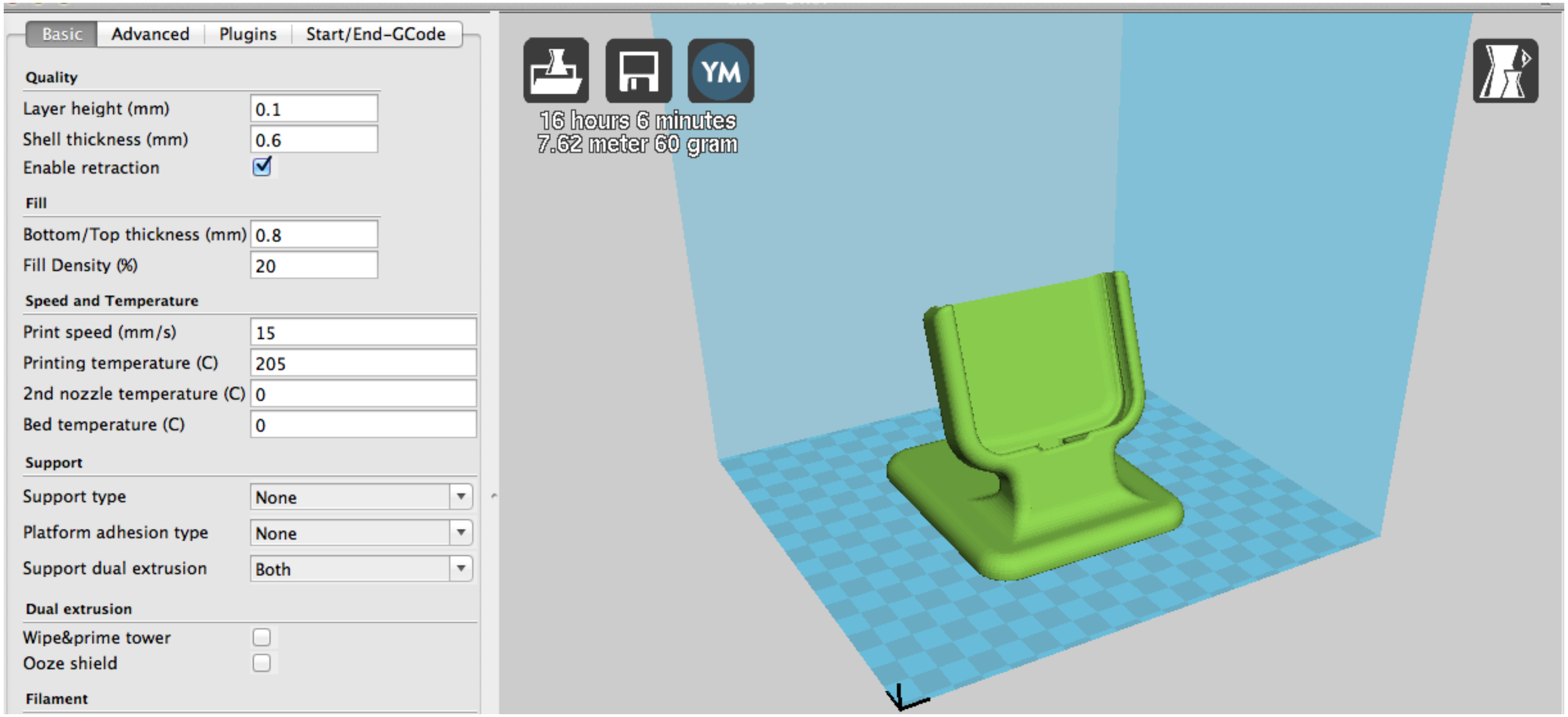
- Solid Modelling
- Tesselation/Generation of STL file
- Support Generation
- “Slicing” of the Model
- Model Physical Buildup
- Cleanup and Post Curing
- Surface Finishing

from idea to design

from idea to design



from design to object



from design to object

from design to object

Additive manufacturing Process Flow

File

CAD FILE → STL FILE → GCODE

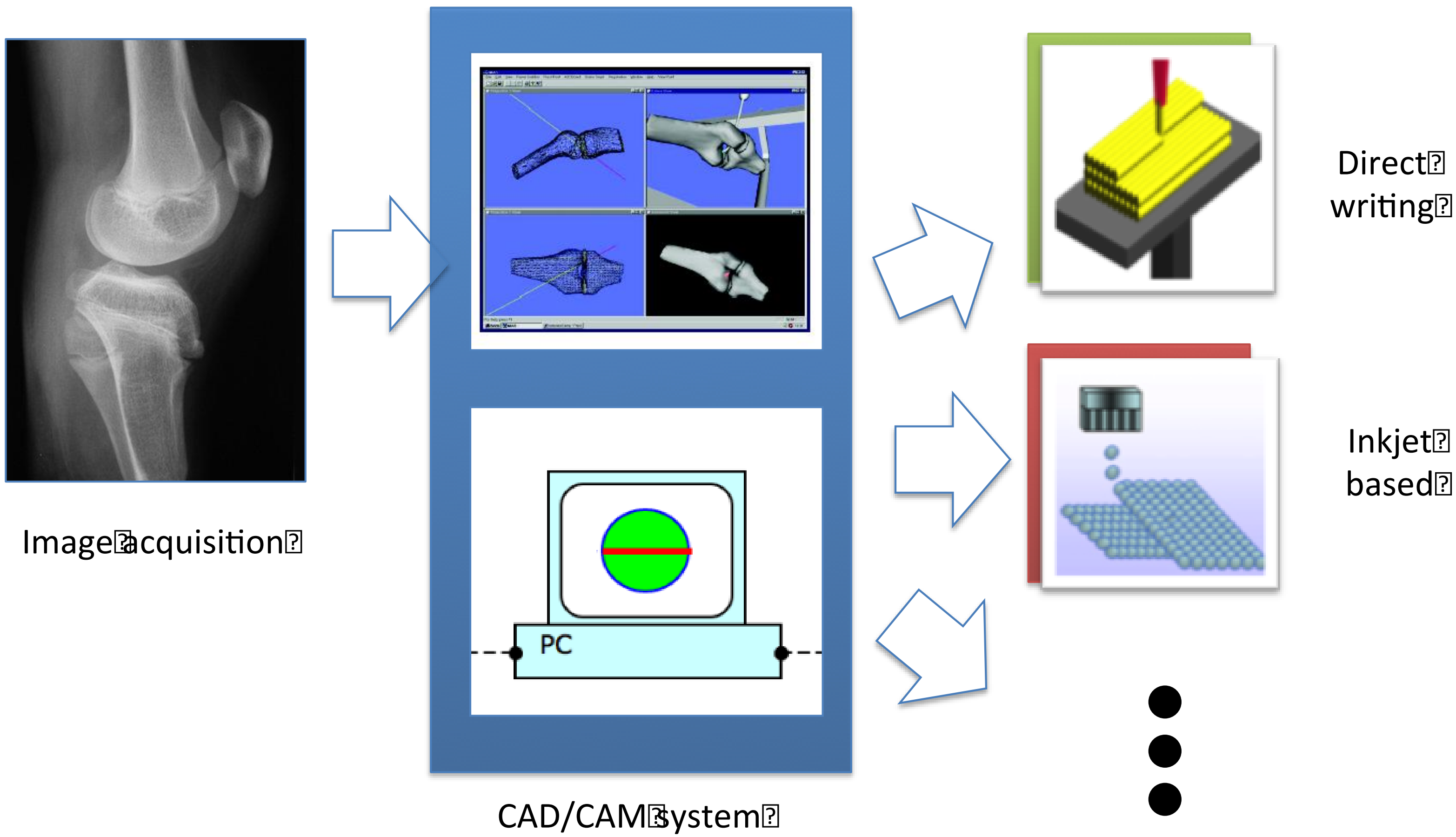
Description

3D object → Triangle and vertex → Toolpath

Software

FreeCAD → FreeCAD (MeshLab) → Slic3r (CURA) → Printrun to 3DP

Additive manufacturing Process Flow



DATA SOURCE

Data source

- Representation of a volume
  - CAD model
  - Instruments output
    - CT
    - RM

