Issues in Mechanical Engineering Design Management

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ABSTRACT

The Virtual Parts Engineering Research Center (VPERC), funded by the Army Research Office, focuses on building frameworks, tools, and technologies for making engineered systems sustainable and maintainable thanks to a virtual engineering environment intended to transform the engineering process, thus supporting extremely fast turnaround times for urgent part supply needs. One of its key research thrusts is data management targeted for the design process. The invitational VPERC workshop held at Arizona State University in June 2003, involved 38 participants from academia, governmental institutions and industry who discussed legacy systems engineering. This paper presents the data management needs to support mechanical engineering design as they were discussed at the meeting.

1. INTRODUCTION

Many organizations own and operate various complex electro-mechanical systems that were designed 25-50 years ago and continue to be used well beyond their intended design life. Continued maintenance requires spare parts that are typically difficult to find. Either the type of the part cannot be identified, or the original manufacturer is no longer producing it. Data management happens to be critical in any comprehensive plan for prolonging the life of such legacy systems.

When a part needs to be replaced and is not available, a first plan consists in producing as close of a replica of the original part. This reverse engineering plan involves the collection of all available information about the original part: specifications, design data (e.g., geometry), and documentation. Mechanical engineering design data are mostly very complex geometric data (e.g., aircraft engine) composed of large numbers of parts (e.g., the 777 engine has 30,000 parts) often stored on paper (drawings) or in electronic files typically in the proprietary format of the computer-aided design (CAD) system used to produce them. Available information needs to be translated in up-to-date formats and integrated into the current product life cycle. But part information typically is incomplete and many strategies must be designed to collect missing information.

When a part that was designed a decade or more ago needs to be replaced, it is likely that current knowledge, as well as the availability of new materials, manufacturing methods, and analysis tools, may produce an improved part. A part may be improved by using cheaper material, involving less manufacturing resources, having a lower production cost, having better properties (e.g., less polluting), etc. In a re-engineering (RE) plan, data management also plays a critical role. Specialized analysis tools, knowledge bases and databases are needed to facilitate tweaking the original design. As in the previous plan, all known information and design data must be integrated and made available to the designer.

Finally, in some situations the replacement part may require a whole new design. This situation may occur when the data available for the original part is missing, or when the part may be a standard device such as a motor that can easily be replaced by a new part with the same specifications. In the context of re-design, like in the more general context of an initial design, engineers try to reuse previous designs because they generally tend to get better with experience [3]. Designers gain experience about which solutions are effective and about the scenarios used to satisfy different problems. When a design problem is provided to an experienced designer, the designer first searches for a similar past design. This proves beneficial for two reasons: re-design generally is less time consuming than novel design and the performance of the base design is known. Reuse of design information generates significant cost savings cutting product development time by as much as fifty percent

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[1]. Thus, the development of design aids should not ignore that designers reuse design knowledge and past designs in the course of engineering design. Before the re-design or substitution can be done, the characteristics of the part must be specified. These characteristics include various performance requirements and inter-facing constraints such as spatial constraints (e.g., size, shape), physical constraints (e.g., weight), mechanical constraints, electrical constraints (e.g., connections, flow and potential variables at the connections), and signal constraints (e.g., types, magnitudes). These requirements may be documented and available to be used in the design otherwise, physical testing of the existing system in operation may be needed to collect them.

2. REPRESENTING DESIGN DATA

Mechanical engineering design data are typically divided between geometric and annotations. Geometric data include geometry, shape, and topology of the artifact, whereas annotations relate to all non-geometric attributes such as function, material (e.g., homogeneous, surface coating), construction history, parametric (e.g., tolerance, dimension), features (e.g., form), procurement (e.g., cost), etc. The first effort to normalize design data produced the Initial Graphic Exchange Specification (IGES) that characterizes physical objects, in particular electrical and mechanical artifacts [8]. Geometric data are represented by entities and their annotations through attributes or relationships. This high level representation favors annotation-based systems with very limited query expression through the defined attributes.

Nowadays, design data are generally represented with the Standard for the Exchange of Product data model (STEP - ISO 10303). STEP was designed as a standard for the exchange of product data to enable the interoperability of computer-based systems that generate and manipulate such data. STEP specifies product information specific to domain applications through application protocols (AP). For example, AP224 defines mechanical products. STEP provides a generic design representation [4] through a logical representation with EXPRESS [7], and a physical representation with constraints capturing the geometry. The most complete representation of mechanical engineering design data thus remains annotated drawings and a variety of CAD systems' proprietary formats.

