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Visualization Applications for Manufacturing– A State-of-the-Art Survey

Final Report

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ABSTRACT

A state-of-the-art (SOTA) survey was performed for visualization software applications (VAs) in the context of a rapid response manufacturing (RRM) environment. VAs are standalone, commercially-available products, that have sophisticated capabilities for interactively visualizing data. The data includes geometry, image, and scientific data. VAs' capabilities to visualize data can be advantageously applied to manufacturing if VAs are integrated within RRM.

In general, integration enables any RRM process to access data from other RRM processes in the product life cycle. However, having access to data isn't necessarily useful if it is too overwhelming for a human to use it. VAs offer the potential for users to cognitively integrate the data from multiple RRM processes to make sense of it and to intelligently use it.

This SOTA describes the capabilities of VAs and methods for integrating them within RRM to ultimately enable the full potential of VAs to be realized.

KEYWORDS

manufacturing; RRM; rapid response manufacturing; visualization.

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1 INTRODUCTION

Reading and writing were only democratized in the past 100 years, and are the accepted communication tools for scientists and engineers today. A new communication tool, visualization, in time will also be democratized and embraced by the greatest researchers [and engineers] of the future.

J. McCormick [ed.] Computer Graphics 21, 6 (N.Y.: ACM SIGGRAPH, 1987), as cited in [Rodriguez90].

Typically, the types of applications considered to support the manufacturing life cycle of a product—from initial concept through production and finally disposal or recycling—include applications such as computer-aided design, process planning, numerical control (NC) code generation, inspection planning, etc. Visualization has generally not been considered as a separate application to be included in the planning of a complete manufacturing system.

However, that omission needs to be reconsidered. The market for visualization applications (referred to in this report as VAs) has exploded. According to Carl Machover, a computer-graphics consultant based in White Plains, N.Y., the scientific-visualization market was $1.5 billion in revenues in 1992 [Wendorf93]. The reason for this explosion is that VAs provide solutions to applications that were previously provided by customized solutions, or were provided not as well by other types of applications with less powerful visualization capabilities, or were not provided at all. This last case includes the capability to explore voluminous and complex data sets, and enable a user to gain insights from them that are difficult and time-consuming or even impossible to achieve otherwise. Because of their capabilities, VAs can be applied advantageously to rapid response manufacturing (RRM).

The objective of this report is to provide a state-of-the-art (SOTA) survey for VAs in the context of an RRM environment. The capabilities of VAs are more far-ranging and more powerful than the visualization capabilities built into computer-aided design and analysis applications. The additional capabilities can enable improved manufacturing proficiencies that cannot be attained by reliance on current design and analysis applications alone.

For example, using a VA to "miniaturize oneself" to "fly" around a complex part, through all the crevices, holes, etc. could be useful to an engineering team to understand the part and to communicate the design to the customer. As another example, using a VA's animation capabilities could enable assembly and other manufacturing operations to be simulated as an aid

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[1]This survey was performed for the National Institute of Standards and Technology (NIST) Rapid Response Manufacturing (RRM) Intramural Project under the sponsorship of the U.S. Department of Commerce Advanced Technology Program. The RRM Intramural Project is being performed by the Factory Automation Systems Division of NIST in collaboration with the National Center for Manufacturing Sciences RRM industry consortium.

to process planners. As a third example, using the VA's environment to manipulate scientific data graphically could help a design engineer make sense of the results of several analyses superimposed on top of the design representation [Robertson91]. By manipulating the information in a sophisticated graphic environment, the complexity of information might be simplified. As a final example, using a VA's ability to generate a physically accurate synthetic image could be useful to configure a vision system to locate parts. The image data could be sent to a numerical simulation of the vision system to help tune it to a particular part family in a particular environment [Rushmeier92].

Because of examples such as the ones cited above, VAs will be an important component of RRM systems in the future. To fully exploit the use of VAs for RRM, three efforts are necessary. First, the current visualization capabilities of VAs, as well as new capabilities expected for the future, must be studied. Second, VAs must be integrated within the RRM environment in an intelligent way. Third, manufacturing applications, in particular, design and analysis applications, must be studied with an eye towards using visualization capabilities to improve RRM. This report will document results of the first two efforts—studying capabilities of VAs and determining methods for VAs to be integrated to other applications.

2 WHAT IS A VISUALIZATION APPLICATION (VA)?

No. 1, you can visualize the data; No. 2, you can operate on the data in an interactive mode—you can do a lot of what-if scenarios in a very relative short period of time. I just saved doing a $10,000 test three days ago using a software visualization program. That probably took one engineer four hours, and it would have taken us two weeks to run the test otherwise.

Rich Bond, supervising engineer of design analysis, Ford Motor Co., as cited in [Wendorf93].

2.1 Description

A VA is a standalone software application that has sophisticated capabilities for interactively visualizing data. One use of a VA is to direct how data is graphically displayed to best communicate information from the data. A second use is to apply filters, mappings, and other transformations to the data to interactively "explore" it. The goal of the exploration is to gain insights into the underlying phenomena that the data represents. The process of interactively studying or exploring data in the field of scientific computing is referred to as "scientific visualization," or simply "visualization" [Brodlie92]. The visualization of phenomena in three dimensions (3D) is referred to as "volume visualization." In volume visualization, three dimensional "voxels" (volume elements) are projected to two dimensional "pixels" (picture elements) on a screen. Volume visualization is currently one of the fastest growing and hottest areas of research in scientific visualization [Todd93].

Visualization brings together many different disciplines including image processing, solid modeling, signal processing, sophisticated rendering, animation, user-interface methodology, and cognitive psychology. The combination of these disciplines through a VA provides a synergy which enables capabilities that extend beyond the capabilities of the individual disciplines (for example, the free-ended exploration of data). A VA can be thought of as providing a window into any process within a complex system where data is available, either as an off-line or a real-time application.

In manufacturing, a VA could be used at many points throughout a product's life cycle. For example, a VA could be used for any of the following:

- to communicate product designs and manufacturing processes;
- to verify clearances of parts, fixtures, and machine tools in process plans;
- to study the interaction of phenomena such as thermal effects on a product design in its anticipated environment and/or in the product's manufacture; and
- to compare experimental and simulation-generated data to develop improved manufacturing process knowledge.