CAD model

Dimensions of CAD Elements	Elements	Type of CAD Model
0D	Point	Corner Model
1D	Line	Edge Model
2D	Surface	Surface Model
3D	Solid/Volume	Solid or Volume Model

Example 1

FROM MEDICAL IMAGES TO STL

Segmentation

- Segmentation subdivides an image into its constituent regiorns or objects.
- The level to whhc the subdivision is carried out depends on the problem being solved

Software per l’analisi delle bioimmagini

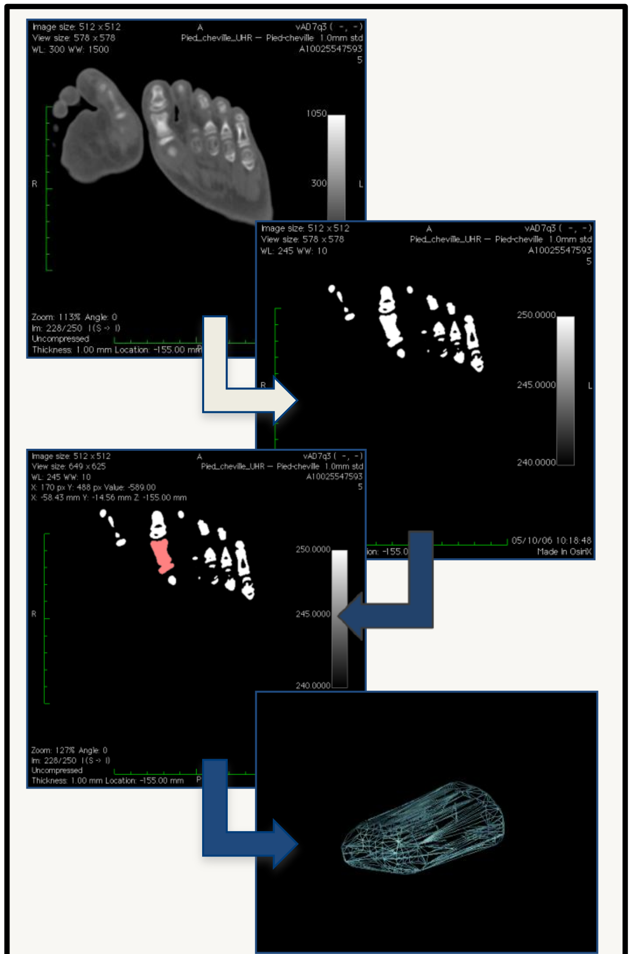
- OsiriX (www.osirix-viewer.com)
- 3DSlicer (www.slicer.org)
- ImageJ (rsb.info.nih.gov/ij)
- MIPAV (mipav.cit.nih.gov)
- itk-SNAP (www.itksnap.org)

Image Analysis: OxiriX imaging software

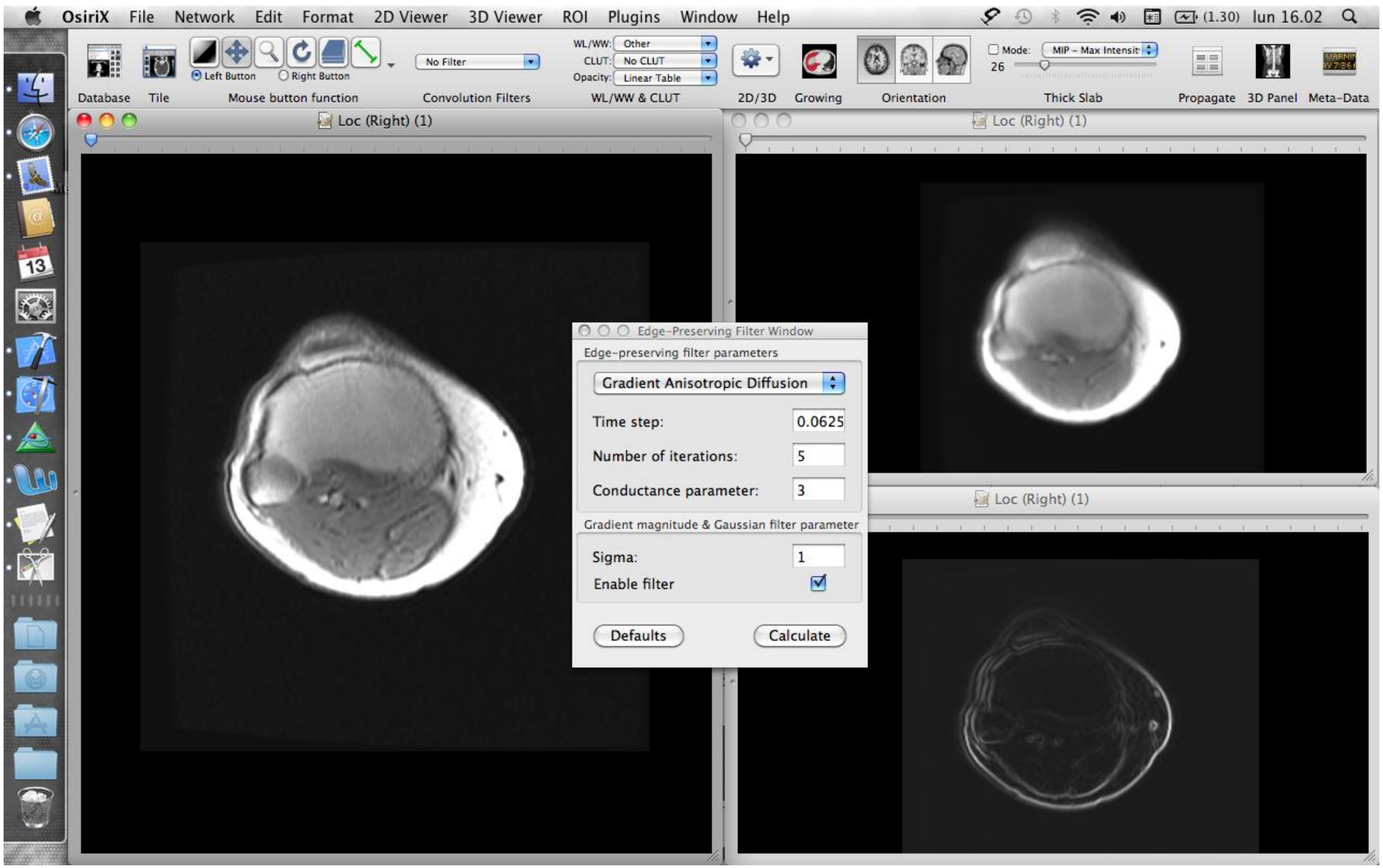
- Advanced open-source DICOM PACS workstation
- Image processing
- Better communication with surgeons

Geometry extraction

- From original CT DICOM image to final volume
  - Semi-automatic procedure
- Positive results in 95% of cases

