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Product and Shape Representation for Virtual Prototyping

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Abstract

Instead of being an exciting step towards more rapid product development, virtual prototyping could become a new term to cover the existing computer tools collected under the terms CAD, CAE, CAx. The computer technology to enable realistic "handling" and distributed design consultation is now demonstrable. However, effective management and distribution of the information to be processed and, hence, use of the results could remain constrained by the many ad hoc data conversions imposed by our current inability to most effectively represent that information for shared use and reuse.

The first issue is to provide a framework for the information that supports product development and that is developed during product development. In order to create the integrated information system that virtual prototyping implies, the Open Distributed Processing Reference Model (ODP-RM) [deMeer 1992] for distributed information systems is an apt basis and a useful route map.

The role of STEP in such an information system needs explanation. It is encouraging that the ISO Standard for Exchange of Product Model Data (STEP) [Owen 1992] development methodology is using a similar map to that provided by the ODP-RM. The STEP work, particularly the tools used developing Application Protocols (AP) and the integrated resource models themselves, is an integral part of our way ahead. The learning from that community is already exploitable. As discussed below, however, their difficulty in defining the requirements of STEP, and the general lack of understanding of what STEP can provide, needs urgent resolution.

Another issue is the constraints imposed by representational techniques for geometry used in today's CAx systems, particularly parts with sculptured surfaces. Because shape is so fundamental to mechanical design and visualisation on computers, it is important that shape information can be related properly to other information and altered simply. This is not currently so.

Finally, one must understand the relative value of real and virtual prototypes and more importantly the need for physical models to test in order that confidence in computer simulations is well founded. This is particularly necessary where the virtual prototyping uses complex flow analyses, namely Computer Fluid Dynamics (CFD). The advent of layered

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manufacturing (additive manufacture, rapid prototyping) potentially expedites the making of real prototypes with minimal manufacturing planning. "Computer Aided Rapid Prototyping" and the "Integration of CAD, CAE and Fast Free Form Fabrication" are alternative titles for a project, briefly known as CARP[1], researching these subjects to reduce the time to prototype automotive powertrain components.

This paper discusses some of the issues and some pieces of the solution.

1 BACKGROUND

In order to prototype on the computer an increased integration of the activities involved in evaluating products is needed to facilitate communication between them. For example, analysis of the behaviour of a component may suggest alterations in its shape and also the shape of other components with which it interacts. With current technology, this is inhibited by data conversions between different representations and lack of appropriate associative data. More important, shape should be related to functional requirements - not usually represented in the computer.

The word, integration, is widely and loosely used. The complex association of people, processes, materials and information that is the product introduction process needs decomposition to aid understanding so that possible improvements can be identified, controlled and are achievable. This is the role of a reference model. In considering integration in the product life cycle, the authors view the whole process as a distributed information system and find the ODP-RM helpful. This model advises the consideration of such a system from five viewpoints:-

a) business or enterprise, that is, the things to be done (activities or processes) to achieve the objectives of the system;
b) information, that is, its form and the flows to achieve necessary communications and,
c) computing, system engineering and technical implementation often classed together as the software support environment.

The advantage of this model is that the integration of the enterprise with respect to its objectives and of the information requirements can be addressed independently of and preferably before the computer implementation issues. This can help to avoid the trap of being driven by current computer based applications. Gielingh [Gielingh 1994] breaks the integration of product data into the problems of enterprise integration, application (computer) integration and data integration. Application integration is interfacing today's software using data exchange technology. The solution to data integration, sharing, is seen in terms of networks, files and data bases software suport in ODP-RM terms rather than the appropriate integrated product representation.

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1 CARP is a three year collaborative research project organised under the auspices of the DTI EUREKA programme. The primary objective is the integration of design, analysis and rapid manufacturing methods such that prototype components can be produced rapidly and with greater confidence of "right first time", the secondary to realise the potential of layered manufacturing technology. The consortium is lead by Ricardo Consulting Engineers Ltd, of the UK, and includes CADDETC, Delcam International plc, Webster Mouldings Ltd, and the University of Leeds, all from the UK, Volkswagen AG of Germany and Dott. Vittorio Gilardoni SpA of Italy.

