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Standard Specification for Additive Manufacturing File Format (AMF)[1]

This standard is issued under the fixed designation F XXXX; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last re-approval. A superscript epsilon (ε) indicates an editorial change since the last revision or re-approval.

1. Scope[1]

This standard describes a framework for a interchange format to address the current and future needs of additive manufacturing technology. For the last three decades, the STL file format has been the industry standard for transferring information between design programs and additive manufacturing equipment. An STL file contains information only about a surface mesh, and has no provisions for representing color, texture, material, substructure, and other properties of the fabricated target object. As additive manufacturing technology is quickly evolving from producing primarily single-material, homogenous shapes to producing multi-material geometries in full color with functionally graded materials and microstructures, there is a growing need for a standard interchange file format that can support these features.

The AMF file may be prepared, displayed, and transmitted on paper or electronically, provided the information required by this specification is included. When prepared in a structured electronic format, strict adherence to an XML schema is required to support standards-compliant interoperability. The Adjunct to this specification contains a W3C XML schema and Annex A1 contains an Implementation Guide for such representation.

This standard does not purport to address manufacturing safety and data security concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate security, safety and health practices and determine the applicability of regulatory limitations prior to use.

This standard also does not purport to address any copyright and intellectual property concerns, if any, associated with its use. It is the responsibility of the user of this standard to meet any intellectual property regulations on the use of information encoded in this file format.

[1] This specification is under the jurisdiction of ASTM Committee F42 on Additive Manufacturing Technologies and is the direct responsibility of Subcommittee F42.4 task group on Data Interchange.

2.1 Contributors

This standard has been prepared based on a survey and consensus among stakeholders representing designers, equipment manufacturers, CAD software developers, and academicians. A list of contributors is provided in Appendix 3.

2. Key considerations

There is a natural a tradeoff between the generality of a file format, and its usefulness for a specific purpose. Thus, features designed to meet the needs of one community may hinder the usefulness of a file format for other uses. In order to be successful across the field of additive manufacturing, this file format is designed to address the following concerns:

2.1 Technology independence: The file format shall describe an object in a general way such that any machine can build it to the best of its ability. It is resolution and layer-thickness independent, and does not contain information specific to any one manufacturing process or technique. This does not negate the inclusion of properties that only certain advanced machines support (for example, color, multiple materials, etc.), but these are defined in such away to avoid exclusivity.

2.2 Simplicity: The AMF file format is easy to implement and understand. The format can be read and debugged in a simple ASCII text viewer to encourage understanding and adoption. No identical information is stored in multiple places.

2.3 Scalability: The file format scales well with increase in part complexity and size, and with the improving resolution and accuracy of manufacturing equipment. This includes being able to handle large arrays of identical objects, complex repeated internal features (e.g. meshes), smooth curved surfaces with fine printing resolution, and multiple components arranged in an optimal packing for printing.

2.4 Performance: The file format should enable reasonable duration (interactive time) for read and write operations and reasonable file sizes for a typical large object. Detailed performance data is provided in the appendix.

2.5 Backwards compatibility: Any existing STL file can be converted directly into a valid AMF file without any loss of information and without requiring any additional information. AMF files are also easily converted back to STL for use on legacy systems, although advanced features will be lost. This format maintains the triangle-mesh geometry representation in order to take advantage of existing optimized slicing algorithm and code infrastructure already in existence.

2.6 Future compatibility: In order to remain useful in a rapidly changing industry, this file format is easily extensible while remaining compatible with earlier versions and technologies. This allows new features to be added as advances in technology warrant, while still working flawlessly for simple homogenous geometries on the oldest hardware.

3. Structure of this standard

Information specified throughout this standard is stored in XML format [1]. XML is an ASCII text file comprising a list of elements and attributes. Using this widely accepted data format opens the door to a rich host of tools for creating, viewing, manipulating, parsing and storing AMF files. XML is human-readable, which makes debugging errors in the file possible. XML can be compressed and/or encrypted if desired in a post-processing step using highly optimized standardized routines.

Another significant advantage of XML is its inherent flexibility. Missing or additional parameters do not present a problem for a parser as long as the document conforms to the XML standard. Practically, this allows new features to be added without needing to update old versions of the parser, such as in legacy software.

Precision

This file format is agnostic as to the precision of the representation of numeric values. It is the responsibility of the generating program to write as many or as few digits as are necessary for proper representation of the target object. However, a parsing program should read and process real numbers in double precision (64 bit).

Future amendments and additions

Additional XML elements can be added provisionally to any AMF file for any purpose but will not be considered part of this standard. An unofficial AMF element can be ignored by any reader, and does not need to be stored or reproduced on output. An element becomes official only when it is formally accepted into this standard.

Terminology

This section provides definitions of terms specific to this standard—these terms also include the common terms seen in many documents related to XML and Additive Manufacturing. See also Annex for definitions of additional terms specific to this specification.

Attribute—a characteristic of data, representing one or more aspects, descriptors, or elements of the data. In object-oriented systems, attributes are characteristics of objects. In XML, attributes are characteristics of elements.

Comments—all text comments associated with any data within the AMF not containing core relevant, technical, or administrative data, and not containing pointers to references external to the AMF.

Domain-specific applications—additional, optional sets of AMF data elements specific to such areas as novel additive manufacturing processes, enterprise workflow and supply chain management. Data sets for optional AMF domain-specific applications will be developed and balloted separately from this specification.

Extensible markup language (XML)—a standard from the WorldWideWeb Consortium (W3C) that provides for tagging of information content within documents, offering a means for representation of content in a format which is both human and machine readable. Through the use of customizable style sheets and schemas, information can be represented in a uniform way, allowing for interchange of both content (data) and format (metadata).

STL (file format)—a file format native to the stereolithography CAD software. This file format is supported by many software packages; it is widely used for rapid prototyping and computer-aided manufacturing. STL files describe only the surface geometry of a three dimensional object as a tessellation of triangles, without any representation of color, texture or other common CAD model attributes. The STL format specifies both ASCII and binary representations.

