Dealing with Data Imprecision, Design Tolerances, and Manufacturing Limitations in SIF

Sara McMains, Carlo Séquin, Jordan Smith
EECS Computer Science Division
University of California, Berkeley

1 The Role of SIF

Rapid prototyping of mechanical parts would be much easier if the designers themselves could operate the fabrication equipment. The many decisions that always need to be made– concerning the selection of materials and tools, tradeoffs between costs and expected part performance, and judging the acceptability of fabrication tolerances and deviations from the original design – could then be made on the spot in the heads of the designers. As the design process gets separated from the fabrication process, and we aim to rely on a "one-time, one-way" communication to transmit a design to a fabricator for rapid prototyping, there are basically two alternatives: 1.) Transmit all the background information surrounding the actual use of the specified part, so that these tradeoffs can be made appropriately by the remote manufacturer. This is clearly impractical because of the unlimited scope and diversity of the information that would have to be transmitted. 2.) Transmit a complete, detailed specification for the part to be made, so that there is no need left for any decision-making on the part of the fabricator. This implies that, at least in principle, the part description can be compiled into the necessary low-level operating instructions for the fabrication equipment. This is impractical, too, since it would require an undue amount of fabrication knowledge in the head of every designer.

A compromise appropriate for rapid prototyping is to rely on fabrication processes that have a simple yet effective conceptual model that can be easily understood by the designers. The designers then specify the desired parts via descriptions and parameters commensurate with this conceptual fabrication model, and the fabricators use their engineering skills to uphold the conceptual image of an idealized fabrication process performed on "real-world" manufacturing equipment. Fabrication processes that are particularly suitable for such an abstract conceptual definition include many of the Solid Free-Form (SFF) fabrication processes, such as Stereolithography (SLA) and Selective Laser Sintering (SLS), as well as CyberCut, a developing technology based on numerically controlled (NC) milling with a restricted design space and semi-automated fixturing system, in which the part is embedded in a rigid plastic encapsulation that gets replenished after a certain coherent set of subtractive machining operations have been carried out. In both of these approaches to rapid part prototyping, one expects a mostly automated computer-controlled sequence of processing steps to fabricate the whole part without intermediate measurements steps or adjustment operations. In this

context, the bulk of the part specification is carried through a selection of fabrication process and material and through a description of the desired part geometry. It is expected that the designer is aware of the capabilities and limitations of the chosen fabrication process. It is for this domain of rapid prototyping that a need exists for a Solid Interchange Format (SIF) that carries the right amount of information in the most appropriate form.

While focusing on the overall geometry of a given part, SIF cannot ignore issues of design tolerances, data imprecision, and manufacturing limitations. Restricting SIF to an unambiguous description of *ideal* part geometries would be impractical and inadequate for most real-world applications. In this paper we discuss the degree to which we have tackled the above issues during the initial phase of defining SIF and while using it in our own research and instructional environment.

2 Goals for SIF

The purpose of the Solid Interchange Format (SIF) under development with NSF sponsorship is to transmit a feasible solid model from a designer to a fabricator for fabrication processes that lend themselves to a simple conceptual abstraction in which most of a part specification is carried by its geometrical shape. SIF should carry enough information so that the traditional back and forth interactions between designers and fabricators can be reduced to a single one-way part submission. Before submitting a design, the designer should run some standardized test programs to assure the consistency of the SIF representation and the manufacturability of the part with the given process. These pre-submission tests rely on standardized part analysis algorithms and test structures for process evaluation. This protocol should allow a fabricator to take such tested SIF files (with no questions asked) and turn them into parts that should satisfy the designer.

A first implementation of SIF is based on a boundary representation. This should be a *process-* and *resolution-independent* ideal shape specification with explicit connectivity and topology information. SIF should be *compact* to reduce storage needs and transmission times on the Internet. This implies that SIF must allow shared and repeated geometric constructs to be defined once as sub-parts and thereupon instantiated multiple times. It should further have provisions for meshes and triangle strips, and use higher-level constructs to describe curved surfaces. SIF should be *non-restrictive*, supporting specification of exact cylinders and spheres. SIF has to be *extensible* to allow the addition of new constructs at a later point in time.

