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3D data export for Additive Manufacturing - improving geometric accuracy

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Abstract

3D data exchange between different CAD systems and from design to manufacturing has largely moved to ISO STEP based formats. The Additive Manufacturing (AM) process today requires an approximate, planar triangle tessellated 3D model as an input. Improving accuracy in STL file exports is done differently in different CAD systems. Poor tessellation accuracy results in built parts with poor geometric accuracy because of errors in source data.

In this study, results of tessellation from six different CAD systems are compared. Roundness accuracy for the different settings is calculated. Results show that tessellation effects may be visible even when roundness requirements are fulfilled. A method for 3D data exchange for AM using STEP and geometric requirements is proposed until better accuracy AM formats can be used.

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Keywords: Additive manufacturing, 3D printing, STL, STEP, tessellation, accuracy, roundness

1. Introduction

Manufacturing in the digital age use file based design descriptions. Sometimes the drawings themselves are omitted, replaced by 3D annotated data. 3D-printing use tessellated data for geometry description where other manufacturing methods use a mathematically accurate representation. Tessellation is the process of building every surface regardless of curvature by using a mesh of triangles. A cube can be described exactly using 12 triangles whereas a sphere would be described as an approximation. The number of triangles depends on an accuracy setting, usually some sort of chord deviation. This setting is user controllable in most CAD systems.

3D printing is an Additive Manufacturing (AM) method that builds a part layer by layer. Initially it was used to create prototypes in plastic material but now it is possible to print directly in many metallic materials. Depending on part, shape and serial volume, using metal 3D printing as a serial manufacturing method is possible, creating a need to reduce build cost and improve geometric quality.

3D File formats can be divided into exact and approximate types. Source CAD format are vendor proprietary and cannot be exchanged readily. Exporting and importing 3D data to manufacturing and from other engineering tasks usually involves separate software licensing. Files are usually ASCII text based. Exact formats carry the unit of measure but Stereo Litography or Standard Tessellation Language (STL) does not, creating ambiguity. Knowledge of STL being an approximate format is fairly uncommon among designers.

The most common file types for traditional and additive manufacturing respectively are STL and STEP. Emerging formats include 3DMF and AMF. The latter two are under development.

STL – Stereo Lithography or Standard Tessellating Language – initial 3D plastic printing format. It is usually included as an export option using no additional licensing and import to 3D-printing codes is a standard procedure.

STEP – ISO 10303 standards is a mathematically exact data format. Several Application Protocols (AP) exist where AP203 and AP214 are most common for exchanging 3D geometry data. Depending on software capabilities 3D annotations may be included in STEP AP2013/214 protocols.

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Later protocols like AP242 will carry semantic and associative 3D annotations. AP242 edition 2 also introduces curved triangle patches similar to the Additive Manufacturing Format (AMF) [1].There are also initiatives to handle lattice definitions; a possible cost reduction and performance increasing design theme made possible by AM.

AMF – ISO/ASTM 52915:2013 is a new additive manufacturing file format under development. It allows for curved triangle patches that can increase geometric accuracy by sub tessellation. It also has data structures to allow different materials and different densities in the same part [2,3,4].

3MF – A Microsoft and industry-driven initiative. It has similar features to AMF but seemingly no address of geometric accuracy by using curved triangle patches like AMF [5].

Table one summarises these geometry formats.

Table 1. 3D data file formats.

	STEP ISO 10303	STL	AMF	3MF
Type	Exact (203/214) Exact & approximate (AP242)	Approximate	Approximate	Approximate
Units of measure	Yes	No	Yes	Yes
License based export	Yes	No	No	-
Curved surface patches?	Yes, exact & approximate (242)	No	Yes	No

Many studies have studied the inaccurate properties of STL based formats suggesting different variants of curved patches and slicing of source data [6-9]. Lipson shows that using curved triangular patches makes it possible to reduce chord deviation errors [4]. The subdivision would then be located to the slicing step; keeping data load low during interactive use, and grow as needed during the computationally intensive slicing process. The XML structure within the AMF file has allocated space for this type of geometry definition.

Until slicing algorithms are developed to handle curved surface patches or mathematically correct CAD data directly, there is an industrial need to use existing tools and still get accurate enough prints. How can geometric accuracy be improved using existing CAD and AM preparation tools today without the use of curved surface patches? What is a "good-enough" tessellation accuracy and when is a good time to convert from accurate to approximate file definitions?