2.2 Visualization Cycle

The three basic steps in visualization are [Haber90]:

- data enrichment/enhancement,
- visualization mapping, and
- rendering.

In data enrichment/enhancement, the data is filtered or transformed into a more usable form for whatever further processing is intended for it. The "enriched" data is then mapped to geometric primitives, such as triangles, spheres, isosurfaces, etc. Finally, color characteristics, viewing conditions, light sources, surface properties, etc. are applied to the geometric primitives to convert them to a rendered image to generate on a display or to save in a file.

The user interface, the display, and the source of input data are considered outside the basic visualization cycle. They are discussed in Sections 2.3 and 2.4, respectively.

2.3 User Interfaces

VAs are tools that professionals can use to serve their visualization needs in their particular fields of expertise. A primary feature of a VA must be ease of use. VAs should not require a computer science degree or any other special expertise other than brief instruction. Unfortunately the tools, by virtue of the complex sophistication built into them, are not necessarily easy to use.[2]

The user interface incorporates one or more of the following techniques:

- command line,
- direct manipulation, and
- visual programming.

The command line interface (CLI) is the old, familiar interface from the worlds of teletypes, DOS[3], and UNIX. Though more primitive than newer, graphical user interfaces (GUIs), CLIs allow more complex instructions and programs to be executed by the VA than with a GUI alone. The second type of interface, the direct manipulation interface, is the now familiar "point and click" interface where the user positions the mouse over "buttons" or "menu items" and clicks the mouse button for selection. This type of interface allows the user to approach the VA as if it were a turnkey program to do simple tasks such as display a particular data file under particular viewing conditions, etc. A great variety of work can be done using a VA with this type of interface alone. The third interface, visual programming, is an extension of the direct manipulation interface in that modules can be selected and connected to each other to form the

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[2]In fact, the interim results of a survey conducted by Microsoft Corporation showed that, of 10 respondents (a very small sample), a majority believed that computer programming and/or computer graphics knowledge was required to operate VAs [Dickerson93].

[3]Microsoft MS-DOS, commonly known as DOS (disk operating system), is a product of Microsoft Corporation.

visualization networks described in Section 2.6.3 below. As mentioned, the command line interface still provides the user the most flexibility. However, the intention of a VA is that most work can be done with the GUI only.

As VAs have matured, they have become much more complex. They may be difficult to learn, and even then, valuable features may be forgotten if not used on a regular basis. No matter how intuitive the user interface appears, a help feature, in particular context-sensitive help, is a valuable feature for the user.

2.4 Visualization Data

The types of data displayed and manipulated by VAs include geometry, image, and scientific data. Geometry data, consisting of points, lines, and other geometric primitives, as well as the relationships among them (the topological relationships), is used to represent two- or three-dimensional objects. For manufacturing applications, the three dimensional objects are generally the more important and are used to represent the part, fixture, machine tools, etc. The visualization of the object may be studied as an end in itself by selecting alternative viewing transformations, lighting conditions, etc.

Image data is used to represent scalar values in two dimensions (2D). It is concerned with pixel data on a surface, where each pixel represents a value. The value is translated to a color or a shade of gray in order to render the image.

Scientific data is the data acquired in monitoring some type of phenomena. The data may be acquired from physical instruments or from a computer simulation or from a computer analysis application. The data input to a VA may be generated (and studied) in real time, or it may be taken from an archive that was previously stored.

The structure of scientific data can be very complex, and is dependent on the nature of the phenomena and how it is being modeled. In this report, the term "scientific data" is broadened to include scientific, engineering, and other application-generated data. Types of scientific data for manufacturing applications include temperature, pressure, velocity, stress, etc.

Scientific data consists of one or more dependent variables that are associated with one or more independent variables. It is often represented as scalar or vector or tensor values at specified "grid" locations in space (though more complicated data structures are possible). Various types of grids can be used, to enable the user to map the data to the most suitable grid structure. The types of grids are shown in Table 1 in order of their increasing generality [Todd93][Hagen93].

Each data record can represent whatever simple or complex data structure is necessary to "properly" capture the information desired. Voluminous, complex data does not easily yield insights to the nature of the phenomena it captures. Interactive visualization is exploited to determine those insights.

For manufacturing applications in particular, studying the scientific data in relation to the target part data can give insights to improve the manufacture of the part. Scientific data is generated from other applications and must be read into the VA. The application that produces the data may be tailored in some cases to produce data in a specified format. However, in other cases, an archive of expensively generated data may already exist and need to be used as is.

2.5 Visualization Techniques

A visualization technique is used to display data in a form that will lend insight to the underlying phenomena. There are three steps in a visualization technique:

- modeling the data in an appropriate data structure that can capture the phenomena,
- choosing an appropriate metaphor to communicate the phenomena, and
- converting that metaphor to graphic primitives that can be rendered.

In other words, the phenomena must first be captured in the data and structured in a way that the data can reveal it. Next, the investigator considers the data structure and the phenomena to understand to decide on what type of visualization technique will best show the phenomena. Finally, the investigator chooses viewing parameters to manipulate the rendered image to uncover the phenomena and reveal the appropriate insight.

Table 1 Types of Grids Used for Representing Data

Grid Type	Description
Cartesian	The simplest grid, in which the coordinates are not explicitly stored or referenced. The addressing is done by integer subscripts (i, j, k). In 3D space, the Cartesian grid is a rectangular grid with three identical axes that are orthogonal to each other. The grid can be thought of as filling the space with cubes.
Regular	Similar to the Cartesian grid, except the increments may be different along each of the three axes. Instead of filling the space with cubes, the space is filled with axis-aligned hexahedra.
Rectilinear	Usually rectangular with a nonuniform spacing along each coordinate axis. The space is filled with axis-aligned hexahedra.
Structured	The hexahedra are not necessarily rectangular. Spherical and cylindrical coordinates are examples.
Block Structured	Includes several structured grids.
Unstructured	Polyhedra with no implicit connectivity. Tetrahedra are popular.
Hybrid	Any collection of grids that fill a space.