4. General structure

The AMF file begins with the XML declaration line specifying the XML version and encoding, for example:

```
<?xml version="1.0" encoding="UTF-8"?>
```

Blank lines and standard XML comments can be interspersed in the file and will be ignored by any interpreter, for example

```
<!-- ignore this comment -->
```

The remainder of the file is enclosed between an opening `<amf>` element and a closing `</amf>` element. These elements are necessary to denote the file type, as well as to fulfill the requirement that all XML files have a single root element. The version of the AMF standard as well as

all standard XML namespace declarations can be used, such as the `lang` attribute designed to identify the human language used. The unit system can also be specified (mm, inch, ft, meters or micrometers). In absence of a units specification, millimeters are assumed.

```
<amf unit="millimeter" version="1.0" xml:lang="en">
```

Within the AMF brackets, there are five top level elements:

1. `<object>` The object element defines a volume or volumes of material, each of which are associated with a material ID for printing. At least one object element must be present in the file. Additional objects are optional.
2. `<material>` The optional material element defines one or more materials for printing with an associated material ID. If no material element is included, a single default material is assumed.
3. `<texture>` The optional texture element defines one or more images or textures for color or texture mapping, each with an associated texture ID.
4. `<constellation>` The optional constellation element hierarchically combines objects and other constellations into a relative pattern for printing. If no constellation elements are specified, each object element will be imported with no relative position data. The parsing program can determine the relative positioning of the objects if more than one object is specified in the file.
5. `<metadata>` The optional metadata element specifies additional information about the object(s) and elements contained in the file.

Only a single `object` element is required for a fully functional AMF file.

5. Geometry specification

The top level `<object>` element specifies a unique `id`, and contains two child elements: `<vertices>` and `<volume>`. The `<object>` element can optionally specify a material.

The required `<vertices>` element lists all vertices that are used in this object. Each vertex is implicitly assigned a number in the order in which it was declared, starting at zero. The required child element `<coordinates>` gives the position of the point in 3D space using the `<x>`, `<y>` and `<z>` elements.

After the vertex information, at least one `<volume>` element must be included. Each volume encapsulates a closed volume of the object, Multiple volumes can be specified in a single object. Volumes may share vertices at interfaces but may not have any overlapping volume.

Within each volume, the child element `<triangle>` shall be used to define triangles that tesselate the surface of the volume. Each `<triangle>` element will list three vertices from the set of indices of the previously defined vertices. The indices of the three vertices of the triangles are specified using the `<v1>`, `<v2>` and `<v3>` elements. The order of the vertices must be according to the right-hand rule, such that vertices are listed in counter-clockwise order as viewed from the outside. Each triangle is implicitly assigned a number in the order in which it was declared, starting at zero.

```
<?xml version="1.0" encoding="UTF-8"?>
<amf unit="millimeter">
  <object id="0">
    <mesh>
      <vertices>
        <vertex>
          <coordinates>
            <x>0</x>
            <y>1.32</y>
            <z>3.715</z>
          </coordinates>
        </vertex>
        <vertex>
          <coordinates>
            <x>0</x>
            <y>1.269</y>
            <z>2.45354</z>
          </coordinates>
        </vertex>
        ...
      </vertices>

      <volume>
        <triangle>
          <v1>0</v1>
          <v2>1</v2>
          <v3>3</v3>
        </triangle>
        <triangle>
          <v1>1</v1>
          <v2>0</v2>
          <v3>4</v3>
        </triangle>
        ...
      </volume>
    </mesh>
  </object>
</amf>
```

Figure 1. A basic AMF file containing only a list of vertices and triangles. This structure is compatible with the STL standard.

Smooth geometry

By default, all triangles are assumed to be flat and all triangle edges are assumed to be straight lines connecting their two vertices. However, curved triangles and curved edges can optionally be specified in order to reduce the number of mesh elements required to describe a curved surface.

During read, a curved triangle patch shall be recursively subdivided into four triangles by the parsing program in order to generate a temporary set of flat triangles at any desired resolution for manufacturing or display. The depth of recursion shall be determined by the parsing program

but a minimal level of four is recommended (i.e. convert a single curved triangle into 256 flat triangles).

During write, the encoding software shall determine automatically the minimum number of curved triangles required to specify the target geometry to the desired tolerance, assuming that the parser will perform at least four levels of subdivision for any curved triangle.

To specify curvature, a vertex can optionally contain a child element `<normal>` to specify desired surface normal at the location of the vertex. The normal should be unit length and pointing outwards. If this normal is specified, all triangle edges meeting at that vertex should be curved so that they are perpendicular to that normal and in the plane defined by the normal and the original straight edge.

When the curvature of a surface at a vertex is undefined (for example at a cusp, corner or edge), an `<edge>` element can be used to specify the curvature of a single non-linear edge joining two vertices. The curvature is specified using the tangent direction vectors at the beginning and end of that edge. The `<edge>` element will take precedence in case of a conflict with the curvature implied by a `<normal>` element.

Normals shall not be specified for vertices referenced only by planar triangles. Edge tangents shall not be specified for linear edges.

When interpreting normal and tangents, Hermite interpolation will be used. See Annex 3 for formulae for carrying out this interpolation.

The geometry shall not be used to describe support structure. Only the final target structure shall be described.