Tessellation accuracies for different CAD systems using different accuracy settings were tested to find a "best practice" for design to interface to 3D printing. The chord deviation in STL source data was calculated for different tessellation accuracy settings and compared to an asserted drawing requirement of roundness.

2. Method

Three different geometries were tested for STL translation using different CAD systems and different accuracy settings. A simple tube was first modelled in respective CAD system with a diameter of Ø320mm. The data was exported to STL and opened in a 3D visualization tool. The edge length (L) was measured and from there a chord deviation (b) was calculated as seen in figures 1 and 2. This non-roundness value will exist in the source data even before manufacturing takes place. Two wheel rim geometries were downloaded from *GrabCad* and exported to STL and STEP [10,11]. The geometries were scaled down so they would fit in a metal 3D printer build chamber, in this case, an imagined EOS SLM machine. The use of these more realistic geometries was done to see how tessellation algorithms of different CAD work on real shape data. Each part was translated using different accuracy settings for comparison. Default accuracies, if provided, were recorded together with file size. A circular edge was chosen for chord deviation evaluation. The tessellation accuracy was increased and the part was retranslated, trying to find a "maximum accuracy" for the respective CAD system. The 3D-printer preparation tool (*Materialise Magics*) was then allowed to import a mathematically accurate STEP file directly and was tessellated using accuracies of <0.1mm. The results were compared to the CAD-driven tessellation results.

The surface used for chord deviation was assumed not to be required for machining and could be serially produced by accepting the as-printed surface if the form requirement was met. The number of triangles on the evaluated surface would affect the measured and visually perceived roundness of the part. A roundness requirement of Ø0.3mm was asserted. According to ISO 2768 this value would be between "fine" (0.2) and "medium" (0.5). A 3D printer accuracy of ±0.1mm was asserted. If the non-roundness value *b* in figure 1 in the source data is larger than Ø0.3 (roundness requirement)-0.1 (manufacturing tolerance) mm the result was classified as "too low tessellation accuracy".

Selecting tessellation accuracy is a user defined setting and is done differently in different CAD systems. Some CAD tools provide a default accuracy setting, see table 2.

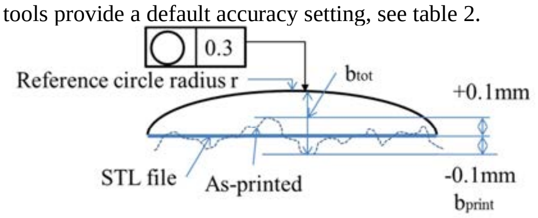

Figure 1 The non-roundness is a combination of error due to tessellation and actual printing.

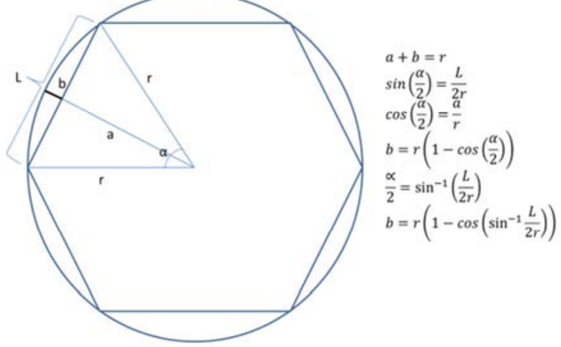

Figure 2. STL approximation of a circle with chord deviation.

Table 2. Tested CAD system STL tessellation settings.

	NX Ideas 6.3	NX 9	Catia V5-6 2012	PTC Creo3	Solid Works 2015	Solid Edge ST3
Tessellation settings	Absolute Facet Deviation	Triangle Tol & Adjancency Tol.	3D accuracy proportional or fixed & Curve accuracy ratio	Chord height & Angle control & Step size	Deviation & Angle	Conversion tolerance & Surface plane angle
Binary STL	No	Yes	No	Yes	Yes	Yes
Unit of measure STL	Inch	Varies	Varies	Varies	Varies	varies
Default accuracy setting?	Yes, 0.25	Yes, 0.08 / 0.08	Yes, inherited from display accuracy	Yes, ~2 / 0.5	Fine, course, custom	No
Geom. Dep. default accuracy	No, static 0.25	No, static 0.08	Yes, see above	Yes	Yes	No

3. Results and discussion

3.1. Tessellation results comparison

Tables 3 to 9 show results of the tessellation study. Where default accuracies were not available a low and high accuracy were selected similar to default values for other CAD systems. A Star symbol indicates too coarse tessellation to fulfil the roundness requirement.