Table 2 lists a number of visualization techniques and briefly describes each one. The table is a compilation of information from several references [Bailey93][Stolk92][Brodlie92] [Hagen93], but the list of techniques is not meant to be complete. Rather, it is intended to give the reader an idea of what a visualization technique is.

Table 2 Description of Visualization Techniques

Visualization Strategy	Description
one to n-dimensional scatter plots	1D: scalar values plotted as points on a single axis; 2D: pairs of values plotted as points on a plane; 3D: projection of three values to a 2D plane, with some property of marker (such as color) used to represent the third component nD: icons containing multidimensional information plotted on a plane, for example, Chernoff faces [Chernoff73], where the different variables are "attached" to different features of the face such as the shape of the eyes, mouth, etc. Differences are easily recognized. Up to 12 parameters have been represented this way.
line graph	scalar value plotted as a continuous line in a plane
histogram	scalar value defined over regions along an axis
bar chart	scalar value defined over an enumerated set
isoline	from a set of values at points in a 2D plane, a continuous line that connects points associated with the same value
image display	2D grid of cells, where the color of each cell represents a value at that cell; generally used for densely packed data such as an image from a satellite
surface view	similar to image display to represent a function value over a 2D area; area is projected as a 3D surface to a 2D plane, the height of the surface representing the value
height-field plot	surface view that shows two scalar fields over a 2D domain, one field by the surface view, and the other by using a color scale
multiple scalar fields	image display in which an icon with multiple attributes occupies each cell to express multiple scalar variables
isosurface	surface that contains the same data value throughout in a 3D field
volume rendering	projection of 3D "voxels" onto 2D "pixels;" techniques include contour connecting, opaque cube, marching cubes, ray casting, and splatting
arrow plot	direction of vector in 2D or 3D
hedgehog	surface with arrows that represent velocities; arrows point in the direction of the velocity, and the length of the arrows indicate the magnitudes at each point
streamline	flow line for the motion of a particle in a static vector field

streakline	evolving curve that results from the equivalent of a stream of tracer particles being continuously injected in a flow from a fixed location
particle path	particle path that is the equivalent of a particle being transported through the flow
tuft	small vane anchored at a fixed location in the flow
blob tracing	path of a blob, or volume of fluid, as it moves through the flow
ribbon	flat polygonal surface enclosed by two streamlines or streaklines; shows twists in the flow
stream polygon	n-sided polygon that is swept along, perpendicular to the flow; radius of polygon can indicate magnitude of a corresponding scalar attribute
glyph	a graphical object whose properties such as size, shape, color, transparency, etc. convey multi-dimensional information
boid	a glyph that has additional information by its animated behaviors in a flow
surface-particles	very small flat part of a surface, modeled as a point with a surface normal; combined use of many surface-particles can lead to surfaces; the combination of particle tracing and shaded surface rendering shows more information
image processing	many techniques that involve image enhancement, feature extraction, or image transformation (for example, Fourier transformation)
animation	sequence of scenes that is played as a movie; useful for showing time-varying activities, but any variable may be chosen as the independent variable; also useful for depth-cueing in complex 3D scenes by moving objects in relation to each other
aids for perception in 3D	scene context, perspective, occlusion (nearer objects hide more distant objects), lighting, shading, stereo views, movement, user control to navigate 3D display

2.6 Classification of VAs

VA products can be divided into three categories, which roughly maps to the evolution of these products. The three categories, from earliest to most recent, are:

- graphics libraries and presentation packages,
- turnkey visualization systems, and
- application builders [Brodlie92].

As expected during the VA technology's normal evolution, the more recent VAs are more sophisticated, but less mature than the earlier VAs. For example, presentation packages and turnkey visualization systems are more widely distributed, more extensively field tested, but less capable than application builders. Also tracking with the technology's development is that more computer power is required as you go from the first to third VA category. Personal computers are generally sufficient for graphics libraries and presentation packages. However, computer workstations and even computer networks may be required for turnkey visualization systems, and particularly, for application builders.

As the VA technology matures and computer performance increases while prices decrease, more sophisticated features of the high-end VAs migrate to newly released versions of the low-end VAs, and new features are added to the high-end VAs as well. Over time, you may expect a VA to have more functionality, more ways of interfacing to other applications, and eventually user group and other types of support (for example, electronic mail groups, module archives, etc.).

A description of each category is given below, along with one or more VA packages listed as examples for each category. The VAs are categorized according to the author's understanding of them at publication time. If new features are added, some VAs may evolve to more advanced categories than they are listed in below.

2.6.1 Graphics Libraries and Presentation Packages

This category includes the traditional method of developing a customized program for visualization using a graphics library. The library contains functions that simplify the interface from the program to the graphics hardware. Examples are the NAG Graphics Library[4] and GL[5].

Additionally, this category includes simple presentation packages that enable a user to display graphics files with limited interaction capabilities for the user. A good amount of work is still necessary to achieve good results. An example is the PC-based package, Harvard Graphics[6].

2.6.2 Turnkey Visualization Systems

These systems allow the user to enter data to visualize and generally have a convenient user interface. The category can be further divided into geometry viewers and turnkey systems for scientific data. Geometry viewers are convenient for entering computer-aided design (CAD) models as input data and, with further user instructions, can produce photo-realistic images of 3D objects. They may also produce animations, requiring key-frame inputs, and interpolating between them. Examples are Alias Animator[7] and VoxelBox[8].

Turnkey systems for scientific data can input and display that data with a limited set of operations accessible to the user. The system may also allow the input of geometry data so that the scientific data, possibly associated with the geometry, may be superimposed on top of it. Often, products in this category are application specific, such as Fieldview[9], VIS-5D[10], IAP[11],

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[4]The NAG Graphics Library is distributed by the Numerical Algorithms Group (NAG), Ltd. from England.

[5]Graphics Library (GL) is a product of Silicon Graphics, Inc.

[6]Harvard Graphics is a product of Software Publishing Corporation.