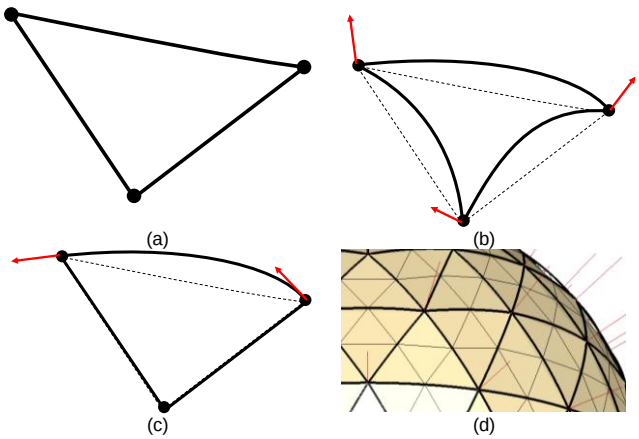
Restrictions on geometry

All geometry must comply with the following restrictions:

1. Every triangle must have exactly three different vertices
2. Triangles may not intersect or overlap, except at their common edges or common vertices
3. Volumes must enclose a closed space with nonzero volume
4. Volumes may not overlap
5. Every vertex must be referenced by at least three triangles
6. Every pair of vertices must referenced by zero or two triangles per volume
7. No two vertices can have identical coordinate
8. The outward direction of triangles that share an edge in the same volume must be consistent

6. Material specification

Materials are introduced using the `<material>` element. Any number of materials may be defined using the `<material>` element. Each material is assigned a unique `id`. Geometric volumes are associated with materials by specifying a `materialid` within the `<volume>` element. Any number of materials may be defined. The `materialid` "0" is reserved for no material (void).




```
<?xml version="1.0" encoding="UTF-8"?>
<amf unit="millimeter">
  <object id="0">
    <mesh>
      <vertices>
        <vertex>
          <coordinates >
            ...
          </coordinates >
          <normal>
            <nx>0</nx>
            <ny>0.707</ny>
            <nz>0.707</nz>
          </normal>
        </vertex>
        ...
        <edge>
          <v1>0</v1>
          <dx1>0.577</dx1>
          <dy1>0.577</dy1>
          <dz1>0.577</dz1>
          <v2>1</v2>
          <dx2>0.707</dx2>
          <dy2>0</dy2>
          <dz2>0.707</dz2>
        </edge>
        ...
      </vertices>

      <volume materialid="0">
        <triangle>
          ...
        </triangle>
        ...
      </volume>
    </mesh>
  </object>
</amf>
```

(e)

Figure 2. Specifying curvature: (a) A default (flat) triangle patch, (b) A triangle curved using vertex normals, (c) a triangle curved using edge tangents. (d) subdivision of a curved triangle patch into four curved sub-patches; (e) An AMF file containing curved

geometry.

Material attributes are contained within each <material>. The element <color> is used to specify the RGBA appearance of the material (see section 7 on color). Additional material properties can be specified using the <metadata> element, such as the material name for operational purposes, or elastic properties for equipment that can control such properties. See Annex 1 for more information.

```
<?xml version="1.0" encoding="UTF-8"?>
<amf unit="millimeter">
  <material id="1">
    <metadata type="Name">StiffMaterial</metadata>
  </material>
  <material id="2">
    <metadata type="Name">FlexibleMaterial</metadata>
  </material>
  <material id="3">
    <metadata type="Name">MediumMaterial</metadata>
    <composite materialid="1">0.4</composite>
    <composite materialid="2">0.6</composite>
  </material>
  <material id="4">
    <metadata type="Name">VerticallyGraded</metadata>
    <composite materialid="1">z</composite>
    <composite materialid="2">10-z</composite>
  </material>
  <material id="5">
    <metadata type="Name">Checkerboard</metadata >
    <composite materialid="1">
          floor(x+y+z%1)+0.5) </composite>
    <composite materialid="2">
          1-floor(x+y+z%1)+0.5) </composite>
  </material>

  <object id="0">
    <mesh>
      <vertices>
        ...
      </vertices>
      <volume materialid="1">
        ...
      </volume>
      <volume materialid="2">
        ...
      </volume>
    </mesh>
  </object>
</amf>
```

Figure 3. Homogenous and composite materials. An AMF file containing five materials. Material 3 is a 40/60% homogenous mixture of the first two materials. Material 4 is a vertically graded material; Material 5 has a periodic checkerboard substructure.

Mixed and graded materials and substructures

New materials can be defined as compositions of other materials. The element <composite> is used to specify the proportions of the composition, as a constant or as a formula dependent of the *x*, *y*, and *z* coordinates. A constant mixing proportion will lead to a homogenous material. A coordinate-dependent composition can lead to a graded material. More complex coordinate-dependent proportions can lead to nonlinear material gradients as well as periodic and non-periodic substructure. The proportion formula can also refer to a texture map using the tex(textureid,x,y,z) function (See Annex 1).

Any number of materials can be specified. Any negative material proportion value will be interpreted as a zero proportion. Material proportions shall be normalized to determine actual ratios.

Although the <composite> element could theoretically be used to describe the complete geometry of an object as a single function or texture, such use is discouraged (but see Appendix 2). The intended use of the <composite> element is for the description of cellular mesostructures.

Porous materials

Reference to materialid "0" (void) can be used to specify porous structures. The proportion of void can be either 0 or 1 only. Any fractional value will be interpreted as 1 (i.e. any fractional void will be assumed fully void).

Stochastic materials

Reference to the rand(x,y,z) function can be used to specify pseudo-random materials. For example, a composite material could combine two base materials in random proportions where the exact proportion can depend on the coordinates in various ways. The rand(x,y,z) function produces a random scalar in the range [0,1) that is persistent across function calls (see Annex 4).

7. Color specification

Colors are introduced using the <color> element by specifying the red, green, blue and alpha (transparency) values in a specified color space. By default, the color space be sRGB [2] but alternative profiles could be specified using the profile attribute (see Annex 1). The <color> element can be inserted at the material level to associate a color with a material, at the object level to color an entire object, at the volume level to color an entire volume, or at a vertex level to associate a color with a particular vertex.

Object color overrides material color specification; a volume color overrides an object color, and vertex colors override volume colors.

Graded colors and texture mapping

A color can also be specified by referring to a formula that can use a variety of functions including a texture map.