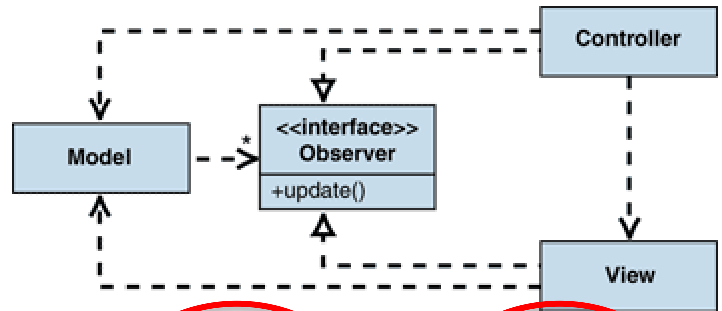


Osirix Plugins: edge preserving smoothing

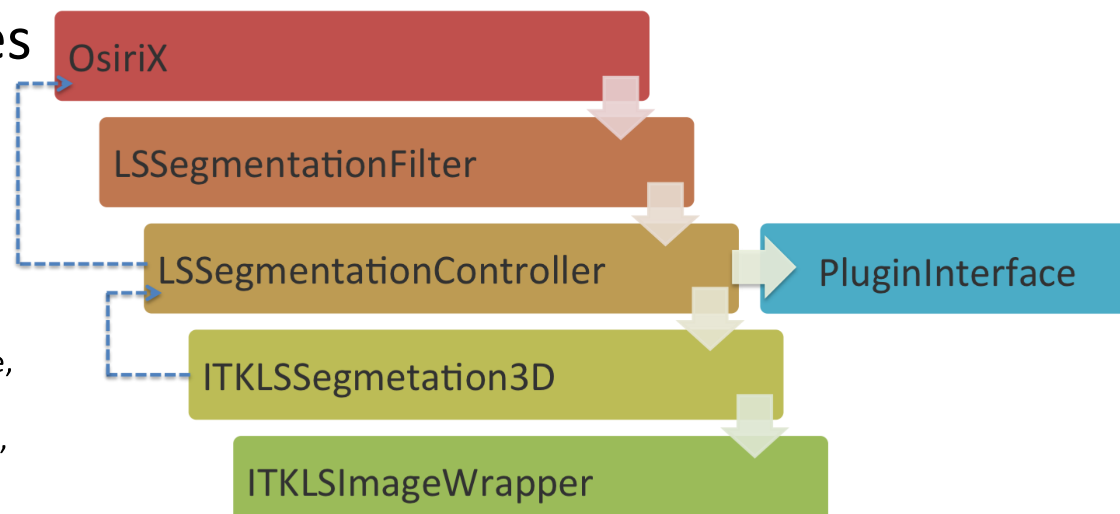


Osirix Plugins: Level-Set segmentation

- Two algorithm
  - Shape detection
  - Geodesic Active Contours
- Evolution based on
  - Propagation
  - Curvature
  - Advection
- Programming principles

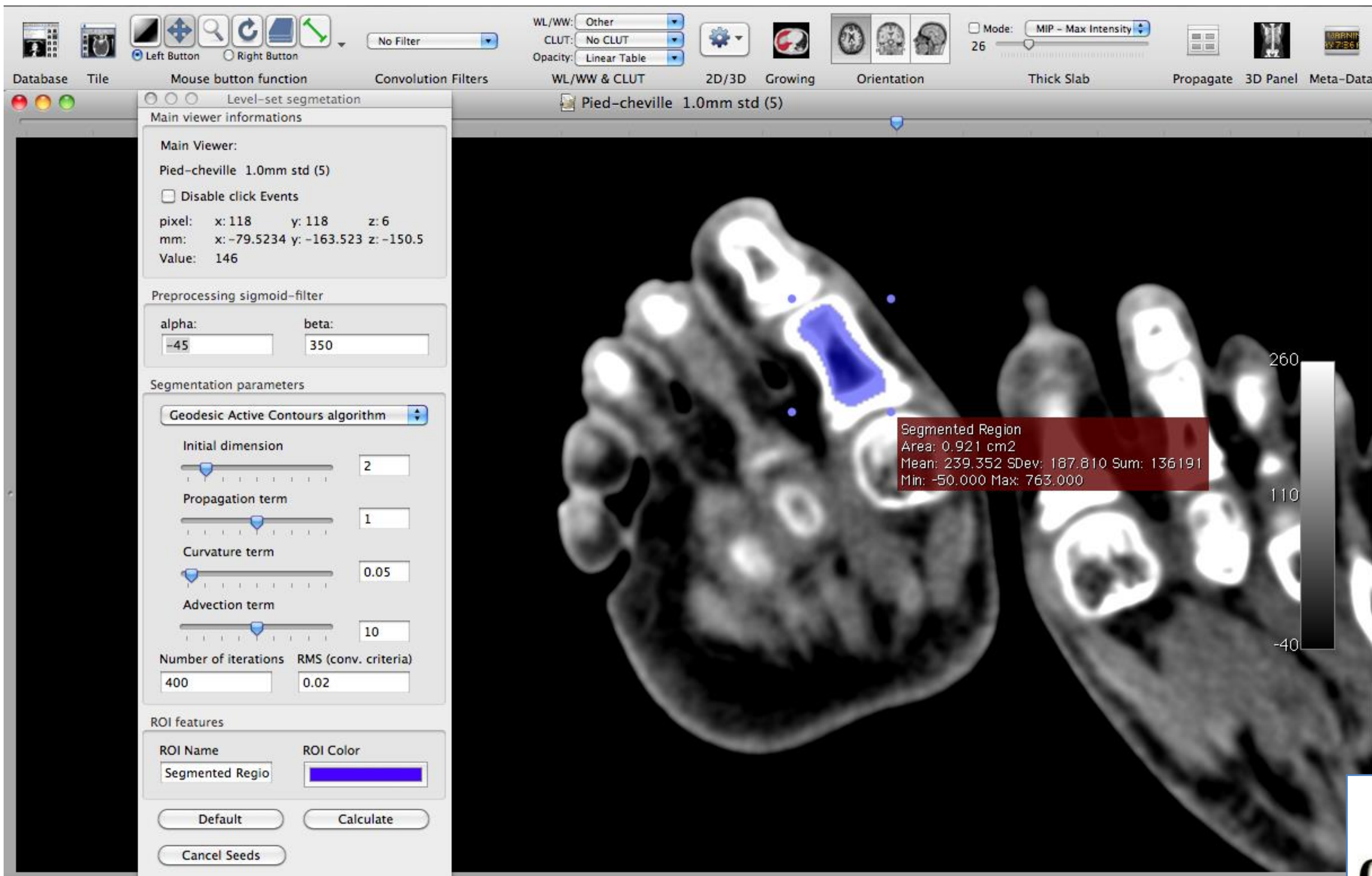


$$\frac{d}{dt}y = -a\mathbf{A}(\mathbf{x})\cdot\nabla y - bP(\mathbf{x})\left|\nabla y\right| + gZ(\mathbf{x})k\left|\nabla y\right|$$



R Malladi et al. Pattern Analysis and Machine Intelligence, IEEE Transactions on, 17(2):158 – 175, Feb 1995.
V Caselles et al. International Journal of Computer Vision, 22(1):61–79, 1997.