[7]Alias Animator is a product of Alias Research Inc.

[8]VoxelBox is a 3D volume renderer, produced by Jaguar Software Inc., with features that include direct ray-traced volume rendering, color and alpha mapping, gradient lighting, animation, reflections and shadows.

[9]Fieldview is a product of Intelligent Light that is used in investigating fluid dynamics data sets.

[10]VIS-5D is a VA used for weather applications and was developed by the University of Wisconsin.

[11]Imaging Applications Platform (IAP) is used for medical visualization and is a product of ISG Technologies of Canada.

and ISVAS[12]. More general examples include FVS[13], SciAn[14], PV-Wave[15], IDL[16], Data Visualizer[17], and VoxelView[18].

All capabilities of a "turnkey" VA are provided by the VA vendor. As a consequence, the vendor has greater control of the product's quality than the extensible, application builders that have been augmented by third parties. The turnkey VAs are not as flexible as the application builders, but do offer the advantage of greater reliability and consistency that is a natural consequence of their reduced flexibility. Furthermore, they have been out in the field longer and have had the opportunity to have more of their kinks worked out.

2.6.3 Application Builders

Application builders allow users to interactively and easily configure a customized visualization application from a pre-existing collection of function modules. The building elements of these VAs consist of data types, modules, and the connections among the modules that determine the data flow as the data is processed. When assembled for a particular application, the resulting connection of modules and data flows is called a visualization network. VAs that are packaged this way provide a library of modules in the basic system, and instructions for the user to develop new modules that can be configured as plug compatible into it. Additionally, a number of data types are provided within the VA, and new data types can be created by the user that are constructed from the ones provided. New modules should generally be designed so that they will do something intelligent on any data type. In that way the whole network can be modified as part of the data exploration procedure to look at the data in new ways. (In practice, modules are often not that general in their use of different data types.) Examples of application builders include AVS[19], apE[20], Khoros,[21] Data Explorer[22], WIT[23], and IRIS Explorer[24].

As mentioned above, new capabilities can be added by simply adding new modules. In some cases, a complete turnkey VA has been converted to a module for use in an application builder VA. For example, IDL is now available as a module in AVS, and development has recently begun to provide IDL as a module in Data Explorer as well.

VAs have become very sophisticated and consequently complex. Particularly, the VAs that are application builders have grown very large as customers have created their own modules and donated them to the VA community. User groups have sprung up around these VAs for users to

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[12]Interactive Software for Visual data AnalysiS (ISVAS) is a visualization system for the analysis of 3D finite element simulations. It is available from the Fraunhofer Institute for Computer Graphics in Germany.

[13]FVS is a VA for computational fluid dynamics and is available from the Information Technology Institute of the Republic of Singapore.

[14]SciAn was developed by Florida State University and is primarily intended to do 3D visualizations of data in an interactive environment with the ability to generate animations using frame-accurate video recording devices.

[15]PV-WAVE is a product of Visual Numerics, Inc.

[16]Interactive Data Language (IDL) is a product of Research Systems, Inc.

[17]Data Visualizer is a product of Wavefront Technologies, Inc.

[18]VoxelView is a product of Vital Images.

[19]Application Visualization System (AVS) is a VA that was first introduced in 1988 and is a product of Advanced Visual Systems, Inc.

[20]apE is a VA that was originally developed at the Ohio Supercomputer Center and is now produced as a product of TaraVisual. Corporation.

[21]Khoros is a VA that was developed by the University of New Mexico.

[22]Data Explorer is a product of IBM Corporation.

[23]WIT is a product of Logical Vision Ltd.

[24]IRIS Explorer, also know simply as "Explorer," is a product of Silicon Graphics, Inc. Versions for other computers are available from IRIS Explorer Center.

help each other use it, share modules, and share experience. Learning one VA will simplify learning another, but the knowledge is not totally interchangeable.

Application builders now have features beyond what could be considered "just" a VA. For example, 2D or 3D model development, formerly the domain of CAD systems are now sometimes packed into VAs. Additionally, the programming capability of a VA can be used for more than just presentation or exploration of data. For example, a radiation oncologist from the University of Michigan uses a VA for medical applications he sees as analogous to the manufacturing applications of design, analysis, and production [Kessler93]. He uses raw data gathered from medical instruments to reconstruct a visualization of a tumor (computer-aided design or CAD), analyzes it to determine how to attack it (analysis), and finally controls a radiation machine directly from the VA to hit the tumor with multiple bursts of x-rays from different directions, depths, and intensities (production or CIM—computer-integrated manufacturing). The CAD, analysis, and CIM are all accomplished using a visualization network that he has constructed. He estimates that, in general, about 50% of the modules he uses are from user libraries and the other 50% are custom developed.

As demonstrated in the example described above, VAs can help integrate other applications in the manufacturing life cycle. A future evolution of a VA could conceivably provide a universal interface for a user to all, or at least many, of the RRM applications used in a manufacturing facility. The VA could provide a very sophisticated and intuitive interface to the applications and could be customized by the user according to preference.

2.7 Selecting a VA Product

A number of considerations must be taken into account to determine the proper VA product for a particular RRM application for a particular environment. Those considerations are described here.

2.7.1 Capabilities

The VA must have the capabilities to support the particular RRM visualization requirements. Different VAs may support the same requirements to different extents, and the extent necessary for the application must be determined.

2.7.2 Pricing

Pricing is always a consideration. The prices for VAs range a great deal—they are generally lower cost on personal computers and much more expensive on workstations. Some very powerful VAs are public domain, but may not have the support necessary for the user. Commercial VAs are sometimes licensed for use. A site may need to purchase more than one license to allow multiple users at one time. Some VAs are licensed according to a session. Since VAs may execute many modules within one visualization network, the computing load may be distributed to other computers over a network. For VAs licensed according to a session, there is no problem in distributed computing, because only one license is required to run a session throughout an entire network. However, some VAs are licensed per computer. In that case, each computer that contributes to a visualization network in a session is counted as a separate license. The latter pricing arrangement might still be desirable, depending on the actual prices and each site's particular needs, and must be individually determined.