When referring to a formula, The <color> element can specify a color that depends on the coordinates, such as a graded color or a spotted color. Any mathematical expression that combined the functions described in Annex 2 can be used. For example, use of the rand function can allow for pseudo-random color patterns. The

`tex` function can allow the color to depend on a texture map or image. To specify a full color graphic, typically three textures will be needed, one for each color channel. To create a monochrome graphic, typically only one texture is sufficient.

When the vertices of a single triangle have different colors, the interior color of the triangle will linearly interpolate between those colors, unless a triangle color has been explicitly specified (because a triangle color takes precedence over a vertex color). When two triangles specify different colors to the same vertex, the colors will be averaged.

Transparency

The transparency channel <a> determines alpha compositing for combining the specified foreground color with a background color to create the appearance of partial transparency. A value of 0 specifies zero transparency, i.e. only the foreground color is used. A value of 1 specifies full transparency, i.e. only the background color is used. Intermediate values are used for a linear combination. Negative values are rounded to 0 and values greater than 1 are truncated to 1. The background color of a triangle is the vertex color. The background color of a vertex is the volume color, then object, and material in decreasing precedence.

8. Texture specification

The `<texture>` element can be used to associate a `textureid` with particular texture data. The texture map size will be specified and both 2D and 3D maps are supported. The data will be encoded string of bytes in Base64 encoding, as grayscale values. Grayscale will be encoded as a string of individual bytes, one per pixel, specifying the grayscale level in the 0-255 range. The ordering of data will start with the top left corner and proceeding left to right then top to bottom. A 3D texture will specify the first layer initially and repeat for all subsequent depths. The data will be truncated or appended with zero values as needed to meet the specified texture size.

```
<?xml version="1.0"?>
<amf unit="millimeter">

  <material id="1">
    <metadata type="Name">StiffMaterial</metadata>
      <color>
        <r>0</r>
        <g>z</g>
        <b>1-z</b>
      </color>
  </material>

  <texture id="1" width="10" height="26" type="grayscale">
    TWFuIGlzIGRpc3RpbmdlaXNoZWQsIG5vdCB
    vbmx5IGJ5IGhpcyByZWFzb24sIGJ1dCBieS
    B0aGlzIHNpbmd1bGFyIHBhc3Npb24gZnJvb
    SBvdGhlciBhbmltYWxzLCB3aGljaCBpcyBh
    ...
  </texture>


  <object id="0">
    <mesh>
      <vertices>
        ...
      </vertices>
      <volume materialid="1">
        <color>
          <r>0.9</r>
          <g>0.9</g>
          <b>0.2</b>
          <a>0.8</a>
        </color>
        ...
        <triangle>
          <v1>0</v1>
          <v2>1</v2>
          <v3>3</v3>
          <color>
            <r>tex(1,x,y)</r>
            <g>tex(2,x,y)</g>
            <b>tex(3,x,y)</b>
            <a>0.1</a>
          </color>
        </triangle>
      </volume>
    </mesh>
  </object>
</amf>
```

Figure 4. Color Specification. Absolute color can be associated with a material, a volume or a vertex. A vertex can also be associated with a coordinate in a color texture file.

9. Print Constellations

Multiple objects can be arranged together using the `<constellation>` element. A constellation can specify the position and orientation of objects to increase packing efficiency and to describe large arrays of identical objects. The `<instance>` element specifies the displacement and rotation an existing objects needs to undergo into its position in the constellation. The displacement and rotation are always defined relatively to the original position and orientation in which the object was originally defined. Rotation angles are specified in degrees and are applied first to rotation about the *x* axis, then about the *y* axis, and then about the *z* axis.

A constellation can refer to another constellation. However, recursive or cyclic definitions of constellations are not allowed.

When multiple objects and constellations are defined in a single file, only the top level objects and constellations are available for printing.

The orientation at which the objects will be printed will default to those specified in the constellation. The *z* axis is assumed to be the vertical axis, with the positive direction pointing upwards and zero referring to the printing surface. The *x* and *y* directions will correspond to the main build stage axes if a gantry positioning system is used.

```
<?xml version="1.0"?>
<amf unit="millimeter">
  <object id="1">
        ...
  </object>
  <constellation id="2">
    <instance objectid="1">
      <deltay>5</deltay>
      <rz>90</rz>
    </instance>
    <instance objectid="1">
      <deltax>-10</deltay>
      <deltay>10</deltay>
      <rz>180</rz>
    </instance>
    ...
  </constellation>

</amf>
```

Figure 5. Print constellations. A constellation can assemble multiple objects together.

10. Meta-data

The <metadata> element can optionally be used to specify additional information about the objects, geometries and materials being defined. For example, this information can specify a name, textual description, authorship, copyright information and special instructions. The <metadata> element can be included at the top level to specify attributes of the entire file, or within objects, volumes and materials to specify attributes local to that entity. Annex 1 lists reserved metadata types and their meaning.

```
<?xml version="1.0"?>
<amf unit="millimeter">
  <metadata type="Description">Product 123</metadata>
  <metadata type="Author">John Smith</metadata>
  <metadata type="CAD">SolidX 2.2</metadata>
  <metadata type="Name">Part 1</metadata>
  <metadata type="Revision">1.3A</metadata>
        ...
  <object ObjectID="0">
     <metadata type="Name">Component 1</metadata>
        ...
  </object>
</amf>
```

Figure 6. Meta Data. Additional information can be stored about the object using the metadata element.

11. Compression and distribution

An AMF shall be stored either in plain text or be compressed. If compressed, the compression shall be in ZIP archive format [4] and can be done manually or at write time using any one of several open compression libraries, such as [5].

Both the compressed and uncompressed version of this file will have the AMF extension and it is the responsibility of the parsing program to determine whether or not the file is compressed, and if so to perform decompression during read.

Additional files may be included in the ZIP archive, such as manifest files and electronic signatures. However only the AMF file with the same name as the archive file will be parsed. Absence of a file with that name will constitute an error.

This standard does not specify any explicit mechanisms for ensuring data integrity, electronic signatures and encryptions.