STEP, the STandard for the Exchange of Product model data [Owen 1992] addresses computer applications in the product life cycle. It was initiated in 1984 to enable better interchange of data between computer aided activities (CAx) than that provided by the current data exchange "standards", e.g. IGES [Smith 1991], SET: 268-300 [1989]. Many hundreds of man years have been voluntarily contributed under the aegis of ISO TC184/SC4.

STEP is a methodology and data models. These latter are loosely based on the ANSI SPARC, Application, Logical and Physical layers [ANSI/X3/SPARC 1975] and the methodology suggests understanding the engineering requirements for a particular exchange by studying the activity and information flow first. This is encouraging and we use the tools adopted by STEP contributors for these operations.

Implementations of STEP will have a collection of Application Protocols, data models to which exchange software must conform. Exchange software converts between the data representation of the CAx system and a neutral representation in the form, currently, of a physical file. Application Protocols are constraining in order to enable data exchange, i.e. so that conforming processors cover the same range of entities and use them in the same way. The requirement to enable data exchange enforces an emphasis on what current CAx systems represent. The Application Protocol 203, Configuration Controlled 3D Design, has a wider view embracing product structure and configuration. Unfortunately supposed prototype implementations by vendors, do not impose conformance which is required by STEP if it is to revolutionise data exchange. Current attempts at STEP based data exchange can be categorised as "IGES STEP" with much of what was wrong with IGES and its contemporaries remaining. The current debate is the perceived need for data sharing which we define as applications viewing, or dipping into, parts of a single representation of the product model conforming to an integrated product data model. Intuitively STEP should enable this but current thinking is confused. The contribution of the Integrated Resources, particularly the Generic Product Description Resource [ISO 10303-41 1994], is explained in this paper.

Sections 2 and 3 use this background to progress towards the type of product data model we need to integrate the information and enable sharing. We, then, complete the picture with a discussion of a novel geometry representation.

2. ACTIVITIES AND INFORMATION MODELLING

Models based on SADT(IDEFO) [Marca 1988] cemented understanding of the issues among the technically diverse group of collaborators in CARP. Although IDEFO has its critics as a communication medium, the thought and rigour required to understand the inputs, controls, outputs and mechanisms and agree viewpoints and purpose is a necessary prerequisite to understanding the required *information* and software support. At this stage the depth to which one expands such diagrams should be compatible with understanding the product development activities and the information requirements, not the details of computer processing and data requirements. As a simple example, we identify the geometric functionality that the activities themselves require, i.e. we do a stress analysis of a solid part, a flow past a surface or in a cavity, we machine a surface, not the data requirements imposed by current shape representations or the computational methods we normally use to simulate behaviour.

3. INFORMATION

One is then in a position to understand information flows, forms and content. In choosing a formal notation, differences between the engineer and the information technologist appear. Our contention, not novel, is that the activities which the information system supports and the information flows should be clearly understood before the role of the computer is defined. An information model can be evolved as is, for example, the Application Reference Model of STEP. The direct use of STEP's Data Definition Language (DDL) Express [ISO TC184/SC4/WG7 1991] may suit those who know the computer applications for which they are catering and hence the data requirements, but is not appropriate as a first step to an information model to support product development. It is, however, very difficult to separate the product information from those representations, data, which are needed to support the computer processing and the form in which results are presented, e.g. stresses on meshes rather than stresses available throughout the body. Today information systems are usually studied with preconceived views of the computer processing to be applied because commercial systems, e.g. CAD, FE, are already in use. Collaborators selling CAD or CFD systems are interested in improving current systems and thus start from current technology.

3.1 The integrated product data model

The information model in EXPRESS-G (Figure 1), the graphical form of EXPRESS [ISO TC184/SC4/WG7 1991], from the CARP project falls into this trap because implementation is driven by existing CAx systems. However, we do try to identify the conditions to be applied to geometry or shape description rather than to the discretisations required by particular computational techniques. The model also uses STEP models where these are available, e.g. the advanced BRep AP204 for solids.