2.7.3 Ease of Use

Another consideration concerns ease of use. What type of skills will be required by the person who will use the VA, and what will the frequency of use be? Will engineers use the VA directly, or will a computer technician be assigned full time to the VA to assist the engineers? Will the person using the VA use it a few days a month, or will the use be continuous over time? The ease of use in using a VA today is inversely proportional to the power you can get from it. The most sophisticated capabilities are not necessarily easy to use, and if not used on a somewhat regular basis, are not easily remembered. In particular, programming new modules is not a simple task. A final note concerning ease of use is the interactive speed that is required. The same VA is likely to run at different speeds on different platforms, particularly if it is run over a network. The interactive speed required is dependent on the VA task needed. For example, exploring data may be frustrating if each transformation takes a couple of minutes before the evaluation is displayed.

2.7.4 Support

Different VA vendors supply different levels of support—technical help over the telephone and/or over an electronic network, newsletters, and user groups. The particular help for any of these sources is sure to vary from one VA vendor or VA product to another. Independently organized user groups can be very valuable, not only in providing quick, technical help needed, but also by sharing modules and methodologies to leverage effort of the entire VA community.

2.7.5 Integration

A fifth factor is integration. Can the VA be integrated to the applications required? The cost for a VA may be greatly increased if a custom interface to a particular application is required. Integration is discussed further in Section 4 of this report.

2.8 Creating Problem-Solving Paradigms

As greater interaction capabilities were built into VA software, VAs eventually evolved to allow "exploration" of the data. That capability enabled the user to gain useful insights of phenomena from the data that were difficult or impossible to achieve otherwise. The exploration capability is profound—"visualization may play a large part in forming the link between hypothesis and experiment, or between insight and new hypothesis [Brodlie92]." For example, the "hole" in the ozone layer over Antarctica has only come to light in the last few years, even though the evidence had existed in data (collected and archived) for over ten years [Brodlie92]. The data was so extensive that traditional methods of studying it did not reveal quick realization of the hole.

Visualization is a powerful human capability that can be used for problem solving. It allows humans to access skills other than purely analytical skills, in fact, intuitive skills. In the sense that VAs allow a user to explore data to gain insights, VAs are tools that enhance intuition. With application builders, a user can piece together problem solving components interactively to search for the best problem solving methodology for a specific application problem.

3 APPLICATION TO RAPID RESPONSE MANUFACTURING (RRM)

Supercomputing and visualization facilities are used in the automotive industry to produce large-scale computer simulations of physical phenomena related to the efficient design, analysis, and manufacture of cars and trucks. Such tools are an economic necessity for creating very high-quality vehicles that can be rapidly brought from concept to production in an increasingly competitive worldwide automotive market.

Myron Ginsberg, General Motors Corporation [Ginsberg93].

3.1 Types of Applications

VAs can offer a window inside an RRM environment in any process at whatever point that data exists and can be acquired. Potential uses of VAs throughout the RRM life cycle are described in Table 3.

3.2 Examples

Examples where VAs are being applied to actual manufacturing applications are described below.

3.2.1 National Institute of Standards and Technology (NIST)

A researcher in the Precision Engineering Division at NIST (working in collaboration with the Department of Energy) is studying 3D data generated from using a coordinate measuring machine (CMM) to measure a calibration sphere [Harary93]. His goal is to study the accuracy of the CMM probe and to understand what is generating any errors that occur in using it. To understand the phenomena involved, he needs to study the data to detect patterns in it.

His analysis of the data using traditional 2D graphics packages was inconclusive. He determined that it was necessary to use a VA with 3D visualization and exploration capabilities to gain good insights into the data. In using the VA, he detected ellipsoidal patterns that represented the errors. His initial assessment is that the design of the probe contributes to the problem and needs to be redesigned for improved accuracy. Alternatively, the accuracy of the probe can be improved by applying an advanced 3D calibration algorithm. The work is ongoing and has not yet been reported. (The work is being done in the Automated Manufacturing Research Facility at NIST and is supported by the Navy Manufacturing Technology program.)

3.2.2 Texas Instruments

At Texas Instruments (TI), a project is underway to use VAs for three separate phases of the product life cycle for microwave housings [Nies93]. First, TI plans to use a VA to show the product idea in the proposal phase. Next, a VA will be used to show the design intent. Third, the VA will be used to show the final product in promotional material. TI believes that the VA capabilities will allow TI to do a better and more efficient job in those three areas than they are currently doing.

In the longer term, TI plans to use VAs to help with the design of the microwave housings. The design must consider thermal effects; if not, the housing could burn up very quickly. A VA will enable engineers to study the design with analysis of thermal effects superimposed on top of it.

The study will show where the important heat stresses are and how fast heat will travel from one point in the housing to another. That understanding will be critical to design the microwave housing for longer life.

Table 3 Potential Uses of VAs in RRM

Life Cycle Process	Objectives for Visualization
design	view alternative designs; communicate design intent to the mechanical designer; verify correct interaction of sub-components; enable management to study design for modifications before first prototype is built
analysis	study effect of aerodynamics, temperature changes, or mechanical stress on the target product in its intended environment; determine if clearances are sufficient for humans to operate, occupy, or maintain; determine if visual field is obstructed from inside a vehicle
process planning	verify clearances of tools, parts, and fixtures while manufacturing a product
inspection	compare CAD model to model derived from inspected data; determine types of errors that result from various machine tools
part handling	modify part parameters/features for easier locating by a vision system; tune the vision system configuration for a particular part family
machining	perform tool path verification
marketing	produce photo-realistic view of product for promotional material before first prototype is built
maintenance	determine whether humans can get to product's components with enough clearance to maintain or repair them

3.2.3 California Institute of Technology

At the California Institute of Technology, researchers are using a VA to explore the results of computational fluid dynamics [Heirich93]. They are studying the flow fields around a Titan IV rocket—the major launch vehicle for the U.S. Air Force. By looking at the velocity vectors surrounding the rocket, they can determine flow back, which results in instability. Additionally, they are looking at pressure, Mach number, temperature, and density—common variables for studying fluid flow. A valuable feature of their VA is the ability to look at their data plotted in unstructured grids.

