The Use of STEP to Integrate Design and Solid Freeform Fabrication

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ABSTRACT

The Standard for the Exchange of Product Model Data (STEP), ISO 10303, is a developing International Standard for the exchange of product information between many different engineering and manufacturing applications. This paper describes an architecture and methodology, using STEP, that integrates a heterogeneous environment of CAD and Solid Freeform Fabrication (SFF) systems. The prototype software discussed in this paper demonstrates the use of STEP to provide CAD product data to a SFF system. The architecture described in this paper also addresses the role of the STEP standards in an environment where STL and other SFF part data formats must also be supported.

1. INTRODUCTION

Advances in Rapid Prototyping (RP) and CAD system technology have placed demands on RP part data formats that exceed the capabilities of the current *de facto* industry standard STL format. These demands can be satisfied, but the RP industry must cooperatively adopt a more sophisticated data format that supports product and production information. RP users and developers have identified several limitations of the STL format including: large file size for complex parts; lack of geometric feature information; a non-robust and imprecise geometric representation; lack of tolerance information; and lack of extendibility [1 – 4]. Perceived problems with the STL file format have led to the development of a number of different mechanisms for transferring part information from CAD systems to SFF systems. While technically successful, none of these methods has achieved widespread SFF industry acceptance and none of these methods has replaced STL as the primary means of CAD-SFF part data exchange. This paper discusses use of the Standard for the Exchange of Product Model Data (STEP), ISO 10303, to convey CAD product information to SFF processes. Unlike part data formats developed specifically for SFF, STEP is already registered as an International Standard with the International Organization for Standardization (ISO) and is already accepted by industry, government and academia. This paper describes a prototype SFF geometry processing system that generates SFF system control geometry from a STEP file. The description of this system follows the part data from CAD system to SFF system controller. The goal of this prototype system is to demonstrate the use of STEP in SFF and to illustrate a migration path for SFF systems from STL to STEP.

2. OVERVIEW OF SFF PART DATA EXCHANGE FORMATS

The STL file format was originally developed in the late 1980's to support data exchange for the Stereolithography process [5]. The STL format represents solid object geometry by approximating the object surface with a collection of triangular facets. This faceted format, while easy to generate from CAD data and a variety of other sources, has a number of technical problems when applied to the manufacture of SFF components. General consensus exists between end-users and RP developers that an alternative to the STL file format and representation is needed; however, little research specifically responsive to this need appears in the literature [1 – 3]. The remainder of this section outlines a few of the SFF part data exchange formats developed over the last few years. Most of the formats proposed fall into two categories: three-dimensional boundary representation formats and two-dimensional slice formats.

2.1 Three-Dimensional Formats

Several three-dimensional file formats have been advanced as candidates to replace STL. The Cubital Facet List (CFL) format was introduced by Cubital [6]. CFL uses an approximate polygonal-based representation. Instead of constraining users to representations comprised of triangular facets, the CFL format is capable of representing n-sided polygons which may have multiple holes within each polygon. Unlike STL, the format does not redundantly represent vertex information and maintains topological information. A flexible and extendible SFF format concept, the RPI format, was advanced in a paper by Rock and Wozny in 1991 [7]. Key elements of this format include its flexibility and extendibility. Consequently, varying amounts and types of information can be used to represent objects, and provisions are made for forward compatibility as new RP functionality or processes evolve. Example uses of the RPI format focused on facet models, with support for additional manufacturing information. When used to store facets, the RPI format provides topological information and eliminates the redundant information found in a comparable STL format file. The RPI format concept is applicable to higher-order geometry; however, extensions to it have not been made. A variant of the STL format, known as STH, was advanced by Brock Rooney & Associates, Inc. [8]. This format purports to provide a more efficient representation for storing STL files. The format also accommodates explicit representation of geometric special cases, such as a "triangle between a point and a curve" [9]. Translators were marketed to provide a conversion path between the two formats; however, the commercial success of this product and format is limited.