More significant to the CARP model, and a feature of all STEP APs, is the influence of the GPDR, the generic product description resource. This imposes a root and a framework to the data model which models product and some accompanying structure. This structured form is essential if sharing is to be enabled. Our research proposes a framework for product data which supports all phases of the life-cycle, specification to disposal, and is detailed only as users and applications require. This is a top-down approach not the bottom-up approach which pragmatic data exchange requirements encourage. This top-down integrated product data model is essential for sharing.

The STEP GPDR distinguishes between the description of and the representation of the properties of products. For example, the STEP Integrated Resources, of which the GPDR is a part, has a geometric description which is shape definition information. We would suggest this should be shape information that comes from the functional requirements. The shape representation itself is what computer processing/applications require, generally the primitives (lines, arcs, polynomial patches, blocks, spheres, cylinders) or discretisations of which computer representations are constructed. From the perspective of the engineering process such representations are of secondary importance.

It is interesting and understandable that many of those in STEP concentrate on data exchange of representations - the area which CAx systems embrace and on which STEP could be best demonstrated - and see the geometric description and the product oriented framework as an unnecessary overhead.

The authors believe it sets the necessary framework for STEP. The authors are using the ideas behind the GPDR that is exploiting a framework to support specification, functional structures and assembly information [McKay 1993].

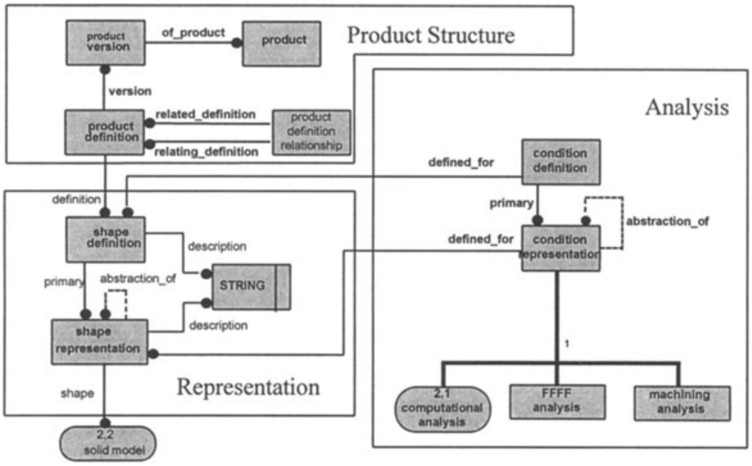

Figure 1 Root of Information Model (in EXPRESS-G) GPDR, Geometric Representation and Analysis.

4. COMPUTER PROCESSING

Having understood the activities and the information requirements, ideally one is in a position to think about the software support environment, firstly the processing that the computer will do and for which we must design software and, lastly, the computer system's architecture and implementation.

By this time one knows the observations, analyses and manipulations that are significant in the development of a given product or type of product, i.e. for what one needs a prototype. Whether this is a physical model or whether the observations etc. can be adequately performed on the computer will depend on the testing to be performed and the possibility of adequate computer simulations. Most parts can now be realistically visualised including movement. Assembly, to test fit and maintainability, can be performed for many functional mechanical parts where the solids involved can be represented. Analyses of stress (commonly using finite element (FE.) methods) can be confidently performed in many situations. In many companies FE based stress analyses are performed by designers, not analysts, using FE codes validated for strictly defined physical situations. Flow analyses are less reliable. Although codes for complex 3D situations are sold, confidence in their use requires experienced fluid dynamicists backed by experimental confirmation. Additionally the time taken to simulate (and convert) can inhibit realistic visualisation which many see as an essential of virtual prototyping. The display of complex models, in digital pre-assembly of aeroplanes or examination of oil rigs today, is built on static computer representations of admittedly complex geometries and relies on view changes to model the human moving through the scene. Visualisation of dynamic environments and those involving models of physics is not yet possible because of accumulations of times built up by various aspects of the computation.