(A similar use of a VA was reported at a recent AVS Users' Group meeting [AVSUsers93], in which an aerodynamicist is looking at isosurfaces to find the shock waves on an airfoil to enable design improvements of it.)

3.2.4 General Motors Corporation

At General Motors Corporation [Ginsberg93], engineers are depending on VAs to analyze voluminous data, often generated by computer simulation for automotive applications. For example, a frontal barrier car crash usually takes place in about 80 to 100 nanoseconds, but the data collected concerning the structural activity can consume several feet of paper. Even photography of the physical event may not capture all of the subtleties. Instead, simulations are done and transferred to video for study of what design changes may be needed. Another example concerns the study of the effectiveness of an air-conditioning system before a vehicle is built. By visualizing a simulation of the temperature distribution over time, designers can determine how many air vents are required and what is their optimum placement. A third example concerns using visualization to verify that individual components and sub-systems will interact correctly with each other.

According to [Ginsberg93], visualization cannot be overestimated. It can save time and money due to decreased need for prototypes for testing, and the quality of designs can be improved by allowing designers to explore many alternatives. Finally, visualization enables upper management to review designs more easily and make suggestions long before there is an actual physical model.

3.2.5 Industrial Design Firms

Conceptual designers and industrial design firms have found that VAs that can render photo-realistic images of their designs are invaluable for communicating ideas to their customers [Puttre93]. Generally, designers use a CAD model as input to a VA to serve as sort of a skeleton on which to create their design. By modeling the surroundings and properly applying light sources, the aesthetic quality of the design in its intended environment can be analyzed.

Realistic visualization is useful throughout the design cycle. A photo-realistic image of a product concept can clearly communicate the originator's design intent to the mechanical designer. Analyzing the image of the product, including possibly its animation, may help to identify design flaws. In the automotive industry, the images could allow engineers earlier access to the design concept, by eliminating the need for wood and clay models. Also, the images could eliminate the need for the physical models to communicate the final design concept to management.

Currently, the major users of VAs for photo-realistic rendering are industrial design firms. However, as hardware becomes faster and engineers learn to appreciate the value of photo-realistic images, it is likely that VAs will grow in popularity among engineers.

4 INTEGRATION WITHIN RRM

To integrate a VA within an RRM environment means that the information that is output by other RRM applications can be input to a VA, and possibly vice versa.

4.1 Current Practice

User needs for high performance visualization of the results from other applications have spawned activities to integrate VAs with those applications. The activities have involved developing file specifications and formats for exchanging information. Often the interfaces are implemented as data translators. During the lifetime of a VA product, the product's developer as well as third-party developers may add new data translators to extend the product's integration potential.

Some interfaces for integration may be built into VA modules, giving the VA user more flexibility. Other interfaces may be provided simply as data translators that run in a command line interface from within the VA's execution or even as a standalone application.

In some cases a VA provides an interface to a specific software product. For example, AVS provides a an optional translator for the exchange of geometry data between AVS and Pro/ENGINEER[25]. In other cases, more generic interfaces are provided for a VA to integrate it to whatever application that shares that interface. For example, a standard to exchange geometry information is needed to integrate a VA to a Computer-Aided Design (CAD) application. IGES[26] is such an interface, though ambiguities in the information exchanged may still result from incomplete or inaccurate implementations of the IGES standard.

In addition, VAs have been integrated to each other. The Advanced Visualization Laboratory at the University of Maryland has created an AVS module for interoperability between AVS and PV-Wave. The Laboratory also uses AVS to integrate the results of a number of software components (including badly written computer programs), rather than figure those components out sufficiently to add visualization capabilities to them [McNab93].

Integrating one VA to another leverages the capabilities of each, allowing the user to mix and match modules and data types from both VAs. Visualization researchers have considered interoperability of visualization tools on the basis of module sharing. However, at a 1991 workshop on visualization environments, researchers determined that standardizing module interfaces was premature. They recognized that the issues related to module sharing represent an important research area [Butler92].

Finally, interfaces to new input devices from the world of virtual reality (VR) are being developed to merge the capabilities of VR and VAs. For example, Digital Equipment Corporation has developed a toolkit for integrating AVS with VR devices [Good93]. (Refer to Section 5.6 for a brief discussion of research issues associated with VR and visualization.)

4.2 Standards for Data Exchange

The common way that standards are used to integrate a VA to another application is by standardizing the geometry, image, or scientific data exchange between the VA and the

[25]Pro/ENGINEER is a mechanical design automation software product of Parametric Technology Corporation.
[26]Initial Graphics Exchange Specification (IGES) is a standard used to communicate CAD data [IGES90].

application. Each of the three types of data requires different types of standards for integration and is discussed separately in this section.

4.2.1 Geometry Data

Geometry (and topology) data is used for representing three dimensional objects. For manufacturing applications, geometry data represents the target part, NC machines, machine tools, fixtures, etc. A number of standards are commonly used for exchanging geometry data between different applications, and these same standards apply to VAs as well. The standards are shown in Table 4.

Table 4 Geometry Standards

Acronym	Acronym Spelled Out. Comments.
STL	Stereolithography format. STL is the defacto industry standard for interfacing to a rapid prototyping (RP) system. The RP system may be based upon technologies such as stereolithography, laminated object manufacturing, selective laser sintering, etc. [Jurrens].
DXF	Data Exchange File Format. DXF was developed by AutoDesk, Inc. for its AutoCAD product. It is frequently used to exchange drawing information between different CAD systems as well as to and from other applications [AutoCAD88].
IGES	Initial Graphics Exchange Specification. IGES is a standard that is used for the exchange of drawings that represent geometry and other information about a product [IGES90].
STEP	Standard for the Exchange of Product Model Data. STEP is an emerging international standard [ISO 10303] for representing the physical and functional characteristics of a product throughout the product's life cycle. As a standard, STEP will permit communications among computer environments, each of which performs various product life cycle functions. An advantage of STEP is that it will support the integration of the computer environments using a shared database. Many of the information requirements as well as the software tools being developed to support STEP are applicable for any manufacturing industry. To serve the needs of a particular industry, Application Protocols (APs) are developed that designate the specific information and application requirements for that industry. The APs draw upon integrated resources[27] to share the same information among different APs. It is likely that VAs will include STEP Application Protocol interfaces in the future.