2.2 Slice Formats

For several years, users have been advocating the development of slice-level interfaces to commercial SFF processes. In response to this demand, 3D Systems introduced the SLC format for representing slice contour information. Technical details have been slow to proliferate; however, this format is not limited to polygonal contours [10]. In this respect, it is a move toward more precise geometry, which is potentially beneficial. However, this further proliferation of private, company specific formats developed without consensus may limit SLC's applicability for other SFF processes and may limit sources capable of supplying SLC format files. Academic efforts have also resulted in slice-level SFF system data exchange. The CLI (Common Layer Interface) format has been advanced as a"universal format" for the input of 2D geometric information to layer-wise RP processes by two European Brite-EuRam projects, "Rapid Prototyping Techniques" and "Phidias". Further refinement and distribution of this specification has been handled by the European Action on Rapid Prototyping (EARP). EARP has continued to develop SFF data exchange formats with the development of a representation for contour information known as LEAF. However, LEAF's useful lifetime is limited by EARP's eventual plans to migrate toward a STEP-based representation [11]. Clemson University also has advanced the use of NURBS slice contours exported from SDRC's IDEAS CAD system as a data input format to SFF [12]. The use of NURBS slice contours resulted in a dramatic increase in part surface finish, quality and overall dimensional accuracy.

2.3 Summary

Since its introduction, the STL file format has been the *de facto* standard for part geometric data exchange in the SFF industry. STL has many perceived weaknesses and there have been many part geometric data formats developed that have addressed these weaknesses. However, each of these alternative part geometric data formats has been developed without widespread industry involvement. Consequently, the development and use of these part geometric data formats has either been abandoned or restricted to a small number of users within a specific CAD-SFF system environment.

3. STEP

The goal of STEP is to standardize a means of exchanging product data among different computer systems and environments throughout the entire product lifecycle including: design, manufacture, logistic support, repair and disposal. Information generated during each of the various lifecycle phases is used in many other lifecycle phases. STEP provides a complete and consistent computer-interpretable product information model that can be used to share product data amongst these processes [13].

3.1 Overview of STEP

STEP provides a product model representation along with the necessary exchange mechanisms. STEP is composed of a series of parts which are published separately. Each STEP part falls into one of the following six categories: schema description methods, integrated resource schemas, application protocols, abstract test suites, implementation methods and conformance testing. STEP uses the EXPRESS language (Part 11) to describe information models. The benefits of adopting a formal, computer-interpretable language for describing information models are the ability to precisely communicate information models to other members of the STEP community; to create extensible information models; and to reduce database implementation errors.

STEP information models are broken up into two main classes: integrated resource information models and application protocols (APs). Integrated resource schemas are information models which are useful for a wide variety of applications. The following are examples of integrated resource schemas: Part 41: Geometric and Topological Representation and Part 46: Visual Presentation. APs use parts of several integrated resource schemas to construct integrated information models applicable to a particular application. Examples of APs are: AP 203: Configuration controlled 3D designs of mechanical parts and assemblies and AP 214: Automotive electro-mechanical design. Implementation methods describe the means of presenting, exchanging and accessing product information, such as text file format and application programming interfaces. Abstract test suites and conformance testing refers to the data and techniques used to verify STEP systems and translators. Attention to conformance testing helps ensure actual interoperability between STEP translators.

In March 1994, twelve parts of the STEP standard were released as International Standards by ISO. These parts are:

Part 1: Overview and fundamental principles,
Part 11: Description methods: The EXPRESS language reference manual,
Part 21: Implementation methods: Clear text encoding of the exchange structure,
Part 31: Conformance testing methodology and framework: General concepts,
Part 41: Integrated generic resources: Fundamentals of product description and support,
Part 42: Integrated generic resources: Geometric and topological representation,
Part 43: Integrated generic resources: Representation structures,
Part 44: Integrated generic resources: Product structure configuration,
Part 46: Integrated generic resources: Visual Presentation,
Part 101: Integrated application resources: Draughting,
Part 201: Application protocol: Explicit Draughting, and
Part 203: Application protocol: Configuration controlled 3D designs of mechanical parts and assemblies.

In February 1995, the American National Standards Institute (ANSI) registered the ISO standard parts of STEP as ANSI standards.

