Computer-Aided Design 46 (2014) 148–159

Contents lists available at ScienceDirect

Computer-Aided Design

journal homepage: www.elsevier.com/locate/cad

Geometric interoperability via queries

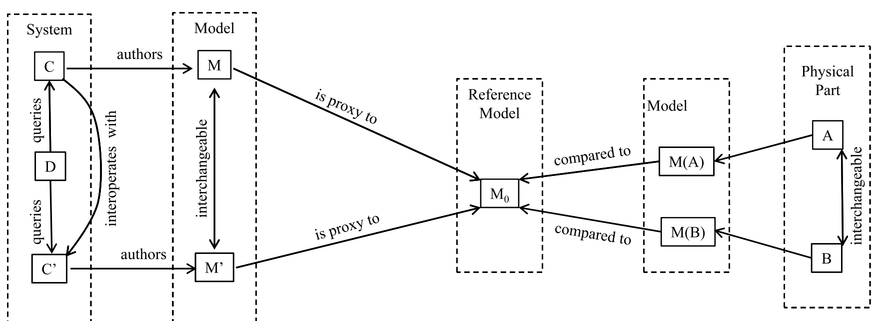
Christoph Hoffmann [a], Vadim Shapiro [b,*], Vijay Srinivasan [c]

[a] Purdue University, United States
[b] University of Wisconsin, United States
[c] National Institute of Standards and Technology, United States

HIGHLIGHTS

- Queries solve interoperability problems that are unsolved by a data-centric approach.
- Interoperability, interchangeability, and integration use a semantic reference model.
- A hierarchy solves interoperation in design and manufacturing of incidence structures.

GRAPHICAL ABSTRACT



ARTICLE INFO

Keywords:
Interoperability
Interchangeability
Integration
Geometric queries
Data exchange
Shape evaluation/comprehension

ABSTRACT

The problem of geometric (model and system) interoperability is conceptualized as a non-trivial generalization of the problem of part interchangeability in mechanical assemblies. Interoperability subsumes the problems of geometric model quality, exchange, and interchangeability, as well as system integration. Until now, most of the interoperability proposals have been data-centric. Instead, we advocate a query-centric approach that can deliver interoperable solutions to many common geometric tasks in computer aided design and manufacturing, including model acquisition and exchange, metrology, and computer aided design/analysis integration.

1. Introduction

There is a bewildering variety of shape representations in use in computer-aided design and manufacturing. From point clouds and tessellated shape representation to NURBS, from net shape to fully parameterized, different stages of the process chain use different representations. The various representations have been evolved and refined so as to respond to the specific needs of the process using them, such as design, analysis, and particular manufacturing processes, to name a few. Moreover, the representations differ in information content, as is appropriate for the task for which they are employed [1].

If digital-based manufacturing is to realize its full potential, the various representations have to be integrated and, acknowledging practice, nominally equivalent representations must be usable interchangeably and should interoperate. This is not a novel insight: there has been substantial work that attempts to reach this goal by seeking to standardize and translate models between different systems that have created them in the various representations [2]. Unfortunately, the translation approach tends to fail in certain instances owing to mathematical reasons of representability, information content, and interpretation. As a specific example, recall that shape representations such as NURBS cannot accurately represent trimmed patches. Consequently, a CAD system has to interpret face extent and the exact location of edges and vertices. Those determinations are made by algorithms that balance what

* Corresponding author.
E-mail addresses: cmh@purdue.edu (C. Hoffmann), vshapiro@engr.wisc.edu (V. Shapiro), vijay.srinivasan@nist.gov (V. Srinivasan).

0010-4485/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.cad.2013.08.027

in principle amounts to uncertain or contradictory results. When such representations are translated, the needed compromises cannot be well supported, if at all. *We therefore argue that the authoring system do the needed interpretations, and that model interchangeability be based on querying models instead of translating them.*

Note that, even if a translation approach worked, it would not even begin to address the larger problem of interoperability which also requires the ability to integrate different computations and applications, as well as to communicate between systems and representations that are often based on different mathematical assumptions.

1.1. Queries, evaluation and comprehension

Despite decades of serious work the model translation approach contends with stubborn difficulties that remain to be solved fully. Therefore, we propose queries as an alternative. When system D requires data from a model M authored in system C, then D should acquire that information through a series of queries, addressed to system C about M. The queries depend on the nature of the task system D is carrying out, for which information about M is needed. This interaction between the two systems suggests a form of model interchangeability: instead of querying C about M, an equivalent model M', authored in system C', can be queried by D. In this scenario the notion of model interchangeability is relativized, restricting the domain of interchangeability to the information that is queried.