Table 3. Tessellation results, Siemens NX Ideas 6.3.

Siemens NX Ideas 6.3	Cylinder Ø320	Rim 1 Ø282	Rim 2 Ø320
default accuracy	0.25	0.25	0.25
file size [kB]	9	1801	2955
edge length L [mm]	17.6	13.85	14.15
b [mm]	0.242*	0.170	0.157
finest accuracy	0.0057	0.005	0.0056
file size [kB]	49	30099	36620
edge length L [mm]	2.6	1.44	1.93
b [mm]	0.005	0.002	0.003

Table 4. Tessellation results Siemens NX 9.

Siemens NX 9	Cylinder Ø320	Rim 1 Ø282	Rim 2 Ø320
default accuracy	0.08/0.08	0.08/0.08	0.08/0.08
file size [kB]	16	5489	8590
edge length L [mm]	7.83	6.4	6.66
b [mm]	0.048	0.036	0.035
finest accuracy	0.001/0.001	0.001/0.001	0.001/0.001
file size [kB]	76	87941	147831
edge length L [mm]	1.45	1.17	1.23
b [mm]	0.002	0.001	0.001

Table 5. Tessellation results Dassault Catia V5-6 2012.

Dassault Catia V5-6 2012	Cylinder Ø320	Rim 1 Ø282	Rim 2 Ø320
accuracy	0.2/1.0	0.2/1.0	0.2/1.0
file size [kB]	67	11179	15075
edge length L [mm]	13.01	12.75	7.26
b [mm]	0.132	0.144	0.041
finest accuracy	0.01/0.1	0.01/0.1	0.01/0.1
file size [kB]	563	152130	188800
edge length L [mm]	1.13	0.94	1.1
b [mm]	0.001	0.001	0.001

Table 6. Tessellation results PTC Creo 3.

PTC Creo 3	Cylinder Ø320	Rim 1 Ø282	Rim 2 Ø320
default accuracy	1.81/0.5	2.27/0.5	2.07/0.5
file size [kB]	5	686	971
edge length L [mm]	45.54	44	40.2
b [mm]	1.629*	1.727*	1.268*
finest accuracy	0.0543/1	0.0683/1	0.062/1
file size [kB]	24	9684	11456
edge length L [mm]	8.25	8.51	8.48
b [mm]	0.053	0.064	0.056

Table 7. Tessellation results Siemens Solid Edge ST3.

Siemens Solid Edge ST3	Cylinder Ø320	Rim 1 Ø282	Rim 2 Ø320
accuracy	0.1/10	0.1/10	0.1/10
file size [kB]	18	7070	10964
edge length L [mm]	11.3	7.38	7.68
b [mm]	0.100	0.048	0.046
finest accuracy	0.01/1	0.01/1	0.01/1
file size [kB]	71	281033	337053
edge length L [mm]	2.78	2.45	2.45
b [mm]	0.006	0.005	0.005

Table 8. Tessellation results Dassault SolidWorks 2015.

Dassault SolidWorks 2015	Cylinder Ø320	Rim 1 Ø282	Rim 2 Ø320
accuracy "fine"	0.249/10	0.2298/10	0.25/10
file size [kB]	6	5831	9023
edge length L [mm]	17.63	11.2	11.96
b [mm]	0.243*	0.111	0.112
finest accuracy	0.02693/0,1	0.02485398/1	0.02645198/1
file size [kB]	141	270877	270696
edge length L [mm]	1.4	2.46	2.76
b [mm]	0.002	0.005	0.006

Table 9. Tessellation results Materialise Magics 18.

Materialise Magics 18	Cylinder Ø320	Rim 1 Ø282	Rim 2 Ø320
accuracy 0,1	0.1	0.1	0.1
file size [kB]	13	5610	6769
edge length [mm]	11.25	5.83	4.00
b [mm]	0.1	0.027	0.013
Accuracy 0,01	0.01	0.01	0.01
file size [kB]	39	30803	44351
edge length [mm]	3.56	3.14	0.91
b [mm]	0.001	0.008	0.001

Figure 3 shows typical results where the edge length was measured on a multi-edged, tessellated approximation of the original circle.