STEP has gained widespread industry acceptance. As of this writing, the following CAD systems have STEP AP 203 translators: Pro/Engineer, Unigraphics, CATIA and Computervision. The following CAD companies are reported to be working on STEP AP 203 translators: SDRC I-DEAS, Mantra Datavision and Aries.

3.2 Use of STEP for SFF Part Data Exchange

Several researchers have suggested applying STEP to improve CAD-SFF data exchange [4, 11, 14]. However, few STEP-SFF implementations exist. Some of the first work using STEP for SFF was the development of prototype AP 203 to STL translator at Ford Motor Company [15]. This translator supports translation of AP 203 faceted boundary representation to STL. The Royal Institute of Technology in Stockholm, Sweden describes a system that uses a STEP model as the input to a SFF system [14]. The system uses AP 204, Application Protocol for Mechanical Design using Boundary Representation, which has been extended to include process parameters, scanning patterns and material data. The Intelligent Manufacturing Systems (IMS) project, a ten year multinational collaborative effort initiated in 1990, has a Technical Subcommittee for Standardization, and this initiative has involved global RP data exchange which resulted in final part production. These efforts have pointed to STEP as the eventual mechanism for CAD-RP data exchange. Other efforts within the STEP community have focused on developing a STEP AP for RP based on existing STEP APs [16]. Despite a growing body of work in the area of STEP-RP data exchange, reports of the use of precise STEP geometry as input to a RP system have been slow to appear in the literature.

4. SFF SYSTEM GEOMETRY PROCESSOR

The SFF System Geometry Processor demonstrates the generation of control instructions for a SFF system using a STEP file as input. The system uses AP 203 of STEP to represent the part geometric data. The architecture of this demonstration system is shown in Figure 1. The SFF System Geometry Processor is composed of three modules: a module that reads a STEP file and creates a solid model, a module that converts the solid model into an internal geometric format, and a module that generates SFF system control geometry from the internal geometry format. The first module is composed of ST-ACIS™ [17], which generates an ACIS™ solid model from a STEP file. The second module generates an intermediate geometric representation from an ACIS™ solid model. The third module generates SFF system control geometry from the internal geometric representation. This control geometry is used as input to an existing experimental SFF system and can be used to control the construction of a part.

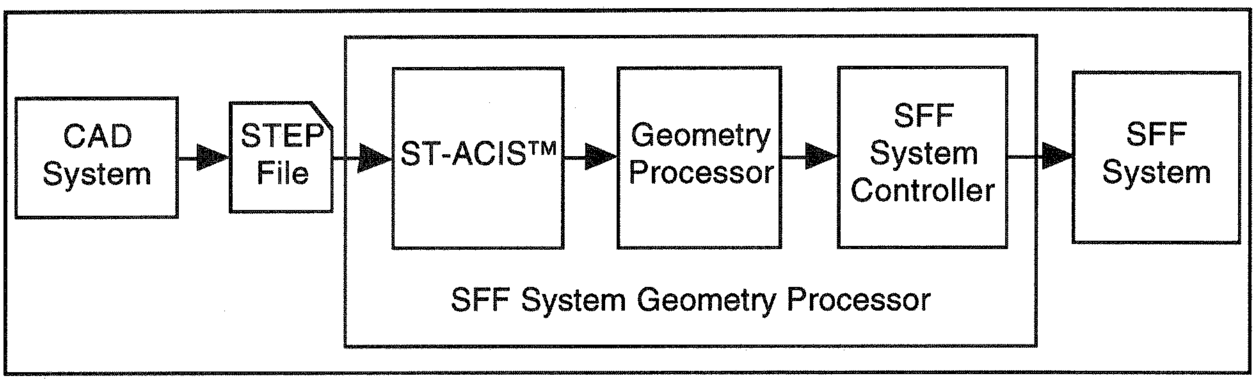

Figure 1 - System Architecture

Of the modules listed above, ST-ACIS™ is a commercial software product, the SFF system controller was a pre-existing software module used to operate a research SFF system, and the geometry processor links these two modules. The current geometry processor generates a faceted boundary representation model stored in the RPI format [2]. This format was chosen to maintain compatibility with the existing SFF system controller. Currently, the SFF system controller accepts information in either STL or RPI format. Creating an approximate faceted boundary representation from the precise solid model stored in the STEP file doesn't present a significant advantage over providing the part data in STL format to the SFF system controller. However, by generating the faceted approximation at the SFF system, the accuracy and quality of the STL file can be controlled at the SFF system where knowledge of SFF process limitations resides. This enables each SFF system to optimize processing based on its unique features without requiring advance knowledge of the manufacturing method at the time of part file creation.