The overhead in conversions is a secondary problem with this virtual prototyping scenario, e.g. from CAD representation to analysis discretisation and, if the prototyping leads to suggested improvement, back from the results of the analyses to improved shape.

As explained in previous sections these conversions can drive the information system rather than being relegated to a simple reliable routine process. However, the associativities required to respond appropriately to the results of analyses demand an integrated top-down product information model as an immediate priority.

5. REPRESENTING SHAPE

One aspect of the work reported here which will help virtual prototyping and also shape synthesis is the definition of geometry where the functional constraints define the shape description, where surface and solid representations have a unified definition and where discretisation suitable for analyses is implicit in the shape definition process. The over-riding objective on the work reported here is not the downstream processing that the method facilitates, but minimising the number of parameters that define the shape and relating those to the design specification not solely the geometry. The aim is optimisation and shape synthesis where the shapes have complex sculptured surfaces. The speed and reliability with which discretisations for layer manufacture, for CFD and for FE based solutions are produced has been remarkable in contrast with current CAD systems.

A new method for the efficient definition of complex shapes has been developed at Leeds. It is based upon a boundary-value approach, in that a surface is defined in terms of boundary-conditions specified along the curves which form its boundaries. A consequence of this boundary-value approach to surface generation is that the CAD geometries produced by the Partial Differential Equation method are described in terms of surface patches that meet perfectly. This facilitates both the computer-aided analysis of an object's physical properties and its manufacture. Furthermore, a design may readily be changed and yet this property - of perfect connectivity - is still maintained.

The definition of the surface shape between defined boundaries by partial differential equations [Bloor 1989] was introduced as a blending problem. The technique has been extended to cover free-form surface design where the aim has been to generate functionally useful surfaces (e.g. propellers, ship-hulls) from patches of PDE surface [Lowe 1990].

The PDE method is not primarily a method for surface representation, but a method for surface generation. It is envisaged that objects whose surfaces are generated by the method are designed to serve some function, and hence it is crucial that the design of an object's geometry is integrated with functional considerations. What makes the PDE approach especially suitable for this is that it can parametrise complicated free-form surfaces in terms of a relatively limited parameter set. This is possible because of its boundary-value approach: surfaces are specified in terms of data distributed around curves, rather than across the surface itself. In practice, this means that the number of shape parameters specifying an object's surface is often small enough for the task of optimising its shape to be computationally feasible; yet at the same time the method is sufficiently flexible for a wide range of shapes to be accessible to it.

Work has been carried out on the integration of an object's geometric design with its functionality in a number of applications, ranging from heat transfer, stress minimisation, and the design of a surface for its hydrodynamic properties [Bloor 1990] [Wilson].

When creating complex surfaces, it is generally necessary to construct the surface from a number of parametric patches, and we need to be conscious of the fact that each patch must be bounded by specified curves with adjacent surfaces having the required degree of continuity across their common boundary. However, when constructing a free-form surface from a number of PDE patches, one still has considerable freedom with which to choose the boundary conditions, despite the continuity requirements in order to achieve the desired shape. The solution remains sensitive to the choice of boundary conditions and this fact is turned to the designer's advantage as it is the boundary conditions that provide him or her with a powerful tool for surface manipulation. A convenient way to demonstrate the relationship between parameters and surface changes it through the series of examples given in earlier papers to which the reader is referred rather than repeating here.