Osirix Plugins: Level-Set segmentation



Use of 123DCatch

FROM 3D SCAN TO STL







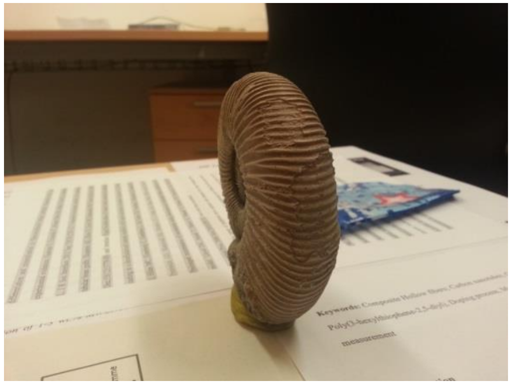




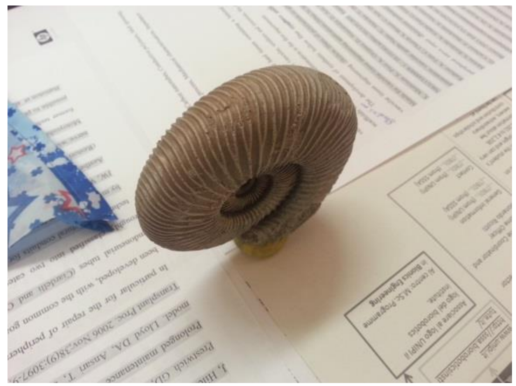


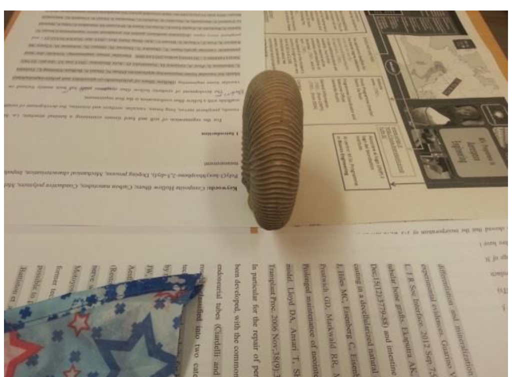


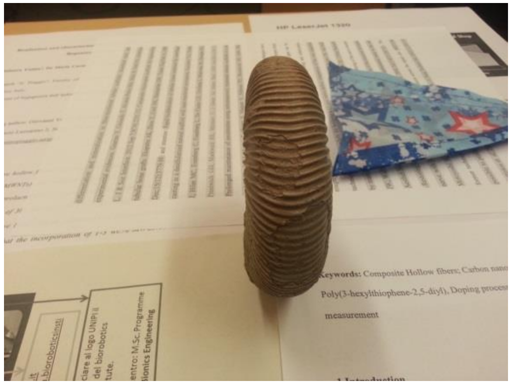


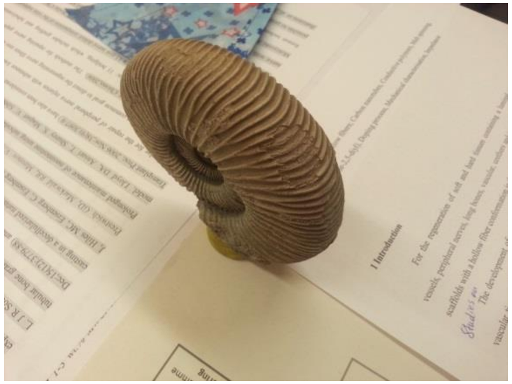










HP LaserJet 1320
Keywords: Composite Hollow fibers; Carbon nano
Poly(3-hexylthiophene-2,5-diyl), Doping process
measurement




Keywords: Composite Hollow fibers; Carbon nano
Poly(3-hexylthiophene-2,5-diyl), Doping process,
measurement
1 Introduction