The system architecture in Figure 1 supports a ready migration path from accepting a STL format file towards using precise geometry for SFF system control. Further development of both the geometry processor and the SFF system controller could further exploit the solid modeler capabilities to directly produce system control geometry to use as input to the SFF system controller. These future capabilities will further enhance SFF system performance and resulting part quality.

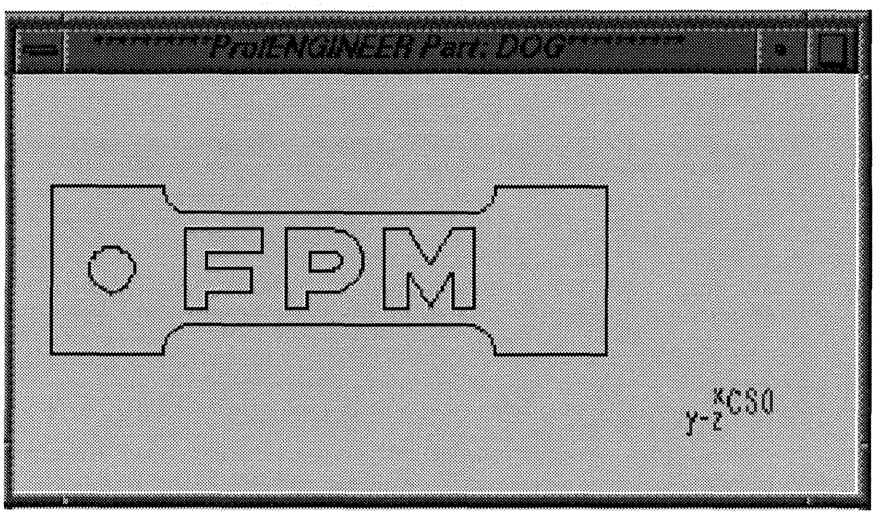

Figure 2 - Key Ring Model Displayed in Pro/Engineer™

5. RESULTS

Part manufacture using SFF typically starts with a CAD model. A Pro/Engineer ™ CAD model of a key ring based on a tensile test specimen "dog bone" geometry rendered is shown in Figure 2. Using the Pro/Engineer™ STEP translator, a STEP file is created for the key ring. Figure 3 shows the STEP model of the key ring displayed in ST-203™, an AP 203 geometry viewer. ST-203™ allows a designer to verify STEP file geometry before transmitting the STEP model to downstream applications.