12. Tolerances, textures, and additional information

It is recognized that there is additional information relevant to the final part that is not covered by the current revision of this standard. Suggested future features are listed in Appendix 2.

13. References

1. W3C Extensible Markup Language (XML) 1.0 (Fifth Edition) http://www.w3.org/TR/REC-xml/
2. A Standard Default Color Space for the Internet - sRGB, http://www.w3.org/Graphics/Color/sRGB
3. See sample code for implementation of an AMF/STL viewer and converter (BSD Open source) at: http://www.mae.cornell.edu/ccsl/amf
4. ZIP File Format Specification, PKWARE Inc, http://www.pkware.com/documents/casestudies/APPNOTE.TXT
5. See zip libraries such as info-zip (http://www.info-zip.org/

14. Annex 1 - AMF Elements

Element	Parent element(s)	Attributes	Multi elements?	Description
<amf>			No	Root XML element
		unit		The units to be used. May be "inch", "millimeter", "meter", "feet", or "micron".
<object>	<amf>		Yes	An object definition
		id		A unique ObjectID for the new object being defined
<color>	<material> <object> <volume> <vertex> <triangle>		No	The color to display the object in, and to print if supported. When conflicting color specifications exist, precedence is given according to the order of the list to the left, where a color specified in a <triangle> element takes precedent over a color specified in a <material> element. The sRGB colorspace will be assumed unless an alternative color profile attribute is provided.
		profile		The ICC color space used to interpret the three color channels <r>, <g> and <b>. Can be one of "sRGB", "AdobeRGB", "Wide-Gamut-RGB", "CIERGB", "CIELAB", or "CIEXYZ".
<r>, <g>, <b>, <a>	<color>		No	Red, Greed, Blue and Alpha (transparency) component of a color in sRGB space, values ranging from 0 to 1. The values can be specified as constants, or as a formula depending on the coordinates.
<mesh>	<object>		Yes	A 3D mesh hull
<vertices>	<mesh>		No	The list of vertices to be used in defining triangles
<vertex>	<vertices>		Yes	A vertex to be referenced in triangles
<coordinates>	<vertex>		No	Specifies the 3D location of this vertex
<x>, <y>, <z>	<coordinates>		No	X, Y, or Z coordinate, respectively, of a vertex position in space
<normal>	<vertex>		No	Specifies the 3D normal of the object surface at this vertex
<edge>	<vertices>		No	Specifies the 3D tangent of an object edge between two vertices
<dx1>,<dy1>,<dz1> <dx2>,<dy2>,<dz2>	<edge>		No	The normalized X, Y, or Z component (respectively) of the first or second edge direction vector
<nx>, <ny>, <nz>	<normal>		No	The normalized X, Y, or Z component (respectively) of a surface normal at a vertex
<volume>	<mesh>		Yes	Defines a volume from the established vertex list
		materialid		Which material to use
		type		What this volume describes can be “region” or “support”. If none specified, “object” is assumed. If support, then the geometric requirements 1-8 listed in section 5 do not need to be maintained.
<triangle>	<volume>		Yes	Defines a 3D triangle from three vertices, according to the right-hand rule (counter-clockwise when looking from the outside)
<v1>, <v2>, <v3>	<triangle> <edge>			Index of the desired vertices in a triangle or edge
<texture>			Yes	Specifies an texture data to be used as a map. Lists a sequence of Base64 values specifying values for pixels from left to right then top to bottom, then layer by layer.

		id		Assigns a unique texture id for the new texture
		width		Width (horizontal size, x) of the texture, in pixels.
		height		Height (lateral size, y) of the texture, in pixels.
		depth		Depth (vertical size, z) of the texture, in pixels.
		type		Encoding of the data in the texture. Currently allowed values are "grayscale" only. In grayscale mode, each pixel is represented by one byte in the range of 0-255. When the texture is referenced using the tex function, these values are converted into a single floating point number in the range of 0-1 (see Annex 2). A full color graphics will typically require three textures, one for each of the color channels. A graphic involving transparency may require a fourth channel.
<material>	<amf>		Yes	An available material
		id		A unique material id. material ID "0" is reserved to denote no material (void) or sacrificial material.
<composite>	<material>		Yes	Compose existing materials. Value provides a numeric constant or mathematical function of coordinates x, y, z specifying the proportion of material of type MaterialID. If the value is negative, is assumed to be zero. The proportions are normalized to add up to 1, unless they are all zero, in which case no material is specified (void). Reference to MaterialID "0" implies reference to no material (void). The void material cannot be mixed. See Annex 2 for a list of allowable mathematical functions
		materialid		Reference to an existing material. Reference cannot be recursive or cyclic.
<constellation>	<amf>		Yes	A collection of objects or constellations with specific relative locations
		id		The Object ID of the new constellation being defined.
<instance>	<constellation>		Yes	An instance of an object or constellation to print
		objectid		The ObjectID of the existing object or constellation being instantiated. Recursive or cyclic references are not allowed.
<deltax>, <deltay>,<deltaz>	<instance>		No	The distance of translation in the x, y, or z direction, respectively, in the referenced object's coordinate system, to create an instance of the object in the current constellation
<rx>,<ry>,<rz>	<instance>		No	The rotation, in degrees, to rotate the referenced object about its x, y, and z axes, respectively, to create an instance of the object in the current constellation. Rotations shall be executed in order of x first, then y, then z.
<metadata>	<amf>, <object>, <volume>, <material>, <vertex>		Yes	Specify additional information about an entity.
		type		The type of the attribute. Reserved types are: "Name" - The alphanumeric label of the entity, to be used by the interpreter if interacting with the user. "Description" - A description of the content of the entity "URL" - A link to an external resource relating to the entity "Author" - Specifies the name(s) of the author(s) of the entity "Company" - Specifying the company generating the entity "CAD" - specifies the name of the originating CAD software and version "Revision" - specifies the revision of the entity "Tolerance" - specifies the desired manufacturing tolerance of the entity in entity's unit system "Volume" - specifies the total volume of the entity, in the entity's unit system, to be used for verification (object and volume only)