[27]Integrated resources are "a set of STEP Parts which provide application-independent information models for widely-used types of information. Integrated resources support communication between diverse applications by

4.2.2 Image Data

Image data consists of a surface of pixels. A number of standards are used to exchange image data, and those are incorporated into VAs as well. Some of the common standards are shown in Table 5.

Work is currently ongoing to develop an International Organization for Standardization (ISO) standard for image compression. The work is being carried out jointly with the Joint Photographic Experts Group, commonly known as JPEG [Wallace91]. The incorporation of compression techniques in image exchange standards is very important for VAs because of the huge data files that are required.

Table 5 Image Standards

Acronym	Acronym Spelled Out. Comments.
GIF	Graphics Interchange Format. GIF is a popular format used for the storage and transmission of color images [GIF87]. It uses a compression technique.
TIFF	Tagged Image File Format. TIFF was originally designed as a tag based file format to exchange image data between publishing packages. It actually encompasses a range of different formats and can use several compression techniques.
PPM	Portable Pixmap File Format. PPM was developed as a convenient intermediate format for converting from one image format to another. Because of its objective, the format doesn't incorporate a compression technique, and consequently requires a lot of memory. PPM, including converters to other formats and tools for manipulating the images, is available in the public domain [Poskanzer89]. PPM uses 24 bits per pixel. Also available in [Poskanzer89] is PGM, the Portable Grayscale Format that uses 8 bits per pixel, and PBM, the Portable Bitmap Format that uses 1 bit per pixel.
EPSF	Encapsulated PostScript Format. EPSF is a page description language with sophisticated text facilities. It is mainly used as an output format.
CGM	Computer Graphic Metafile. CGM was developed for the transfer and storage of picture description information [ISO 8632]. It has the capability to encompass both image and graphical data [Brodlie92]. CGM consists of an ordered set of various elements: information about file, drawing elements, attributes, and control elements [Post92]. CGM is intended for vector images, but currently only can store 2D graphics data.

providing an agreed upon set of definitions and meanings for data that are independent of specific application requirements" [Kramer92].

4.2.3 Scientific Data

A single standard for scientific data does not exist. Some VAs use a file format for such data that consists of two components—a raw data file and a separate "header" file that describes the format of the raw data in a form understandable to the VA. (AVS and the IBM Explorer both use this approach.) In this approach, the raw data does not have to be recorded in a particular format for the VA; so that data previously recorded, no matter what the format (within reason), can still be read by the VA. In some cases, even this approach won't work, and a special module may need to be written to read in data to the VA.

Recognizing the problem of sharing scientific data, a number of technical communities have developed file formats and methods for interchanging, accessing, and archiving scientific data for their areas of specialties. A number of the formats and methods are general enough that they can be used for scientific data no matter what the domain. Unfortunately, no single solution can optimize data interchanging, accessing, and archiving at the same time. Table 6 shows some of the most common file formats and methods for handling scientific data that are used by VAs.

Table 6 Scientific-Data Standards

Acronym	Acronym Spelled Out. Comments.
CDF	Common Data Form. CDF was developed by the National Aeronautical and Space Agency (NASA), and is one of the first implementations of a scientific data model [Gough88]. It is freely available. "CDF is a library and toolkit for multi-dimensional data sets. The basic component of CDF is a software programming interface that is a device independent view of the CDF data model" [Stern93].
netCDF	network Common Data Form. NetCDF was developed by Unidata as an enhancement to CDF [Russ90]. It is freely available. NetCDF is also available as a library and toolkit to support the creation, access, and sharing of scientific data. In addition, "the U.S. Geological Survey has produced and is producing a number of public-domain netCDF utilities" [Jenter]. NetCDF and CDF have evolved independently. "There is no compatibility between data in CDF and netCDF form, and as yet no translation software exists to convert data in one form to data in the other form" [Rew93]. "Both CDF and netCDF describe access mechanisms to Scientific Data Sets, and provide associated tools, but do not actually define data formats" [Lang93].

HDF	Hierarchical Data Format. HDF was developed by the National Center for Supercomputer Applications (NCSA), University of Illinois [NCSA89] at Urbana-Champaign. HDF "is a self-defining file format [see footnote 27 on page 18] for transfer of various types of data between different machines. The HDF library contains interfaces for storing and retrieving compressed or uncompressed raster images with palettes, and an interface for storing and retrieving n-dimensional scientific datasets together with information about the data, such as labels, units, formats, and scales for all dimensions" [Stern93].

Many standard interfaces have been defined for particular domains. The following two standards are for particular communities:

Table 6 continued	
FITS	Flexible Image Transport System. FITS "is the standard data interchange and archival format of the worldwide astronomy community" [Stern93]. The NASA Space Science Data Center's (NSSDC) NASA/Science Office of Standards and Technology (NOST) has completed development of a formal definition of FITS and it has been approved by the NOST FITS Accreditation Panel. The standard will now be submitted to become an international standard" [Schlesinger93].
GRIB	GRid In Binary. GRIB "is the World Meteorological Organization (WMO) standard for gridded meteorological data. Unfortunately it is still not very 'standard,' as some organizations use their own versions" [Stern93].

5 RESEARCH ISSUES

VA technology is still in its early stages and could benefit from research and development in a number of areas. These areas include standardized integration methods, improved data handling, improved user interfaces, new visualization techniques, and validation of visualization algorithms. Also, the new field of virtual reality is sure to impact VA products in the future. Each of these areas is discussed briefly below.

5.1 Integration

Standardizing file formats and providing data access tools for exchanging information to and from a VA would be very useful. In addition, the formats should be self-defining[28]. Currently, VAs use many file formats and VA vendors need to provide translators to and from whatever file format they will support. Single standards for geometry, image, and scientific data would enable VA vendors to maintain only one translator for each of these standards. Still, translators or conversion tools for existing formats will still be needed to be able to use the voluminous stores of data that are already archived.