STEP is primarily being developed in the United States by PDES Inc. PDES is a consortium of large business corporations, who have suffered from being a "data hostage"[1], plus the vendors of various computer-aided design (CAD), computer-aided manufacturing (CAM), computer-aided engineering (CAE), product data management (PDM), component supplier management (CSM), computer-aided process planning (CAPP), and manufacturing execution (MES) systems. The process of developing an ISO standard is not only a painfully slow process but it is also difficult to get the vendors to spend the necessary resources on implementing a new standard or even a subset of that standard once the standard has been adopted by ISO. Consequently, there are a number of STEP Application Protocols (AP) that have attained ISO acceptance level but there is only one major mechanical AP that has been implemented by the vendors and is now being widely used today, that being AP 203, configuration control for 3D designs of mechanical parts and assemblies. AP 203 provides a very robust mechanical part product model geometry transfer capability through its boundary representation structure, which enables driving high precision numerical controlled processing. This provides a capability for the original equipment manufacturer (OEM) to design a part and then farm out the manufacturing of the item by transferring the geometry via AP 203 file accompanied with a standard paper or raster 3-view orthogonal drawing, which carries all the needed manufacturing related data. AP 224, on the other hand, has been designed to carry all the manufacturing and geometry related data needed to manufacture cut parts, plus it uses time saving form features to generate the geometry. However, AP 224 does not currently address all types of manufacturing processes such as forging, castings, etc. As a result of the lack of manufacturing completeness of AP 224 many vendors are currently reluctant to spend the necessary resources needed to implement AP 224 within their CAD/CAM software even though AP 224 has attained ISO acceptance.

As a summarization effort in trying to assess the present day useability of design data in lieu of today's design support technology, qualitative descriptors are presented in Figure 1. Note, the first two attributes *exchange* and *archive* have a higher level of importance than the remaining attributes. While the CAD/CAM industry has made great strides in bringing new capability to the forefront, the table clearly indicates there is a lot more work needed to really facilitate the mechanical design.

3. DATA INTEROPERABILITY

A product life cycle involves phases from product planning (marketing), engineering design, manufacturing, order management, production and procurement, to customer delivery and service [5]. Many tools such as CAD, CAM, CAE, PDM, CSM, CAPP, and MES have been developed to support the execution of each phase. However, product life cycle, and in particular product design, involves more than a juxtaposition of independent phases. The data needs to flow through the product life cycle. The model, as a succession of design activities raises a problem of interoperability between support tools. The data generated from a system must be accessible by the successive system. Interoperability is a difficult problem, even for similar systems. Indeed, transferring data from one CAD system to another is already a difficult task because these systems rely on different internal data representation.

Although in a given phase such as design, data need to be shared among several engineers at design stage. Systems as distinct as CAD, Computation Fluid Dynamics (CFD), Finite Element Analysis (FEA), manufacturing evaluation, and feature recognition systems should be able to share design data. The initial lofting engineer may generate a geometric data set within a CAD package such as CATIA based upon the performance specifications. Data published at the first phase would successively be refined, modified, reconstructed, and analyzed by a CFD tool. The CFD analysis may result in changes that may affect the lofted geometry and the data is sent back to the first phase until the CFD analysis does not require modifications of the lofted geo-

[1] Once a given vendor captures a segment of the market, that vendor's customer becomes somewhat of a "data hostage" to this vendor - i.e., each vendor has a unique way of handling and storing the design and manufacturing data such that this data cannot be readily transferred to other competing systems.

Data	Exchange	Archive	Availability	Quality	Retrieval	Access
Geometry	Good	Weak	Mostly	Poor	Poor	Ok
Function	Weak	Weak	Not	Poor	Poor	Poor
Material	Good	Weak	Mostly	Poor	Poor	Ok
History	Not	Weak	Not	Poor	Poor	Poor
Parametric	Weak	Weak	Weak	Poor	Poor	Poor
Features	Weak	Weak	Some	Poor	Poor	Poor
Design Intent	None	None	Not	Poor	Poor	Poor
PDM/CM	Some	Weak	Some	Ok	Poor	Ok
RE data	Weak	Weak	Weak	Poor	Poor	Poor

Figure 1: Qualitative descriptors of design data

metric data set. At each stage of the process, engineers are working within their own domain with complex domain specific models and knowledge. The rules, heuristics, formulae, and procedures may modify the data before passing them to the next phase. Each phase corresponds to a given model but may affect the part being designed. In other words, each phase provides a different customized view of the design data.

The consensus of the VPERC Workshop Data Group is that while very significant capability improvements have surfaced for generating and maintaining Product Data with the advent of the CAD/CAM/PDM industry as we know it today, there is still much room for improvement in providing support for the design and manufacturing process. The major area of concern that surfaced is that far too much engineering analysis and pre-manufacturing set up time is wasted on data conversion. STEP is making progress in the area of exchanging data among these disparate systems. The central theme behind STEP is that of defining various sets of generic computerized files that define and provide all the data needed to design and manufacture a new product. These product files then serve as a medium for exchanging data among these disparate competing systems. STEP is also addressing construction history transfers among disparate CAD systems. This capability enables transferring each model step placed on the CAD system construction tree plus any parametric relationships established in each of those part design steps. Today, design collaboration within the OEM's supply chain is the low cost way to design and manufacture an item.

Although the community is devoting significant effort to a standard for mechanical data representation to facilitate the exchange of such data among systems, little has been done to exploit this complex data representation for data management.