				"Elastic Modulus" - specifies the elastic modulus of the entity, in SI units (material only) "Poisson Ratio" - specifies the Poisson Ratio of the material, in SI units (material only)

15. Annex 2 - Mathematical operations and functions

Precedence	Operator	Description
1	**()**	Parentheses block
2	**^**	Power
3	*****	Multiply
3	**/**	Divide
3	**%**	Modulus, including fractional
4	**+**	Add
4	**-**	Subtract
5	**=**	Equal*
5	**<, <=**	Less than (or equal to)*
5	**>, >=**	Greater than (or equal to)*
6	**&**	Intersection (Logical AND)*
6	**|**	Union (Logical OR)*.
6	****	Difference (Logical XOR)*
6	**!**	Negation (Logical NOT)*
6	sin(x)	Sine, radians
6	cos(x)	Cosine, radians
6	tan(x)	Tangent, radians
6	asin(x)	Arc sine, radians
6	acos(x)	Arc cosine, radians
6	atan(x)	Arc tangent, radians
6	floor(x)	Round down to nearest integer
6	ceil(x)	Round up to nearest integer
6	sqrt(x)	Square root
6	log(x)	Natural logarithm
6	exp(x)	Natural exponent
6	abs(x)	Absolute value
6	max(x,y)	Maximum value
6	min(x,y)	Minimum value
6	rand(x,y) rand(x,y,z) rand(x,y,z,k)	Maps the 2D or 3D coordinate onto a real (fractional) pseudo-random number uniformly distributed in the range [0-1) (exclusive of 1). The number returned will be persistent across multiple calls (i.e. the same number will always be returned for the same coordinate). If k=1, a second (probably different) number will be returned for that coordinate. See sample implementation in Annex 4.
6	tex(textureid,x,y,z) tex(textureid,x,y)	Returns a scalar value in the range [0-1] that interpolates the texture with the textureid at the coordinate (x,y,z) for 3D textures and (x,y) for 2D textures. if the texture is of type "grayscale", the range [0-1] corresponds to [0-255] in the texture data. Whole coordinate values refer to the center of the texture map pixels. If the values are fractional, linear interpolation shall be used. If the coordinates fall outside the texture, a zero value shall be returned. Any wrap-around functionality should be specified by the calling function, for example by using a modulo operator. If the texture is two dimensional and a z coordinate is specified, the *z* coordinate shall be ignored.

* Logical operators returns a Boolean value of either 1 or 0, representing TRUE and FALSE, respectively. When processing non Boolean numbers as Boolean values, a zero value represents FALSE, and a nonzero value represents TRUE.

16. Annex 3 - Formulae for interpolating a curved triangular patch

Non-planar triangular patches with specified vertex normals or edge tangents shall be interpolated from their three endpoints and six tangent vectors and/or three vertex normals using interpolated Hermite curves, as follows.

1. For each of the three edges of the triangle (refer to Figure 7a):
    a. If the normal n_0 at point v_0 is not specified explicitly using the `<normal>` element, compute the normal n_0 by computing the cross product between the two edge tangents meeting at that point. For this calculation,

use the edge tangents specified by the `<edge>` element if available, from step (f) executed in a prior recursion, or if neither are available, use a straight line connecting the edge endpoints. The resulting normal n_0 should be normalized to unit length and its sign set so that it is pointing outwards.

b. Repeat step (a) for the normal n_1 at point v_1.

c. If the tangents t_0 is not specified explicitly in an `<edge>` element or a previous recursion, compute the tangent vector t_0 such that it is perpendicular to the normal at n_0 and resides in the plane defined by that normal and the vector connecting the two vertices v_0 and v_1. The following formula for t_0 can be used. Given v_0, n_0 and v_1, define $d=v_1-v_0$, and

$$t_0 = |d| \frac{-(n_0 \times d) \times n_0}{\|(n_0 \times d) \times n_0\|}$$

d. Repeat step (c) for the tangent t_1 at point v_1.

e. Compute the center point $v_{01}=h(0.5)$ using 2nd order Hermite curve interpolation

$h(s)=(2s^3-3s^2+1)v_0+(s^3-2s^2+s)t_0+(-2s^3+3s^2)v_1+(s^3-s^2)t_1$

f. Compute the center tangent $t_{01}=t(0.5)$ using the derivative of the 2nd order Hermite curve interpolation

$t(s)=(6s^2-6s)v_0+(3s^2-4s+1)t_0+(-6s^2+6s)v_1+(3s^2-2s)t_1$

2. Using the three new vertices and normals, split the triangle into four sub-triangles

3. Repeat the above procedure recursively for each triangle until the desired display or manufacturing precision is reached or until no significant improvement is obtained (refer to Figure 7b).