Figure 3. Typical tessellation result with measured edge length.

3.1.1. Roundness requirement fulfilment

The default tessellation accuracy provided by *NX Ideas*, *Creo* and *SolidWorks* are too low for the simple tube geometry to fulfil the asserted as-printed roundness requirement. For the two wheel geometries, the tessellation algorithms for NX Ideas and SolidWorks suggest higher tessellation accuracies as default, fulfilling the roundness requirement. Creo creates a too rough tessellation at the suggested default accuracy at our investigated diameters on the two wheel rim geometries.

3.1.2. Tessellation algorithms and max STL accuracy

Tessellation algorithms are functioning as black boxes. Uneven edge length tessellation is seen on the tube geometry in *NX Ideas*, *Catia* and *Magics*. This causes the largest edge length to contribute to the non-roundness value. This uneven dividing of a circular edge might be due to invisible “seem lines” in the 3D geometry definition. Since the mesh algorithm isn’t controllable, the difference in edge lengths has to be accepted as is, see Figure 4.

A maximum possible accuracy for STL translation was found in *NX Ideas*, *Creo* and *SolidWorks*. The two latter provides an accuracy slider that has end values. The end value varies with geometry. The first tool provided no easy finding of max accuracy. The seemingly random max accuracy value is probably due to how triangles are generated, the minimum allowable angle between non-parallel vectors in the planar triangle as caused by the modelling kernel and/or tessellation definition.

File sizes grow rapidly when accuracy is increased for obvious reasons. Different CAD systems create very different meshes. Large file size does not necessarily improve the roundness or chord deviance. Figure 5 shows an increase in roundness accuracy by 0.006mm at a cost of 10x larger file size. Figure 6 shows the edge length on the evaluated diameter. For the same file size, *NX* gave better accuracy or shorter edge length than *SolidWorks* on the evaluated diameter. *Magics* gave the shortest edge length of these four, which in reality would create a “rounder”, less faceted shape when printed. Magics also provide triangles with more uniform side lengths, even when the max edge length parameter is not used.

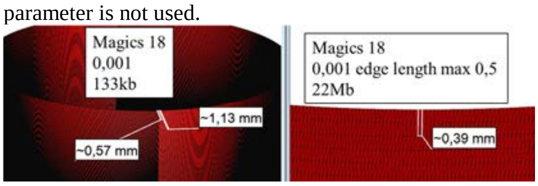

Figure 4. Magics tessellation. Edge length varies (a) but when specifying a max edge length the edge length is constant (b).

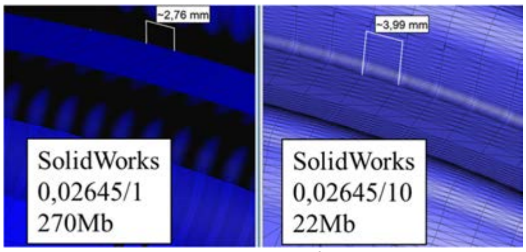

Figure 5. Chord deviance reduces from 0.012mm to 0.006mm at a cost of 250Mb. Seemingly, the “angle” accuracy setting affects the fillets which are created more densely.

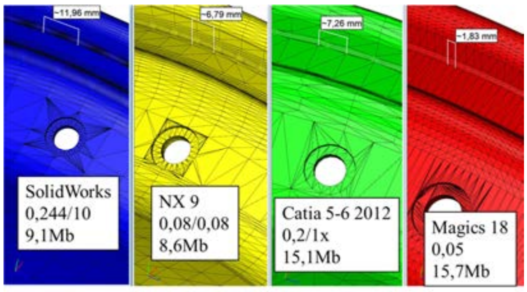

Figure 6. Different tessellation algorithms in work. CAD system, accuracy setting and file size are noted. Magics creates more triangles on the evaluated surface than Catia for the same file size, Magics use binary STL, Catia ASCII.

3.2. Discussion

How can tessellation accuracy be improved using existing tools? Until 3D printer file formats evolve to handle slicing and building directly off mathematically accurate data or sub tessellating curved triangle patches, there is a need to be productive using currently available technology.

Better tessellation quality was achieved when using the AM preparation tool Magics to convert exact STEP data to tessellated data to be used for support structure preparation, slicing and printing. A STEP based translation method from design to Additive Manufacturing is suggested as a solution to overcome the variance in current CAD tessellation algorithms and increase form accuracy. The suggested methodology to increase geometric accuracy is described below.