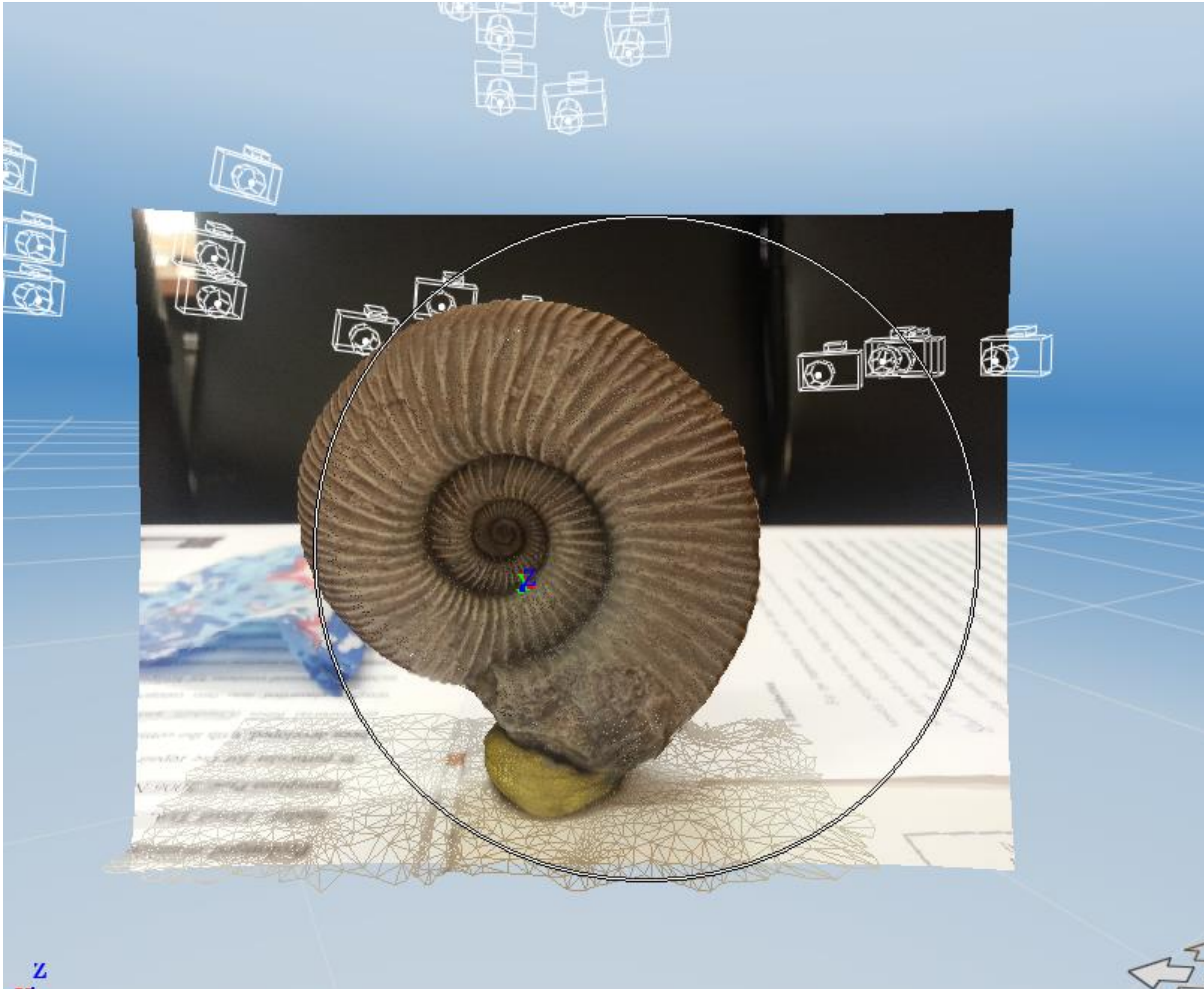


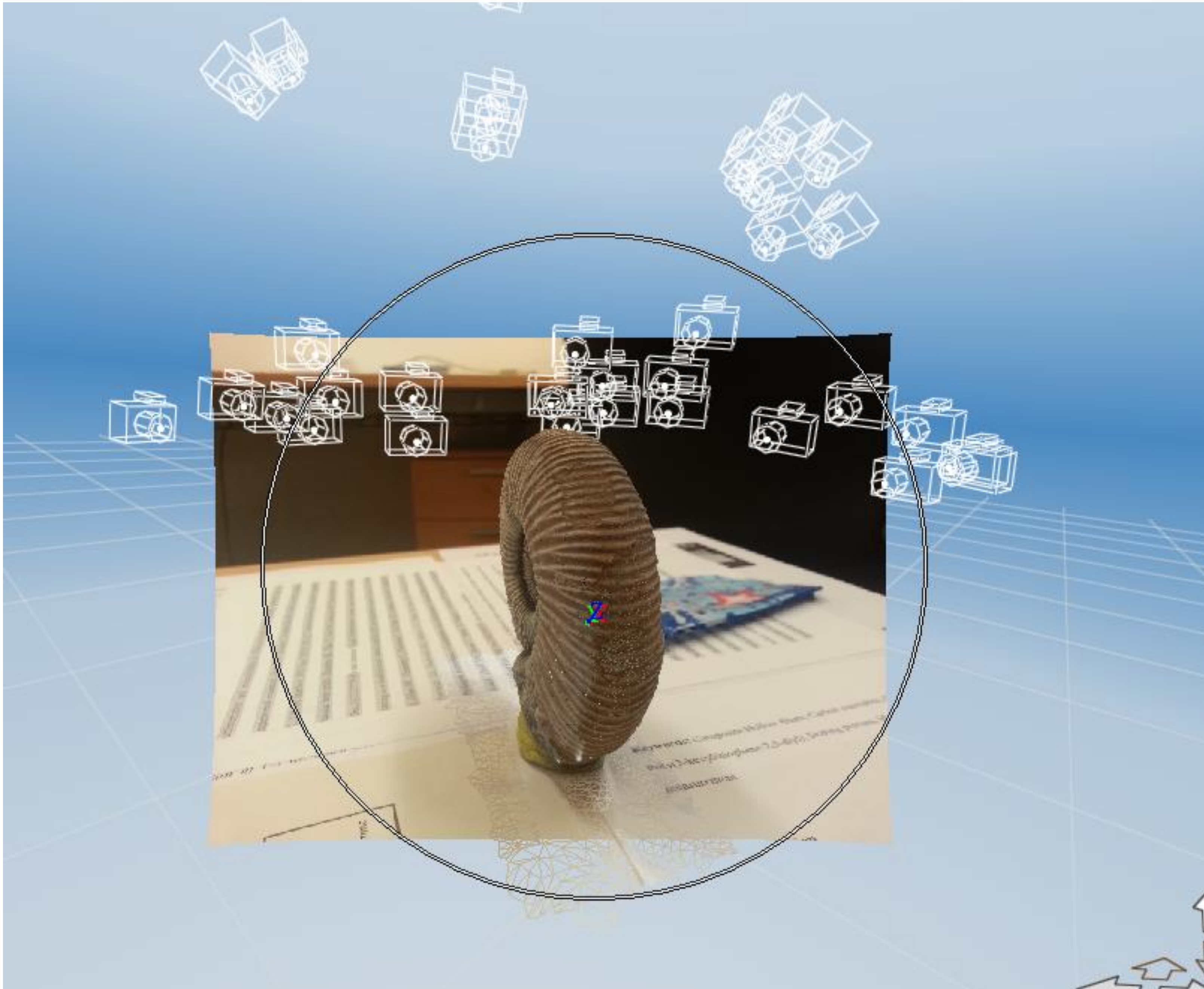


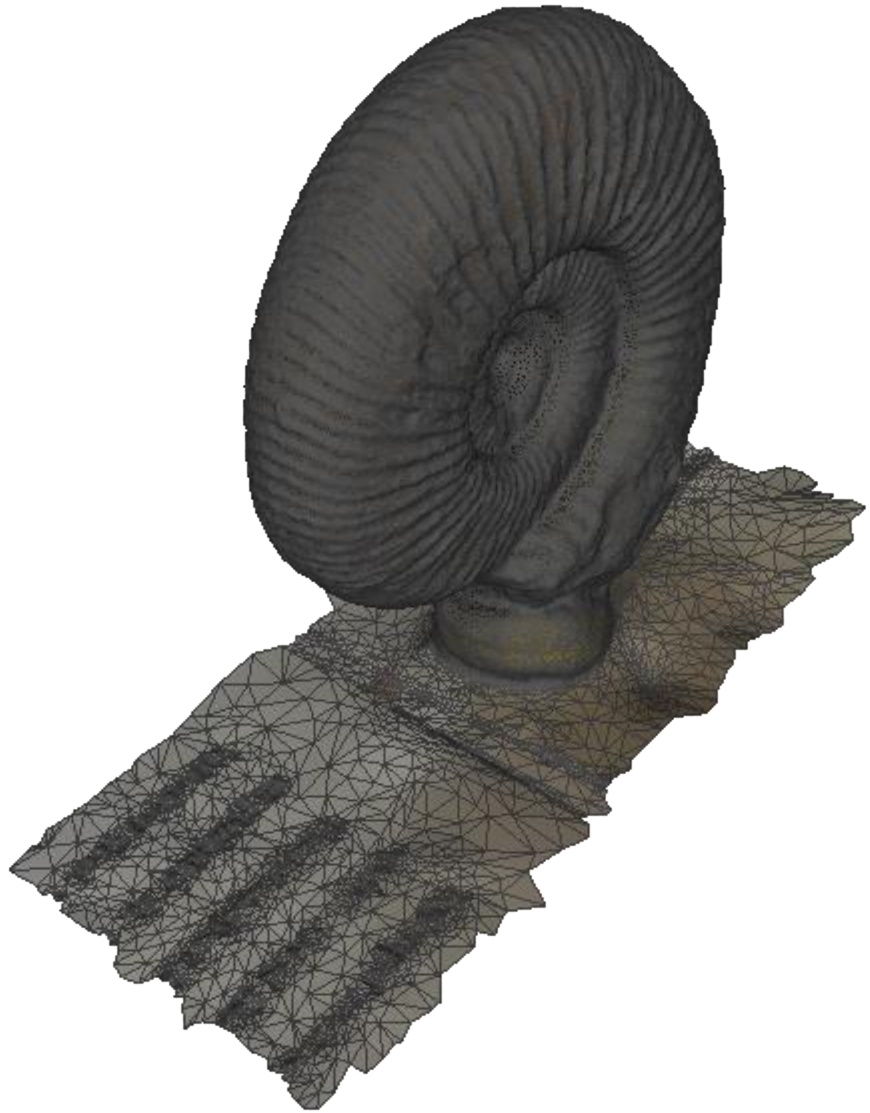


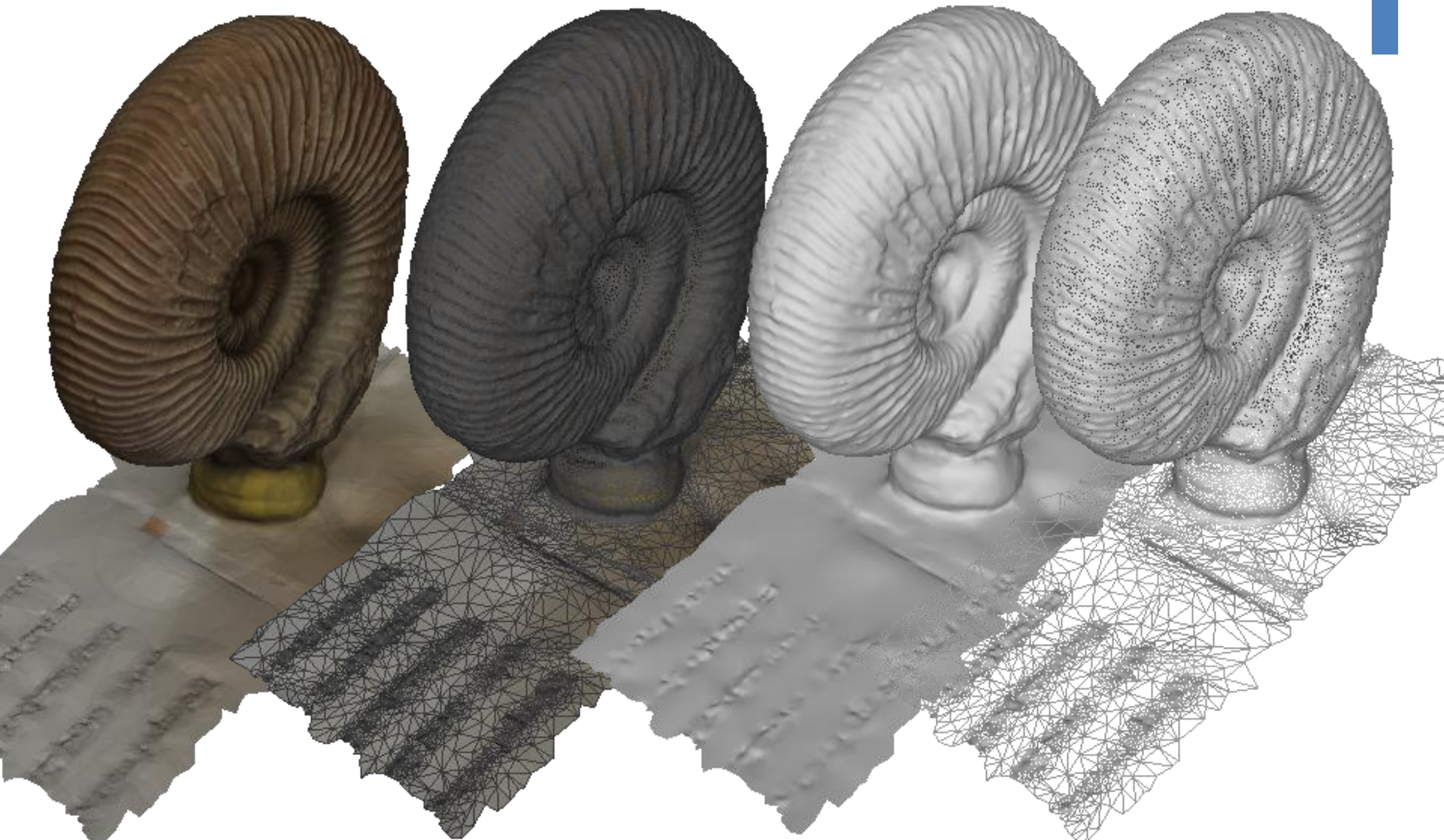










EXCHANGE FORMATS

Stereolithograpy Interface

- Stereolithograpy was first commercial Solid Freeform Manufacturing (SFM) 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 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