4. STORING DESIGN DATA

The storage of design data needs to address several challenges. First design data are complex because of the number of parts involved (e.g., the 777 engine is composed of 30,000 parts), their geometry and various annotations. There is a critical need for systems to store design data. Design data need to be archived within the organization that produced the part, as well as within the organization that manufactured it. In addition to these archival systems that capture all information related to parts, there is also a need for digital libraries of parts to provide a rapid search capability. These automated comprehensive databases may be used in several contexts such as searching for similar parts already being used within the organization or similar parts being available including vendor supply catalogs, identifying the vendor supply able to manufacture the part, etc. A concurrent need is to enable the archival of legacy data as they are currently often stored on paper (drawings) or in electronic files typically in the proprietary format of the computer-aided design (CAD) system used to produce them. Legacy data need to be translated from no longer used formats such as raster format to up-to-date formats and integrated into the current product life cycle. But the information about a part typically is incomplete and many strategies must be designed to collect missing information. The information may also present inconsistencies that need to be resolved. Finally, as the industrial world tends to restructure and merge often their resources, there is a need to support the reorganization and integration of the data repositories.

The STEP file also has a very important side benefit in that of serving as an archiving medium. Sadly, today many big corporations, including the government, have archived data using a CAD/CAM format that is no longer supported by any vendor. STEP central theme of maintaining upward compatibility with new releases is in contrast to the typical vendor's policy of maintaining compatibility only 2-3 versions back. Consequently, an engineer generally finds it necessary to spend a large amount of time updating old product files to the new release version since new releases typically have compatibility bugs - i.e., the CAD customer becomes the CAD vendors unpaid debug agent. Bottom line, the vendors do not really provide a long term archiving solution, everything has to be kept on-line. Existing database approaches such as constraint databases [6] are being investigated to archive design data in STEP format [2].

5. QUERYING DESIGN DATA

Once data are stored, engineers need to retrieve them in various contexts each requiring complex query capabilities. In the design phase, engineers often aim to retrieve previously stored designs that match or nearly match design requirements. These requirements may be expressed upon any characteristic of design data: geometric or annotations. Existing approaches to support design retrieval typically store design documents as files and provide an additional structure to access the documents through the indexing of the entire file and do not offer additional granularity. Indeed, the geometry of the design itself is generally not indexed and no direct access to the portion of the geometry that satisfies the property validated by the index is provided. The limitations of the existing approaches for retrieval of mechanical engineering design include:

- heterogeneous representation splitting geometric and non-geometric information;
- querying limited, pre-computed annotations of the drawing, as opposed to the design data (geometry) themselves;
- retrieval of a whole file instead of the extraction of geometric components of a given design that satisfy interesting geometric, topological or semantic properties;
- domain specific retrieval approaches (e.g., feature based), as opposed to a generic approach;
- no query language that allows the expression of complex queries as combinations of basic operators;
- lack of efficiency to handle large data repositories.

6. SUPPORTING CHANGES

Design intent and history

While the issue of design data representation and STEP dominated much of the VPERC Workshop Data Groups' discussion, it is not a "be all - end all" for all the product data concerns that surfaced. For example, there is far too much engineering development time that is squandered in trying "a new approach" to a problem, which has already proven to be a failure - i.e., design intent and history is seemingly never adequately captured, if captured at all. Therefore, when engineering staffs turn over through normal personnel attrition, corporate design memory also suffers attrition. Present day PDM systems should be able to provide the basic repository for this type of data, but research work clearly needs to done to help automate and facilitate this area. The U.S. Army is, however, making some progress in storing simulation proof of concept models.

Data availability

When the design data is complete the issue of finding a vendor to provide the part remains difficult. In the context of placing a part of a legacy system, if the company that produced the part is identified, it might not exist any longer, or it has been merged within a new organization that has reorganized its catalog. In general there is a need to match the description of the part on the designer's side and the actual resources that may manufacture it in order to find the needed part in a vendor's stock, or to identify the vendor that can make it.

Expressing and validating constraints

As illustrated above, the design data go through multiple changes from the early design stages to manufacturing. Each of these changes may affect significantly the part properties and the part specifications need to be validated at each of these changes. Currently no system supports the successive steps of the design from its conceptual design to its manufacturing with an internal constraint system that would automate the validation of the requirements.

7. CONCLUSION

Although this workshop covered all issues involved in legacy systems engineering, it was noted that the need for data management to support legacy systems maintenance is intertwined with the need for data management in general mechanical engineering design. The choice of the plan to replace a part from a legacy system depends on the answer to the following questions.

- How much information is known about the part?
- What is the data format? (paper, digital, physical part, etc.)
- How much will it cost to collect additional info?
- Is it a standard or non-standard part?
- What quantities are needed? How quickly? Will there be any future similar demand?
- What is the level of obsolescence of the embedded technology?
- What is the complexity of the part? What is the degree of coupling with other subsystems?
- Do we need an equivalent part or an improved/upgraded one?

Most of these questions involve data management. Managing mechanical engineering design management is challenging as no system currently addresses the issue to manage the wealth and complexity of data that need to be represented, accessed, and transformed.

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