Design - export to exact representation. Keep source data exact in design and interface to manufacture using the same exact data format regardless of manufacturing method, see figure 7. There are many benefits and few penalties in using STEP for 3D data export to 3D-printing.

Benefits of using STEP include:

- Same data format as in traditional manufacturing. Standardized product data package possible regardless of manufacturing interface.
- Lossless translation. Re-translation from STEP possible to newer 3d-printing formats when available.
- Providing exact source data makes it easier to reject parts printed with too low tessellation accuracy resulting in unwanted facets.
- Same file size regardless of curvature accuracy.
- Unit of measure included in dataset.

STEP import and export of STEP data is usually licensed separately and is in many cases not free. License cost is negligible when compared to the cost of a metal AM machine and part cost.

Manufacturing –Select tessellation accuracy with guidance from dimension- and form tolerances on drawing. At least both *Magics* and *NetFabb* (AM preparation software) has the capability to read STEP data. An AM operator would read the annotations from within the 3D dataset or the drawing and select appropriate tessellation accuracy for the part. Increasing the number of triangles in the STL file does not increase print time but affects visual performance. Slicing takes longer time with increased triangle count and consumes more memory.

The 3D printing operator has knowledge that a design engineer might not have of which parameters affects the choice of tessellation accuracy;

- Knowledge of STL being an approximate file format, and the AM operator works with triangle based datasets daily.
- Knowledge of the 3D printer build accuracy as specified from the 3D printer supplier and own experience from previous builds.
- Knowledge of previous jobs' tessellation accuracies and effect on visibility of facets.
- Knowledge of the effect of too-high accuracy and decreased productivity due to long geometric calculations during slicing and slower interactive response.

Use the max edge length parameter. Creo and Magics have the capability to define a *longest allowed triangle edge*. The use of edge length creates more triangles that, depending on curvature, may create a better quality print. CAD tools without this edge length capability may interface to 3D-printer using STEP to benefit from increased tessellation accuracy. Max edge length algorithms create a triangle mesh very similar to Finite Element Analysis (FEA) tools where even length edged triangles are wanted. The drawback is that a rectangular planar surface in need of only two triangles to be defined exactly will get tessellated to many planar triangles with sides fulfilling the max edge length requirement, increasing file size.

Figure 7 shows the proposed workflow from design to manufacture using STEP-based data translation, and how engineering requirements and operator experience is used to select appropriate tessellation accuracy. When STEP AP242 carries a complete product definition and when the AM preparation tool can interpret the information, the two design domain datasets could be replaced by a single file. STEP AP203/214 files from Catia of a 3D-annotated model did not during these tests transfer annotation information into the STEP file to Magics.

3.2.1. Problems with triangles in design & manufacturing

Interoperability between AM and NC machining - Sending an AM blank with support structures for post process machining will export a triangle based geometry format instead of an exact geometry definition.

Expected/visual roundness –Engineers are not used to see non-continuous curved surfaces. Printing parts using a multi-edged approximation cause non-continuous surfaces that reflect light in different angles making the inaccuracies visually easy to observe, possibly resulting in a rejected part. The left part in Figure 8 was tessellated by *Magics*, has an edge length 0.56mm and printed in steel powder on an EOS SLM M290 without visible facets; the surface roughness and the facets were of comparable size. The right part tessellated by *SolidWorks* using highest possible accuracy settings provided similar file size but larger edge length and printed with visible facets. The right part was rejected by the customer due to "visual non-roundness". The part had a calculated non-roundness value in the source data of 0.01 mm.

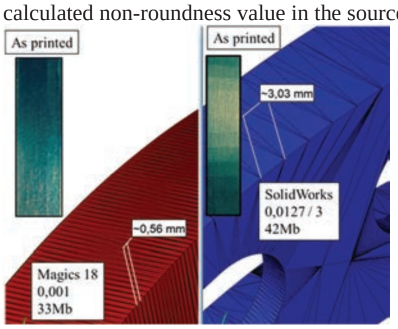

Figure 8. Tessellation accuracy and as-printed result. Left (red) part tessellated by Magics printed without visible facets, right (blue) part was tessellated by SolidWorks at highest accuracy settings and printed with visible facets.