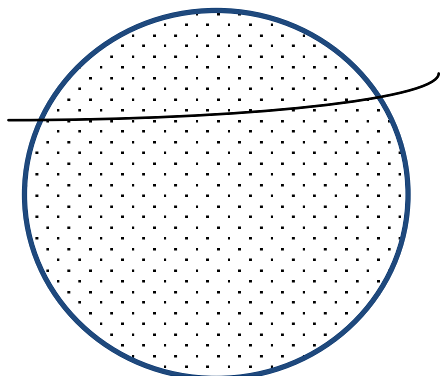
STL Files (*.stl)

- 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 (Smaller facets produce a higher quality surface)
- Triangles assigned normal vectors for outward surface normal
- Parts are defined by representing all their bounding surfaces as faceted surfaces, using the triangular patches

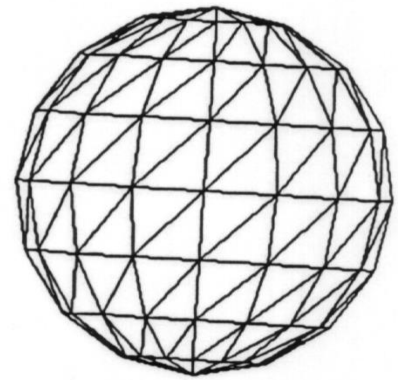
STL Files (*.stl)

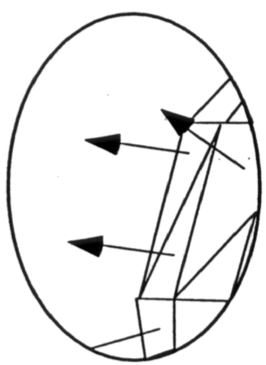
- STL files describe only the surface geometry of a three dimensional object without any representation of color, texture or other common CAD model attributes.
- An STL file describes a raw unstructured triangulated surface by the unit normal and vertices (ordered by the r
the triangles using a thre
Cartesian coordinate syst

Example of *.stl Representation



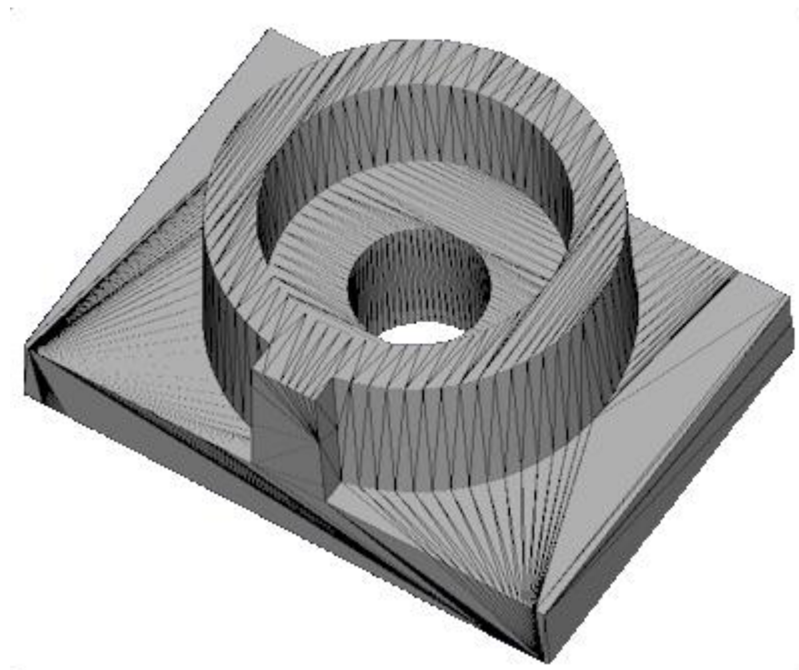
Representing a sphere





```
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
```

Example of *.stl Representation



Existing Formats (1/2)

- 3D PDF
  - Proprietary, closed
- ISO 14649 (STEP-NC)
  - Mostly for NC control, G-Code
- STEP / IGES, SAT, Parasolid
  - Too complex, missing features e.g. no mesostructure
- X3D VRML
  - Mesh, color, texture, lighting

All: no provision for AM, e.g. materials, internal structure

Existing Formats (2/2)

- PLY
  - 3D Scanner data
- 3DS
  - Limited mesh size
- SLC
  - Limited information

All: no provision for AM, e.g. materials, internal structure

New format needed

- Tailor to AM community needs
  - No content constraints
- Retain Community Control
  - Not Proprietary
- Neutral
  - Avoids association with existing companies

Desired features

- simple
- ISO 9000-ish features like product tracking
- Interoperability within different manufacturers
- Compatible with FEA applications
- Identification of parent CAD program
- Restricted number of printings
- Support multiple shells
- Editable ASCII/Text format

Desired features

- Information about build orientation
- Stability/robustness
- No redundancy
- Volume validity
- Lock or encrypt the file with a password
- Ability to put a permanent ‘watermark’
- Supporting geometry in native way
- Keep triangle mesh / No triangle mesh

Reaching consensus, adoption

- Non proprietary / open source
- Endorsement by major CAD / Manufacturers
- Use ASTM / Voting
- Backwards compatible (STL)
- Expandable, XML
- Publish for comments / discussion
- Open source software
- Conversion tools
- Limit the scope: Not a CAD model

Current STL

Advantages	Disadvantages
Simple	Geometry leaks
Sequential memory access*	No specified units
Portable	Unnecessary redundancy
	Incompatible with color, multiple materials, etc
	Poor scalability
*Does not require large amounts of RAM, critical in '80s	Lacks auxiliary information

The new proposed format

- AMF
  - Additive Manufacturing Format
  - Additive Manufacturing File

XML

- Meta-format: Format of formats
  - Text based
  - Easy to read/write/parse
  - Existing editing tools
  - Extensible
  - Highly compressible
- Mentioned by a number of constituents
  - E.g. Materialise
  - Based on work by J. Hiller (Cornell)

Addresses needs: Editable / Extensible / Readable / Open / Non proprietary

General Concept

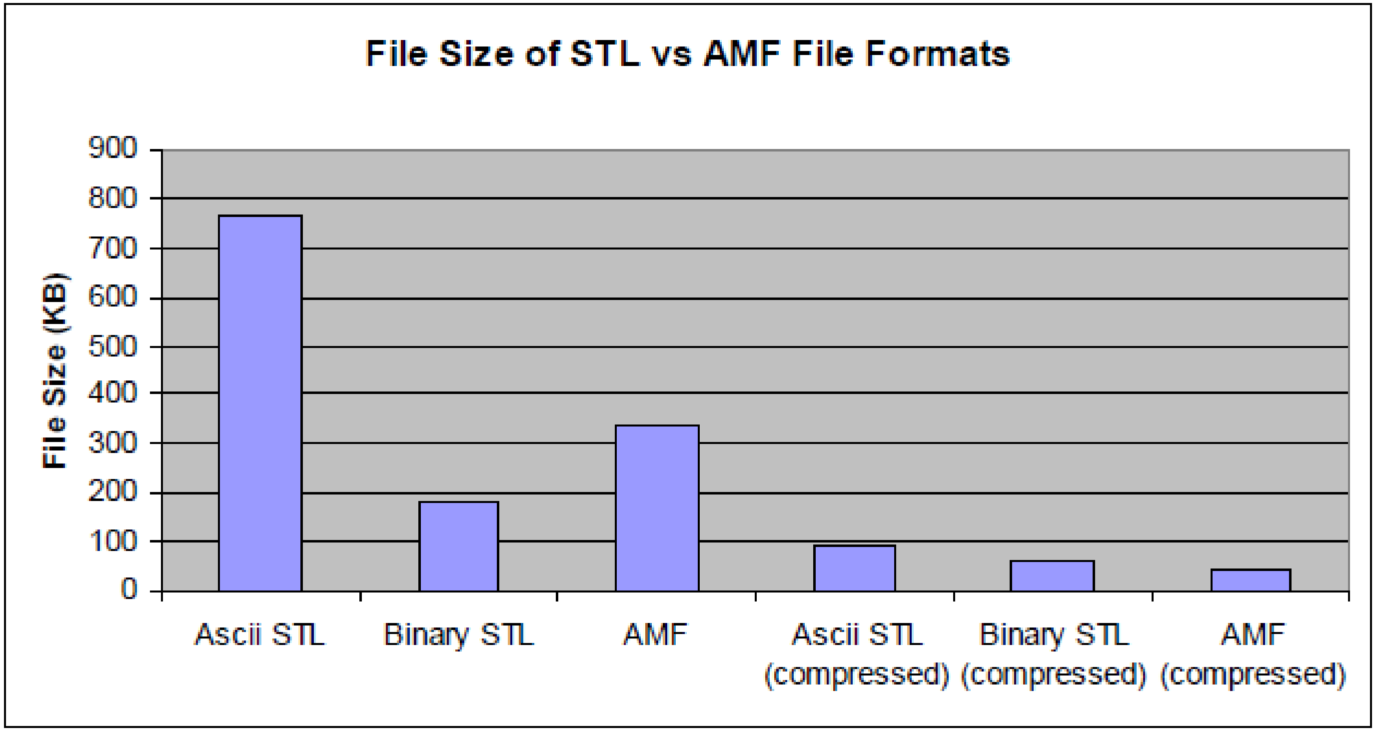
- Part (objects) defined by regions and materials
  - Regions defined by triangular mesh
  - Materials defined by properties/names
- Mesh properties can be specified
  - Color
  - Tolerance
  - Texture
- Materials can be combined
  - Graded materials
  - Microstructure