Not all design features can be translated directly to manufacturing features, which implies that design features should not be part of an interface. However, since the automatic recognition of manufacturing features remains an unsolved problem, it is important to preserve

such information if the designer has already developed it. In particular, in a NC machining environment, milled pockets and drilled holes have much practical importance, and such information should not get lost when the description is transmitted to the fabricator. We have therefore concluded that there should be a few dialects to SIF for particular classes of fabrication processes. A first one is SIF_DSG, for destructive solid geometry features.

We believe that SIF should also carry some boolean CSG operations. An open semantic issue in SIF is whether to include trimmed patches. Clearly it is much easier to describe a cylindrical hole through a complicated fractal object using a CSG operation rather than with an explicit instantiation of all the resulting trimmed patches. If the fabrication process has a drilling operation, then this higher-level information definitely must not get lost. But even if the part description is sent to an SFF machine, it seems to be advantageous to send the information at the CSG level. The questions that remain to be studied are, how should booleans be implemented in different utilities and tools, and when should they be evaluated? Booleans would also permit an effective approach to specifying – implicitly rather than explicitly – trimming curves on mutually intersecting patches. Further study of boolean implementation issues is needed to assess their implications.

3 Nasty Realities

As a consequence of instancing, explicit sharing of all vertices may be impractical. For precisely defined but imprecisely executed geometrical operations, rounding errors are inevitable. Since the originator knows the source of numerical inaccuracies better than the fabricator, the SIF file should include a precision statement that can be used as the merge radius during file consistency checking.

Real-world fabrication processes will of course never be able to exactly reproduce an ideally specified part. For example, the inner corners of "faceted" milled pockets cannot be infinitely sharp; the sharpness obtainable is a function of material, depth of pocket, number of tool-changes one is willing to make, etc. It seems counterproductive to teach each designer all these tricks and trade-offs. Our goal instead is to find an abstraction for the interchange format that specifies how much deviation the designer is willing to accept, and then let the fabricator deal with it as best as possible – for a reasonable price.

For processes with fixed fabrication tolerances, either because the process does not give much variation, or because the provider does not want to tweak the settings for each individual customer, it is the responsibility of the designers who submit parts to inform themselves of these limitations and either accept them or go somewhere else. The SIF file should document that the designer accepts a stated range of deviations of the actual part from the specified ideal geometry.

For other processes, e.g. NC machining, where finer grained control is available at the price of extra tool changes and machining operations, we provide the capability to specify local tolerance information at all levels in a hierarchy of geometrical constructs: at the level of individual facets, at the level of collections of facets, or at the level of individual features, lumps, or parts. These specifications are inherited downwards in the description tree, but can be overridden at lower levels, using a Pascal-like scoping rule.

Full tolerancing requires a more extensive set of specifications for features and for their individual and mutual tolerances. This kind of information is provided by more complete Part Description Interchange Formats (PDIFs) such as PDES/STEP and lies outside the role of SIF as we currently understand it. The easy extensibility of SIF allows for the ready introduction of new keywords and thus permits this kind of information to readily be transmitted from designer to fabricator across the SIF interface. However, the automatic SIF to machine-tool translators that we plan to develop will probably ignore these additional specifications; they could be printed out for the human operator who is assigned to do the post processing on the part.

4 Infrastructure Accompanying SIF

To have a chance to be successful, a new interchange format must be accompanied by a useful infrastructure of tools and test files. Highest priority is given to a consistency checker and vertex merger that examine the manifoldness of the solids' boundary representations, to a minimum dimension checker that assures manufacturability by the chosen process, to a robust slicer tool, and to a convenient visualization tool. The first two tools, in particular, have to work closely with the precision and tolerancing information transmitted with a SIF file.

5 Conclusions

Interacting with a SFF fabrication house through the submission of STL files often leads to follow-up telephone calls concerning bad polygon-fills due to inconsistent numerical coordinates, or questions about the accuracy of the fabrication process, the tolerable amount of faceting, and the needed amount of tessellation. Hopefully, by addressing some of these issues explicitly in the interchange format, the time-consuming back-and-forth interaction between designers and fabricators can be minimized.