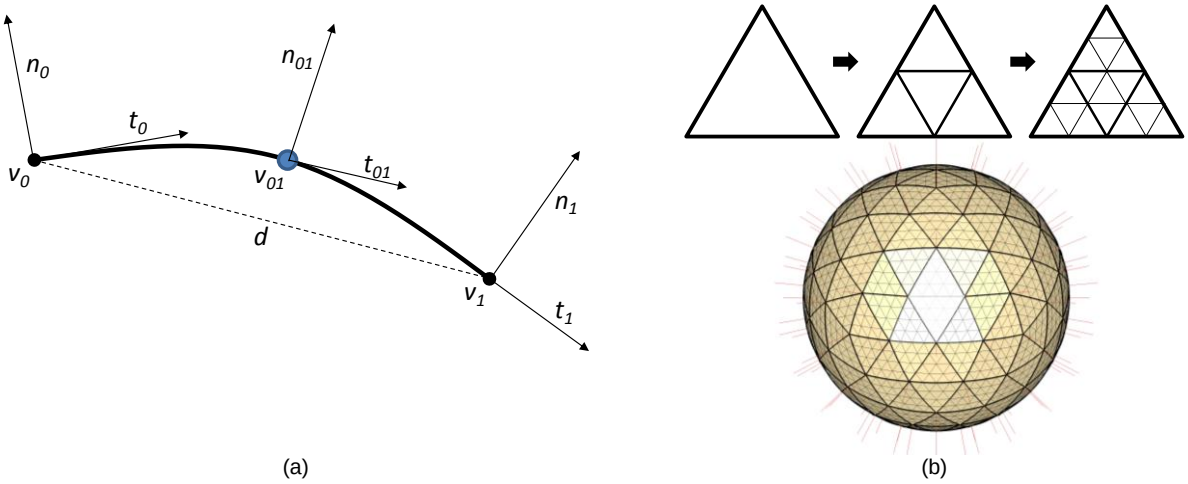


Figure 7. Interpolating a curved triangle edge. (a) Notation used for the subdivision of a curve; (b) Triangles shall be divided recursively to the desired resolution as determined by the display or manufacturing tolerances. Example of a spherical surface represented with 320 triangles, each subdivided into 16 sub-triangles by using the above procedure recursively.

17. Annex 4 - Code for Pseudo-Random Spatial Map (PRSM)

The goal of the `rand` function is to allow for pseudo-random textures to be used in material and color definitions. The `rand(x,y), rand(x,y,z) and rand(x,y,z,k)` return a persistent random number as function of a given coordinate. These functions map the 2D or 3D coordinate onto a real (fractional) pseudo-random number uniformly distributed in the range [0-1) (exclusive of 1). The number returned will be persistent across multiple calls (i.e. the same number will always be returned for the same coordinate). If k=1, a second (probably different) number will be returned for that coordinate. A third (probably different) number will be returned for that coordinate with k=2, and so on. A sample C++ implementation of `prsm(x,y,z,k)` is provided below.

```
/* prsm.h
 *  Spatial random number generator based on the maximally
 *  equiditributedcombined Tausworthe-88 generator.
 *  By Daniel Ly and Hod Lipson (2010)
*/

#ifndef __SPATIAL_TAUS88_H__
#define __SPATIAL_TAUS88_H__

#include <climits>

/**************************************
 * Declarations
 **************************************/

typedef struct
{
    unsigned long int s1, s2, s3;
}
taus_state;

unsigned long int rand_seed(unsigned long int x);
unsigned long int taus_get(taus_state* state);
double prsm(double x, double y, double z=0, int k=0);

/**************************************
 * Definitions
 **************************************/
unsigned long int rand_seed(unsigned long int x)
{
    return (1664525*x+1013904223) & 0x7fffffffUL;
}

unsigned long int taus_get(taus_state* state)
{
    unsigned long b;

    b = (((state->s1 << 13UL) & 0xffffffffUL) ^ state->s1) >> 19UL;
    state->s1 = (((state->s1 & 0xfffffffeUL) << 12UL) &
        0xffffffffUL) ^ b;

    b = (((state->s2 << 2UL) & 0xffffffffUL) ^ state->s2) >> 25UL;
    state->s2 = (((state->s2 & 0xfffffff8UL) << 4UL) &
        0xffffffffUL) ^ b;

    b = (((state->s3 << 3UL) & 0xffffffffUL) ^ state->s3) >> 11UL;
    state->s3 = (((state->s3 & 0xfffffff0UL) << 17UL) &
        0xffffffffUL) ^ b;

    return (state->s1 ^ state->s2 ^ state->s3);
}
```

```
double prsm(double x, double y, double z, int k)
{
    taus_state state;

    float tx, ty, tz;
    tx = (float) x;
    ty = (float) y;
    tz = (float) z;

    /* Convert floating point numbers to ints*/
    unsigned long int ts1 = *(unsigned int*)&tx;
    unsigned long int ts2 = *(unsigned int*)&ty;
    unsigned long int ts3 = *(unsigned int*)&tz;

    /* Convert coordinates to random seeds */
    state.s1 = rand_seed(ts1);
    state.s2 = rand_seed(ts2);
    state.s3 = rand_seed(ts3);

    state.s1 = rand_seed(state.s1 ^ state.s3);
    state.s2 = rand_seed(state.s2 ^ state.s1);
    state.s3 = rand_seed(state.s3 ^ state.s2);

    state.s1 = rand_seed(state.s1 ^ state.s3);
    state.s2 = rand_seed(state.s2 ^ state.s1);
    state.s3 = rand_seed(state.s3 ^ state.s2);

    /* "warm up" generator and generate k-th
number */

    for (int i=0; i<k+9; i++) {
        taus_get(&state);
    }

    return ((double)taus_get(&state)/UINT_MAX);
}

#endif /* __SPATIAL_TAUS88_H__ */
```

Figure 8. Sample C++ implementation code for Pseudo-Random Spatial Map (PRSM) function.

18. Appendix 1 - Performance

It is the goal of this standard to allow for interactive time performance for file read-write and for reasonable file sizes for typical large datasets. The table below summarizes performance statistics for a range of file sizes. The processing times refer to time used to read the file, parse the xml objects and construct an internal data structure [3]. Note that read and parse time are relatively small compared to the total time required to process a file for fabrication (e.g. slicing).