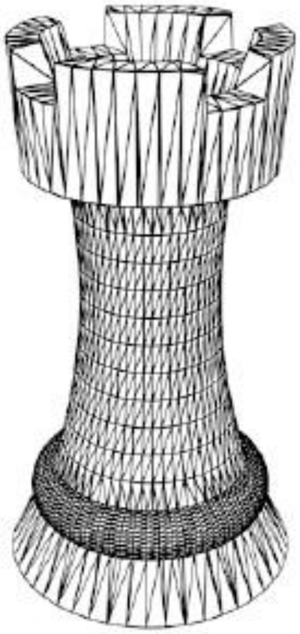
Basic Structure

```
<?xml version="1.0"?>
<AMF>
  <Object PrintID = "0" units = "mm">
    <Mesh>
      <Vertices>
        <Vertex VertexID="0">
          <VertexLocation x="0" y="1.332" z="3.715"/>
        </Vertex>
        <Vertex VertexID="1">
          <VertexLocation x="0" y="1.269" z="3.715"/>
        </Vertex>
        ...
      </Vertices>

      <Region FillMaterialID = "0">
        <Triangle V1 = "0" V2 = "1" V3 = "3"/>
        <Triangle V1 = "0" V2 = "1" V3 = "4"/>
        ...
      </Region>
    </Mesh>
  </Object>
</AMF>
```

Addresses needs:
Simple / Watertight / Backward Compatible (STL)

Compressibility





Need to look at dependency on # of digits

Addresses needs: Small / Compressible

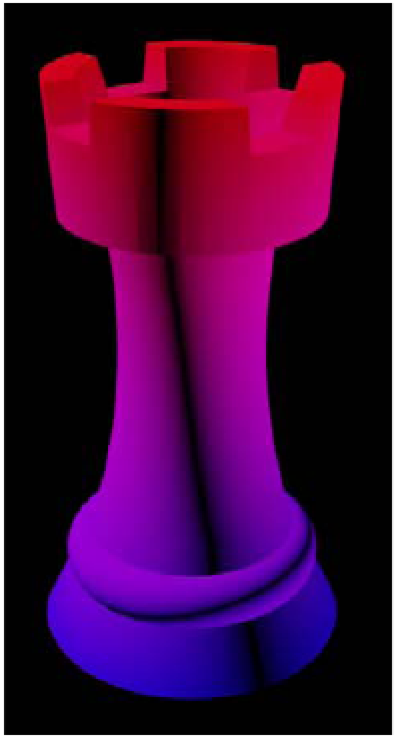
Multiple Materials

```
<?xml version="1.0"?>
<AMF>
  <Palette>
    <Material MaterialID = "0">
      <Name>StiffMaterial</Name>
    </Material>
    <Material MaterialID = "1">
      <Name>FlexibleMaterial</Name>
    </Material>
  </Palette>

  <Object PrintID = "0" units = "mm">
    <Mesh>
      <Vertices>
        ...
      </Vertices>

      <Region FillMaterialID = "0">
        ...
      </Region>
      <Region FillMaterialID = "1">
        <Triangle V1 = "5" V2 = "6" V3 = "7"/>
        <Triangle V1 = "5" V2 = "7" V3 = "9"/>
        ...
      </Region>
    </Mesh>
  </Object>
</AMF>
```

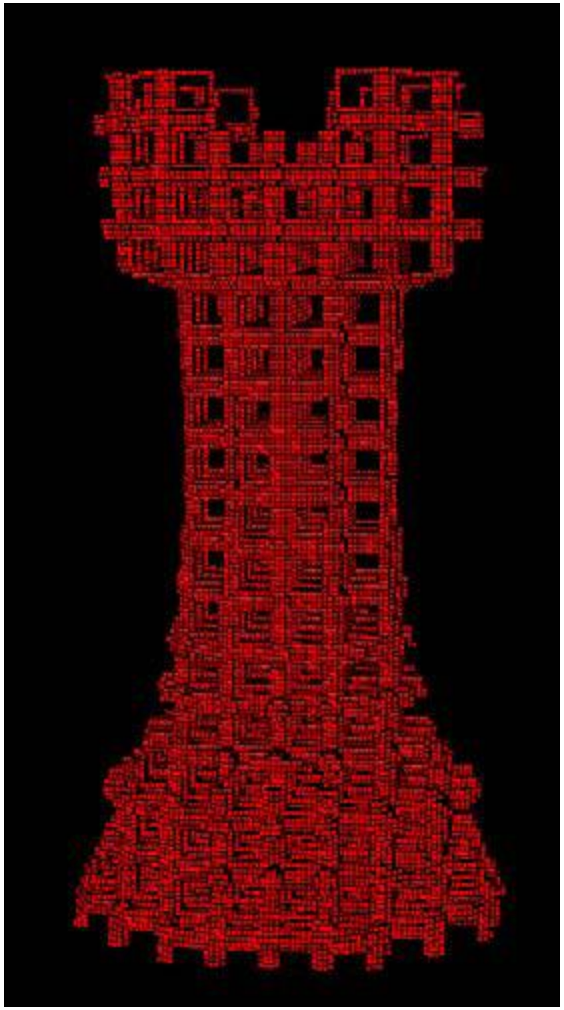
Addresses needs: Multiple Materials, No leaks between regions (shared vertices)

Graded Materials

```
<?xml version="1.0"?>
<AMF>
  <Palette>
    <Material MaterialID = "0">
      <Name>StiffMaterial</Name>
    </Material>
    <Material MaterialID = "1">
      <Name>FlexibleMaterial</Name>
    </Material>
    <Material MaterialID = "2">
      <Name>GradientMaterial</Name>
      <Equation UseMaterialID = "0">0.30*X</Equation>
      <Equation UseMaterialID = "1">0.30*(1-X)</Equation>
    </Material>
  </Palette>

  <Object PrintID = "0" units = "mm">
    ...
  </Object>
</AMF>
```



Microstructure



Addresses needs:
Periodic
meso/microstructure

Material properties

- By manufacturer’s name
  - <Name> **ABS** </Name>
  - <Name>**Tango Black** </Name>
  - <Name>**Nylon 1234** </Name>
- By physical property
  - </Property Type=“Elastic Modulus” Value=“4E9”>
  - </Property Type=“Poisson Ratio” Value=“1.2”>
- External reference (URL)

Addresses needs:
Material specifications/libraries

Color and Graphics

- By volumetric region
  - Solid color
- By vertex
  - Specify Vertex color
  - Specify Vertex coordinate in a bitmap