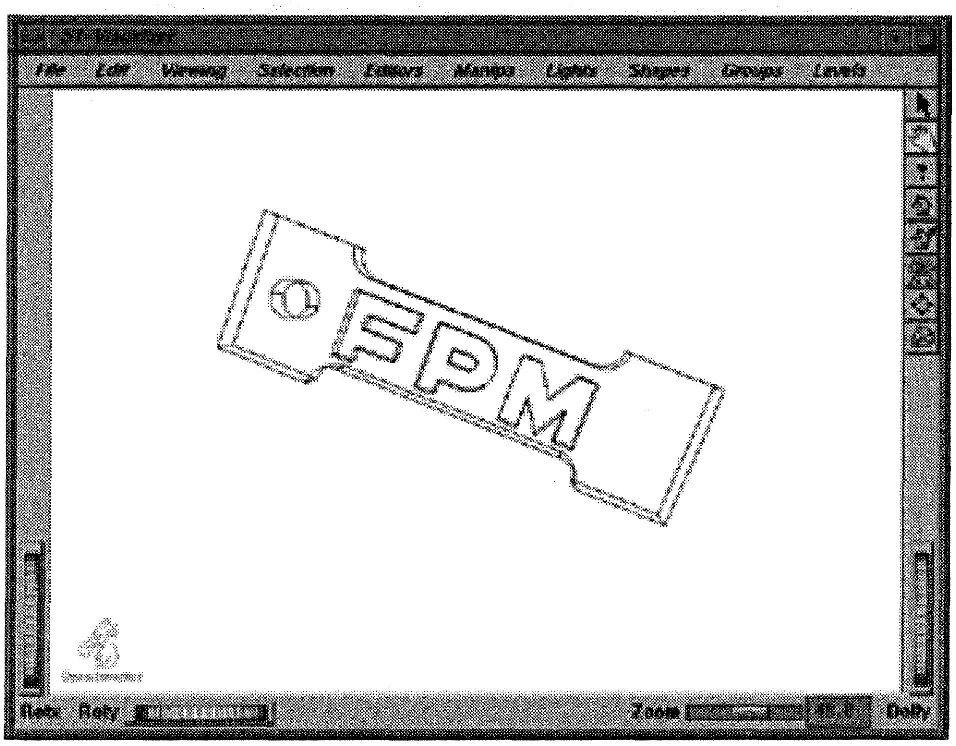

Figure 3 - Key Ring STEP Model Displayed in ST-203™

The STEP file is used as input to the SFF system geometry processor. The first module of the SFF system geometry processor, ST-ACIS™, creates an ACIS™ model from the STEP file. The resulting ACIS™ solid model is shown in Figure 4. The second module creates a RPI format model from the ACIS™ solid model by tessellating the model into a faceted boundary representation compatible with existing downstream software. This faceted model is shown in Figure 5. The RPI format model is used to generate slice information to control process control hardware. Layer slices for this part are shown in Figure 6. This process control geometry is used by the SFF system to produce a part.

Using STEP instead of STL to transfer part geometry to a SFF system has several advantages. One advantage is that STEP files use precise geometry whereas STL files use a faceted approximation. Using STEP prevents the rapid increase in STL file size that occurs when the number of curved surfaces in a model increases or when the demands on the approximation increase. The table below illustrates this point. The table shows the size, in bytes, for both a STEP ASCII text file and an ASCII STL file generated by Pro/Engineer™ for a cube, the key ring shown in Figures 2 – 6, and a sphere. The STL file size shown is a range that goes from a crude faceted approximation to the best faceted approximation offered by Pro/Engineer™ (maximum surface error is .02% diameter of object). The higher the accuracy desired, the larger the STL facet file. For curved surfaces, an exact faceted representation would require an infinitely large STL file.