16.1 File Size

Number of Triangles	Binary STL (uncompressed)	Binary STL (compressed)	AMF (uncompressed)	AMF (compressed)
1,016,388	49.6 Mb	25.3 Mb	205.9 Mb	12.2 Mb
100,536	4.9 Mb	2.3 Mb	20.1 Mb	1.2 Mb
10,592	518 K	249 K	2.1 Mb	129 K
1,036	51 K	20 K	203 K	12 K

16.2 Write time (seconds)

Number of Triangles	Binary STL (uncompressed)	Binary STL (compressed)	AMF (uncompressed)	AMF (compressed)
1,016,388	0.372	~3.4	6.8	15.5
100,536	0.038	0.038	0.79	1.78
10,592	0.005	0.005	0.11	0.21
1,036	0.001	0.001	0.06	0.06

16.3 Read and parse time (seconds)

Number of Triangles	Binary STL (uncompressed)	Binary STL (compressed)	AMF (uncompressed)	AMF (compressed)
1,016,388	0.384	~1.3	6.447	6.447
100,536	0.043	0.043	0.669	0.687
10,592	0.005	0.005	0.107	0.107
1,036	0.001	0.001	0.056	0.056

16.4 Accuracy (error calculated on unit sphere)

Number of Triangles	STL	AMF (with normals)
20	0.102673	0.006777
80	0.032914	0.000788
320	0.008877	8.28E-05
1,280	0.001893	1.01E-05
5,120	0.000455	1.95E-06
20,480	1.13E-04	4.51E-07
81,920	2.81E-05	1.11E-07
327,680	7.03E-06	2.75E-08
1,310,720	1.76E-06	6.87E-09

19. Appendix 2 - List of future features

It is recognized that there is additional information relevant to the final part that is not covered by the current revision of this standard. Elements and specifications for this information are omitted from this revision in order to simplify its initial adoption, but are expected to be added to future revisions of this standard. The following is a list of features to be considered in future revisions. Adoption of any new feature should be conditional on the availability of open-source license-free code that implements that feature.

1. **Future provisions for dimensional and geometric tolerances**. Future revisions of this standard may provide means for specifying critical dimensional and geometric tolerances. A future `<tolerance>` element may be introduced under the `<object>` element to describe critical relationships amongst sets of vertices, such as distance, perpendicularity or parallelism, etc. Such information may be used by the process planner to automatically set various printing parameters, such as part orientation and print resolution, in order to best meet the critical tolerances.
2. **Future provisions for surface roughness**. Future revisions of this standard may provide means for specifying critical surface properties of certain facets of the finished parts. Such information may be used by the process

planner to automatically set various printing parameters, such as part orientation and print resolution, in order to best meet the desired finish.

3. **Future provisions for support structure**. A future `<support>` element may be introduced under the `<mesh>` element on order to describe support structure. In the current revision, the `<volume>` element may only be used to describe closed volumes present in the final part. The `<support>` may describe custom non-volumetric support structures.

4. **Future provisions for function representations**. A future `<frep>` element may be introduced under the `<object>` element to describe object using function representation. In the current revision, only the `<mesh>` element may be used to describe volumes using a tessellated surface. A function representation will describe a geometry boundary as a formula, nested formulae, or algorithm, that computes a value for any spatial location. That value may be used to denote the existence or absence of material at that location, as well as other properties. Although the `<composite>` element could theoretically already be used to support function representations by describing the complete geometry of an object as a single function, such use is discouraged; the current intended use of the `<composite>` element is only for the description of cellular mesostructures.

5. **Future provisions for voxel representations**. A future `<voxel>` element may be introduced under the `<object>` element to describe object using voxel-based representation. In the current revision, only the `<mesh>` element may be used to describe volumes using a tessellated surface. A voxel representation will describe a geometry using a three dimensional bitmap. This type of representation is especially suited for medical imaging technologies. Although the `<composite>` element could theoretically already be used to support voxel representations by describing the complete geometry of an object using the `tex()` function, such use is discouraged; the current intended use of the `<composite>` element is only for the description of cellular mesostructures.

6. **Future provisions for copyright protection and watermarking**. Future revisions may provide elements for specifying copyright information. It is currently possible to encode copyright information by watermarking the data, for example by modifying the least significant digits of vertex coordinates according to some hidden pattern or message. More explicit methods that entangle a copyright message with the data may be explored.

7. **Future provisions for surface textures and coatings**. Future revisions may provide elements for specifying geometric and material modulation of part surface, for example a certain tactile pattern, or a certain surface coating (in multi-material printing). Currently, such properties can be described indirectly by creating a new composite material and using it along the surfaces.

8. **Future provisions for more compact vertex coordinate and mesh encoding**. Future revisions may provide more compact methods for providing vertex coordinates and mesh data. For example, encoding all vertex coordinates in a base64 formatted block may reduce file sizes by up to 30%. Such implementation may however hinder the readability and ease of implementation by non-expert users, which is key to successful adoption.

20. Appendix 3 - List of contributors and stakeholder liaisons

This standard has been prepared based on a survey and consensus among stakeholders representing designers, AM equipment manufacturers, CAD software developers, academicians, and end users. The following is an list of contributors and contact persons. Please contact hod.lipson@cornell.edu to be added to this list or to suggested people and companies who should be contacted about being added to the list. We are looking for representatives from all major stakeholders.

Additive-Manufacturing Equipment Manufacturers contact persons

Name	Affiliation
Fjordén, Tony	Arcam
Napadensky, Eduardo	Objet
Sprauer, Jean	Z Corp
Lewis, Cathy	3D Systems
Robb, Patrick	Stratasys

Semmler, Manfred	EOS
Wigand, John	Solidscape
Such, Alberto	HP

CAD Software Companies contact persons

Name	Affiliation
Brans, Karel	Materialise
Martinez, Gonzalo	AutoDesk
Ding, Joe	SolidWorks
Trainer, Asa	Parametric Technologies
Bacus, John	Google SketchUp
Vilbrandt, Turlif	Uformia

Academia

Name	Affiliation
Hiller, Jonathan	Cornell University
Lipson , Hod	Cornell University
Stucker, Brent	University of Louisville

Societies and organizations

Name	Affiliation
Wellington, Jane	Society of Manufacturing Engineers
Bowyer, Adrian	RepRap
Malone, Evan	Nextfab Organization
Lipton Jeffrey	Fab@Home
Barkley, Jim	MITRE Corporation

End users: Designers, consultants, service providers, and other users

Name	Affiliation
Schwarze, Dieter	MTT Technologies GmbH
Robert Schouwenburg	Shapeways
Overy Charles	LGM
Francis Rabuck	Bentley Systems

* Please contact hod.lipson@cornell.edu to be added to this list or to be removed from this list