Addresses needs: Color graphics

Color and Graphics

```xml
<?xml version="1.0"?>
<AMF>
  <Object PrintID = "0" units = "mm">
    <Mesh>
      <ColorFile MapID="0">
        <File>Logo.bmp</File>
      </ColorFile>
      <Vertices>
        <Vertex VertexID="0">
          <VertexLocation x="0" y="1.332" z="3.715"/>
          <VertexMap UseMapID="0" MapXPixel="65"   MapYPixel="87"/>
        </Vertex>
        <Vertex VertexID="1">
          <VertexLocation x="0" y="1.269" z="3.715"/>
          <VertexMap UseMapID="0" MapXPixel="64" MapYPixel="87"/>
        </Vertex>
        <Vertex VertexID="2">
          <VertexLocation x="0" y="1.310" z="3.587"/>
          <VertexMap UseMapID="0" MapXPixel="32" MapYPixel="10"/>
        </Vertex>
        ...
      </Vertices>

      <Region FillMaterialID = "0">
        <Color R = "0" G = "0" B = "0.5"/>
        <Triangle V1 = "0" V2 = "1" V3 = "2"/>
        <Triangle V1 = "0" V2 = "1" V3 = "4"/>
        ...
      </Region>
    </Mesh>
  </Object>
</AMF>
```

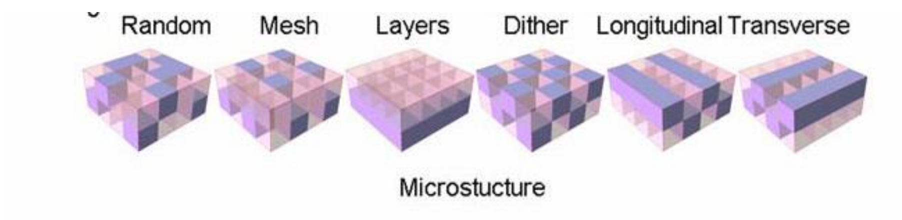
Tolerances

- By volumetric region
  - Nominal tolerance
  - Allowed variation from original volume
- By vertex
  - Specify point tolerance (?)
  - Point to point

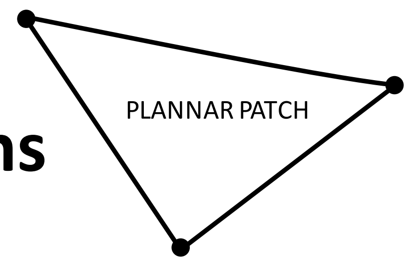
Addresses needs: Tolerance

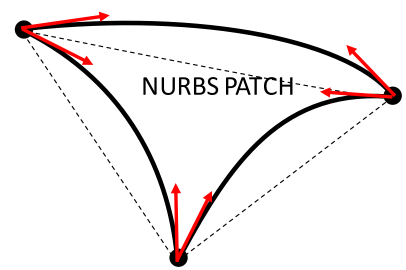
Non-meshed geometry?

- Other representations are not mutually exclusive
- **Voxel maps**
  - For digital/inkjet microstruc



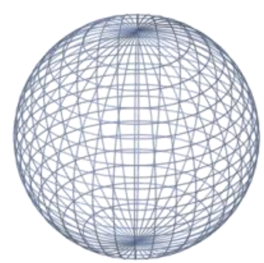
- **NURBS**
  - Add slope vectors to some triangle mesh edges
  - Other STEP types?





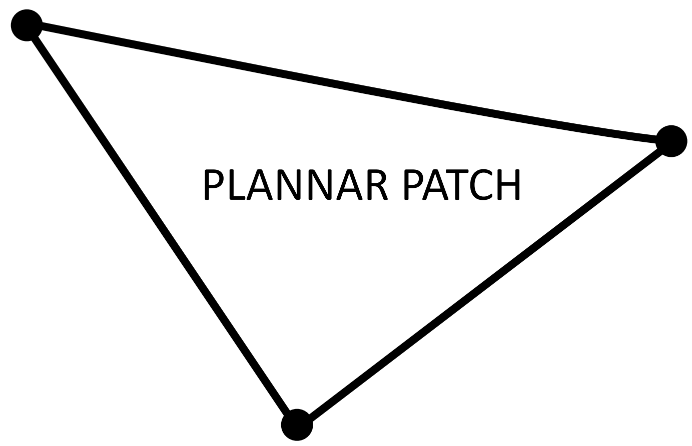
- **Functional Representations**
  - implicit equations

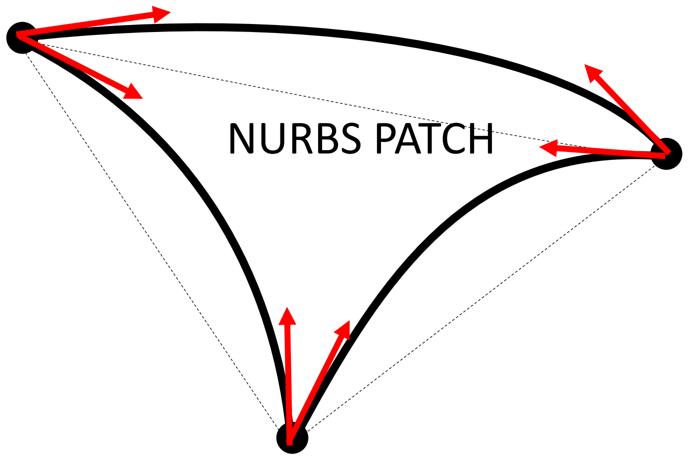
```
<?xml version="1.0"?>
<AMF>
  <Object PrintID = "0" units = "mm">
    <FRep MaterialID = "0">
      <GeometryEquation>
        <![CDATA[X^2+Y^2+Z^2-4 <= 0 & Z >= 0]]>
      </GeometryEquation>
    </FRep>
  </Object>
</AMF>
```



Nurbs patch

- Optionally add slope vectors to some triangle mesh edges to allow for very accurate geometry.
  - Perfect sphere can be made with ~20 patches





Print Constellation

- Print orientation
- Duplicated objects
- Sets of different objects
- Efficient nesting
- Hierarchical

Metadata

```
<Metadata>
    <Datum ID=“Author” Data=“John Doe”></Datum>
    <Datum ID=“Company” Data=“…”></Datum>
    <Datum ID=“Description” Data=“…”></Datum>
    <Datum ID=“Originating CAD System” Data=“…”></Datum>
    <Datum ID=“Originating CAD File” Data=“…”></Datum>
    <Datum ID=“Comment” Data=“…”></Datum>
</Metadata>
```

Encryption

```
<Metadata>
    <Datum ID="Author" Data="John Doe"></Datum>
    <Datum ID="Company" Data="..."></Datum>
    <Datum ID="Description" Data="..."></Datum>
    <Datum ID="Comment" Data="..."></Datum>
    <Datum ID="Encryption" Data="Prompt"></Datum>
</Metadata>
```

```
<Mesh>
  <Vertices>
    <Vertex VertexID="0">
      <VertexLocation x="0" y="1.332" z="3.715"/>
    </Vertex>
    <Vertex VertexID="1">
      <VertexLocation x="0" y="1.269" z="3.715"/>
    </Vertex>
```

Watermark / Copyright

```
<Metadata>
    <Datum ID="Author" Data="John Doe"></Datum>
    <Datum ID="Company" Data="…"></Datum>
    <Datum ID="Description" Data="…"></Datum>
    <Datum ID="Comment" Data="…"></Datum>
    <Datum ID="Copyright" Data="Owner"></Datum>
</Metadata>
```

```
<Mesh>
  <Vertices>
    <Vertex VertexID="0">
      <VertexLocation x="0" y="1.332" z="3.715"/>
    </Vertex>
    <Vertex VertexID="1">
      <VertexLocation x="0" y="1.269" z="3.715"/>
    </Vertex>
```

Other features

- URL can be used in lieu of material data to allow for external libraries
- Validation checksums
  - E.g. Original vs. actual part/region volumes
- Automatic error checking
  - Readers/writers must check for intact topology, e.g.
    - All nodes referenced by at least 3 triangles
    - All edges referenced exactly twice per region

+
ISO STANDARD