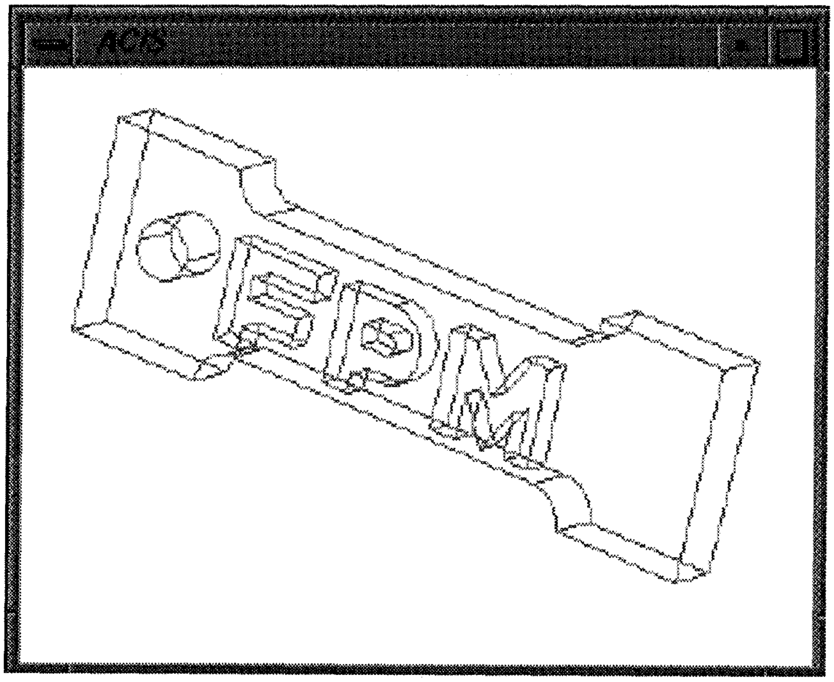

Figure 4 - Key Ring ACIS™ Model Displayed in ACIS Test Harness

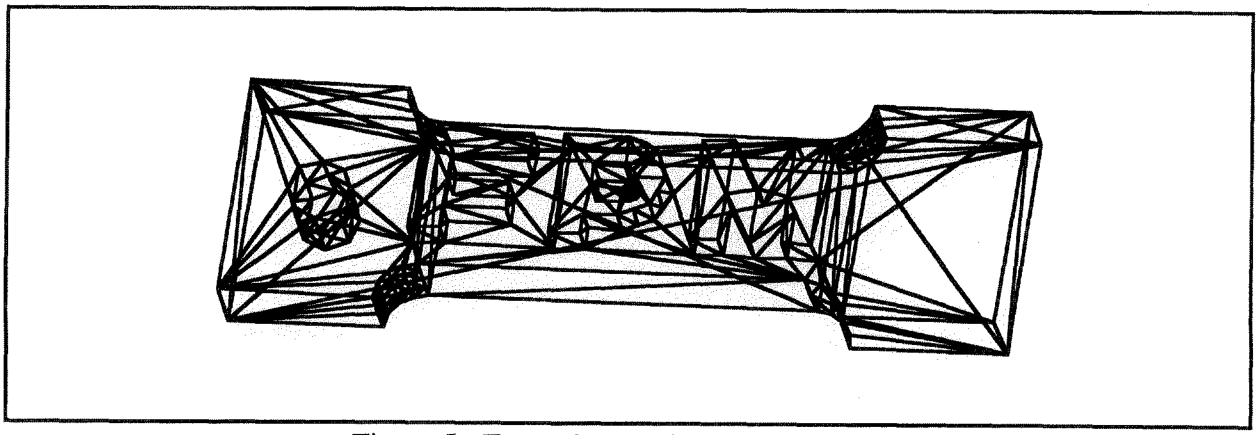

Figure 5 - Faceted Key Ring Representation

Model	STEP File Size (bytes)	STL File Size Range (bytes)
cube	12,659	3,028
key ring	185,273	69,731 – 237,108
sphere	10,610	8,141 – 3,575,809

For simple models with planar faces, such as a cube, the STL file is precise and is much smaller than the corresponding STEP file. However, as the model complexity and accuracy increases, the STL file rapidly increases to unwieldy sizes. The STEP file tends to increase only with the model complexity, not accuracy.

Figure 6 - Layer Slices for Key Ring Part

6. CONCLUSIONS

STEP is an International Standard for the exchange of product model information. As discussed above, STEP has several advantages over STL and other formats. Some of these advantages are: precise geometry, consistent file sizes, ability to support product and production information, conformance testing to increase reliability, extensibility and acceptance as an International Standard. The approval of STEP AP 203 as an International Standard by ISO has lead to the release of STEP AP 203 translators from most major CAD vendors. These STEP translators will make STEP data readily available to SFF system operators.

The SFF geometry processor described in this paper is one example of how SFF systems can support STEP model input. The methodology used to develop the SFF geometry processor also illustrates a migration path for SFF vendors and users from STL to STEP. To maintain compatibility with existing CAD tools, SFF vendors can develop software that converts STEP to STL or to the SFF vendor's preferred internal format. The system described in this paper provides the SFF system operator with the immediate benefits of being able to manufacture components from STEP data at high accuracy while still maintaining compatibility with existing CAD data input tools. This environment will allow CAD-SFF vendors and users to move forward to more advanced data exchange technologies without giving up established capabilities.

7. ACKNOWLEDGEMENTS

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