The notion of interchangeability hinges on equivalence of M *and* M' *which applies only in the context of the application* D *requires information for. This context is determined by a semantic reference model appropriate to the domain of interest.*

Note that model M could very well encode other information not relevant to D's task. Moreover, such interchangeability arises from a basis of interoperability, where C and C' accept the queries of D and give answers in a format understood by system D. Thus the relationship between the interacting systems is, barring further assumptions, asymmetric.

We posit that a query-based approach offers an elegant way around the difficulties of a translation-based approach to interchangeability and interoperability because:

(i) Queries, by D, restrict information transfer to only those data that are needed by the application of interest.
(ii) Queries let the creating system, C, determine the appropriate query result based on proprietary algorithms used to disambiguate idiosyncratic model information in M.
(iii) The query-based approach provides a rigorous foundation for developing broad communication and integration standards, in essence by providing operational semantics for fundamental, geometry-based activities.

We examine a core set of queries that are appropriate to support geometric modeling tasks and applications. The required information may or may not be explicit in the model file, so one may have to make additional assumptions and write code to reveal that information. This situation suggests a theme that we articulate as follows. If the model contains specific information, it should be possible to reveal this information and make it explicit. We call this activity *shape evaluation*. However, if the information is not present in the representation of the shape model, and if it must be derived and computed under additional assumptions or imputations, then we will speak of *shape comprehension*. We will point to this theme periodically.

1.2. Previous research on interoperability

Almost all earlier research on geometric interoperability can be characterized as data-centric by virtue of being focused either on format or specific representation conversions. A geometric representation can be thought of as a composition of geometric primitives by rules specific to a given representation scheme. In data translation, such a representation is transferred explicitly by various translators. However, in practice, the meaning of any representation is determined by the corresponding evaluation algorithms that usually also differ from system to system. Thus, conceptually, every geometric translation procedure involves three ingredients: primitive mapping, rule mapping, and possibly modified evaluation algorithms. While many of the primitives have been standardized in widely accepted STEP [2] and IGES [3] standards, representations in individual CAD systems remain incompatible. System-to-system translators are available in many cases, but they do not solve the fundamental bottleneck of interoperability. Perhaps the most widespread difficulty arises from the mismatch between the accuracy of geometric representation and the precision of the evaluation algorithms used in modeling systems. Attempts to deal with this issue include use of exact computation [4–6], modeling imprecision of data [7], methods for tolerant computing [8–10], and a number of heuristic techniques to "heal" the translated models [11–15].

A fundamental unresolved issue is that all data translation methods implicitly or explicitly rely on theoretical foundations laid out thirty years ago [16,17], assuming that sets of points and functions may be represented exactly by data structures and algorithms. These assumptions fail in the presence of numerical errors or approximations, as shown by researchers who proposed to extend the basic theory of solid modeling to account for geometric errors and tolerances [18,19]. In an effort to bypass the numerical issues altogether, a number of researchers proposed to approach interoperability problems in terms of higher level parametric feature-based representations that are largely symbolic structures with minimal numerical data [20–26]. Great progress has been made, but as of this writing, acceptable formal models are still lacking in a number of important areas, including blending, persistent referencing, constraints, and validity, to name a few. It was also observed that most geometric representations and algorithms may be recast in a canonical form using cellular representations [27–29]. In particular, researchers in [29] advocated a representation-neutral DJINN API based on cellular decompositions as an interoperability solution. While the approach is intellectually appealing, it is nonetheless impractical because it requires that a superset of all useful geometric operations is represented and exchanged in the canonical cellular format, by all interoperable systems.

Meanwhile, Shapiro showed [28,30] that, in the presence of a proper formal model, all exact representation conversions can be reduced to a small number of computations that included the construction of primitives, intersections, sorting, and point membership tests. This approach has been used to solve a number of challenging representation conversion problems, including boundary to CSG conversion [31,32] and maintenance of parametric families [24,26]. He also showed that the same generate-and-test paradigm applies in the presence of approximations and tolerances, provided that robust point membership tests can be performed against a formally defined standard. For example, this approach was effectively used to construct approximations of general sweep and unsweep operations based on a formally defined trajectory intersection test [33]. Independently, Hoffmann demonstrated that expensive and error-prone conversion of boundary representations models can be bypassed altogether, if such models may be tested against formally defined high-level parametric representations [34].

These and other recent results suggest that an effective approach to all "representation conversion" problems is not to convert them, but to compute on them via tests (or queries). The approach still requires a proper formal semantics, but this semantics is interpreted procedurally via computable queries. These observations were summarized in a recent report [1].