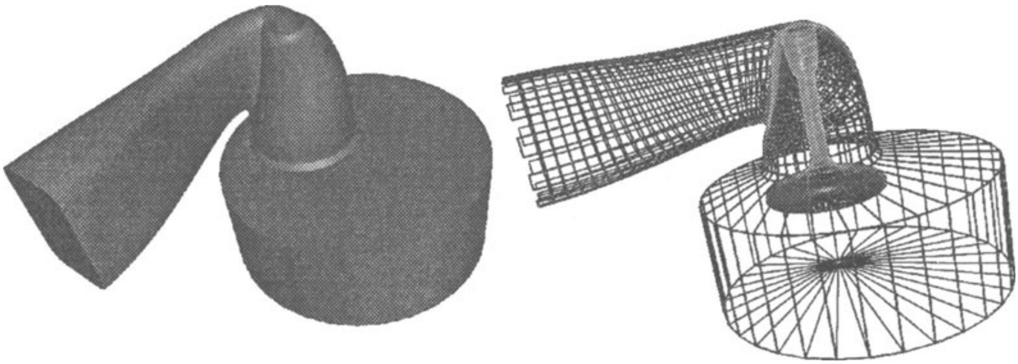

Figure 2 Inlet Geometry for a Diesel Engine.

As an example which combines most of the likely complication which may arise in multiple patch surface generation we consider the inlet geometry for a diesel engine, as shown in Figure 2. Notice that this entails creating the space within the inlet port through which the gas flows before entering the combustion chamber. For this reason the volume forms part of the domain over which a fluid dynamical analysis needs to be carried out. It follows that once this has been done, the definition of the mechanical part surrounding this space requires further, though generally less critical, surface generation to complete the definition of a solid object.

In obtaining the surface as a combination of PDE patches, each of which is a solution of a boundary value problem, there is no problem in ensuring that adjacent patches meet perfectly with the desired degree of continuity. In other words, there are no holes in the final surface, which if need be, can be represented in discrete form by a set of quadrilateral surface patches. This is an extremely important point, from the point of view of both analysis and manufacture through such techniques as selective laser sintering. For instance, in CFD analysis, conservation laws are discretised and fluxes of physical quantities across cells are calculated. Clearly if there are holes in the cells, inaccuracies can arise. More importantly, holes in the surface cause difficulties for inside/outside testing which may be needed for automatic mesh generation. Also, in layered manufacture, holes in the surface description give rise to flaws in the final object.

As it happens, the CFD code (VECTIS) which we use to demonstrate the physical analysis of our model requires a closed surface of triangular facets bounding the solution domain before the automatic mesh generation and CFD analysis can be carried out. Thus, this code provides us with an ideal test both for analysis and rapid fabrication. The geometry for the inlet port, which we have created, is supplemented by additional geometry of the combustion chamber and a valve (created using the PDE method) to make a physically realistic model for analysis. The surface data was put into STL[2] format and was immediately ready for the automatic mesh generation of VECTIS without the necessity for surface 'stitching', i.e. the closing of surface holes.

6. A LAST WORD ON STEP

The virtual prototyping environment requires a shared information model. Although the STEP resources are enabling the data exchange for which STEP is designed, currently it concentrates on the detailed data representations rather than an overall framework for product information. This is emphasised because geometric representations, CAD data, are those most commonly exchanged. Attempts to discuss STEP in the context of sharing, demand solution to a currently unsolved problem [McKay 1994]. Shared data implies a model instance that agents dig into at will, but which inherently shares data and hence ensures consistency. We believe this needs an integrated product data model. How such viewing mechanisms are defined may be related to STEP Application Protocol (AP) interoperation as many believe. The authors fear AP interoperation is directly counter to the design aims of APs and could degenerate into the use of subsets[3] from a single large AP reminiscent of (old) IGES technology. Possibly, interpretation of STEP integrated resources [Ashworth 1993] is a way forward. An experiment which shows how sharing and data exchange can be achieved in the same environment is urgent.

7. CONCLUSION

Building on a range of research this paper proposes an integrated product data model as a top-down a framework for information generated in the product introduction process. The model uses the STEP Generic Product Description Resource extended to cover specification, functional structures and assembly conditions. Additionally a novel representation of geometry designed to facilitate shape design and functional optimisation may prove a unifying link into shape representation and discretisation which will accelerate virtual prototyping for engineering - where models of physics are important.

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2 STL - defacto standard for input to layered manufacture machines, a triangular facetted representation of a solid.

3 As currently proposed subsets are Units of Functionality or Application Integrated Constructs. These lack a context, an important part of the AP Development Method.

8. ACKNOWLEDGEMENTS

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