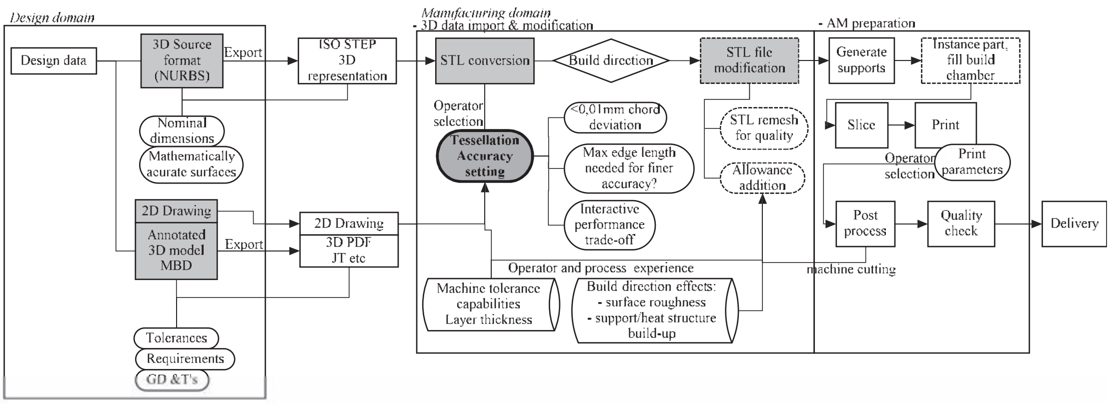

Figure 7. STEP-based data translation for Additive Manufacturing workflow.

STL import to CAD - Not all CAD tools can import a STL file even when only needed for digital mock-up purposes. The parts lack a volume and a unit of measure inside the file definition. Lattice patterns have evolved in some AM preparation tools. These are regular patterns of trusses that can make a part less solid and reduce mass and provide faster prints. Magics has this possibility. Since the definition is based on triangles, it is usually not usable in CAD for inclusion in 3D assembles or to predict stresses using Finite Element Analysis tools. Also, triangle quality is often poor when lattice patterns have been used to modify a part volume.

Selecting STL accuracy - An engineer who exports to STL for the first time has usually no idea that the file format is approximate. Using default accuracies may not always be wise as shown in this paper. Even if the engineer does look up STL accuracy on the internet, suggested values may be for 3D-printing in plastics for home use, for which geometric tolerances and dimensions matter less than for industrial use. Having the 3D printer operator select an appropriate accuracy based on engineering requirements inside the exact dataset removes this problem. Planar triangles as the STL file is defined today, creates a demand for *large datasets* when fine accuracy is needed. Some CAD systems are beginning to handle exports to the AMF format. It seems that metal 3D-printing could benefit more from the curved triangle definition suggested for AMF than plastic parts would, due to the different accuracy requirement and purpose of 3D-printed metal or plastic parts. The high reflectivity of metallic surfaces shows curvature discontinuities well. Online 3D-printing shops using mainly plastic materials might not handle a requirement-based tessellation accuracy selection based on STEP data as described here. In those cases, the designer needs to select an appropriate tessellation accuracy based on capabilities of the CAD system and the geometric requirements on the part.

When dimensions and tolerances are measured and evaluated by the use of thousands of measure points many of the form tolerances as specified by ISO 1101 may be considered and evaluated as a surface profile. Roundness was evaluated because the calculations were easier to perform, but the conclusions that are drawn are equally valid for surface profile and line profile. Since the manufacturing method is layer based, a "*stair case*" effect is created on surfaces that are angled relative the build direction. Depending on layer thickness this may contribute to the as-printed accuracy when measured.

4. Conclusions

A method of sending STEP data as input to additive manufacturing has been proposed. The AM builder with knowledge about tessellation and AM machine accuracies chose tessellation accuracy with input from engineering requirements from the drawing/annotated dataset. *Magics* creates denser and more accurate meshes than some CAD tools even without using the max edge length parameter; a method that limits the individual triangle edge length to provide even finer accuracy. When printing parts in metal, this method allows for a less facetted surface appearance. It also makes it possible to refuse delivery of too-roughly tessellated and printed parts since the source data provided to the AM builder is exact and the dimensional requirements are defined. The designer however needs to be aware that form requirement may be fulfilled even if the part has visible facets and should change geometric requirements if such surface features are not wanted. Finally, the method of using STEP based file transfers keeps file size small and efficient to handle electronically up to the manufacturing phase.

Acknowledgements

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