The new standards should be carefully considered to contain the information required and to be of practical size through the incorporation of compression techniques built in where applicable. Furthermore, computer-aided design and analysis packages should be studied with the goal of determining what additional information could be added for export from those packages that would enhance the capabilities of VAs that would import from them.

In addition to data exchange, standards that would enable module interoperability among different VAs would be valuable to VA customers. However, before developing those standards, the issues related to module sharing must be studied further.

5.2 Data Handling

The data used in computer visualization is voluminous. Current hardware and software available today cannot handle the storage, access, and exchange with sufficient performance required by some VA applications (for example, the virtual wind tunnel [Bryson91]). Advances in technology for data handling for VAs will have a large impact.

5.3 User Interface

User interfaces for sophisticated VAs are graphically oriented. Even so, perhaps because of the tremendous visualization power of VAs, the software is very hard to use. User interfaces for VAs need to be designed for scientists and engineers who have specialty domain expertise, but have limited computer expertise. The VAs must be intuitive so they are easy to learn and so they can be used at short, irregular periods over an extended time frame.

Increased speed for graphics applications will improve the usability of a VA, because the faster feedback to a user's actions will immerse the user closer into the problem domain being investigated. For that reason, work being done to accelerate graphic computations, including

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[28]A self-defining file format is a format that includes facilities that can be used as data entities to specify the format for other file data. For VAs, self-defining file formats are generally implemented in one of two ways. One way is for a separate file to contain information that specifies how one or more other data files are formatted. A second way is for the format information to be contained as header data in the beginning of the data file itself.

parallel architectures and also the incorporation of graphic algorithms directly into hardware, will be very beneficial for VAs.

5.4 Visualization Techniques

There is a need for visualization techniques to provide new ways to look at and explore data, particularly in flow visualization applications. Techniques for flow visualization require combined knowledge from fluid dynamics specialists, numerical analysts, computer graphics experts, cognitive psychologists, and artists and designers [Post92].

Any new techniques must take into account visual perception and mental processes. There needs to be a distinct separation between physical and "virtual devices" in VAs, so that the communication metaphor can be designed for the particular visualization task and is not constrained for a particular physical device. The term virtual device is analogous to logical devices in systems such as the Graphical Kernel System (GKS—an ISO standard for a procedural interface to a graphics system) and the Programmer's Hierarchical Interactive Graphics Systems (PHIGS—an ISO computer graphics standard for the modelling, display, and manipulation of 3D primitives). However, a virtual device may be implemented by one or more physical devices, and possibly include other virtual devices. Furthermore, a virtual device should be user-programmable [Brodlie92].

5.5 Algorithm Validation

As VAs mature, engineers and researchers will depend more and more on them for gaining correct insights into the phenomena they are observing. The techniques used need to be proven to give the correct visualization of the phenomena.

In traversing the visualization pipeline, information may be processed by many functions, and numerical errors can occur. Beyond the accuracy of the computations, the visualization itself can give misleading results due to interpolation artifacts, aliasing, or contradictory depth cues [Post92].

5.6 Virtual Reality

Virtual reality (VR) is the ultimate immersion of a user within the domain investigated. The traditional method of using computers can be viewed as two separate entities of high intelligence (i.e., the computer and the human) connected together by very low bandwidth interfaces (for example, keyboards, mouse devices, etc.). Using new hardware devices such as head-mounted dual displays for stereoscopic vision and a data glove or other 3D interactive device for pointing, VR increases the bandwidth of the interface by immersing the user "directly in the data."

It is expected that VR will be a part of visualization systems in the future. It has been suggested that VR could be used to investigate volume data by moving directly within the data, interactively deleting areas of no interest or uncovering hidden features of particular interest [Fuchs89].

The VR industry is growing rapidly and undoubtedly will heavily impact VAs and the use of VAs. [Ressler93] discusses "Virtual Environments" that employ VR for manufacturing applications.

6 SUMMARY AND CONCLUSIONS

A VA is a valuable tool that can provide a window inside any RRM process where data is available. The window can enable an application specialist to better understand the process in order to improve it, if necessary. In many VAs, the user can interactively direct the visualization to search for the best look at the data. The main power of the VA derives from harnessing the powerful human capability of visualization and enhancing that capability.

Currently, VAs are often difficult for application specialists to use; the more sophisticated and powerful the VA, the more difficult it is to use. To get the maximum value from a VA requires a significant time investment to learn it thoroughly. Also, for application specialists to depend on VAs, they must have assurance that the algorithms used by VAs have been validated. Currently, they do not have that assurance.

To use VAs efficiently for RRM, VAs must be integrated with RRM applications. Standards can help make that happen. Currently, integration is limited to transferring data files to and from the VA, with many file formats and implementations available. Standardizing the data transfers to and from VAs will increase their value to RRM applications by simplifying their integration to those applications. However, other data translators will still be required if it is necessary to visualize legacy data.

Furthermore, when specifications for module interfacing are eventually standardized, module interoperability among different VAs can become a reality. Module interoperability will provide VA customers with more flexibility by allowing them to mix and match modules from different VAs. That capability will help reduce the risk that a particular VA will become obsolete.

Judging from the number of scientific, computer, engineering, and manufacturing journal articles, VAs are widely used in scientific research, but have not yet migrated widely to RRM applications. However, RRM industry leaders have made statements that VAs are necessary for their company's competitiveness in the future.

The full potential of VAs may not yet be realized. The capability of application builders to enable non-computer scientists to construct problem solving paradigms for particular application domains could become a profound strength of VAs in the future. However, current VAs that are application builders are not yet mature products. Not enough applications have been built using them to verify their problem-solving capability [Brodlie92].

VAs may herald a new era for integration of RRM systems. A key objective of RRM is to have access to data concerning a product and its manufacture at any point in the product's life cycle. Standards for exchanging (or preferably sharing) data within a standardized enterprise framework are seen as a key method to provide that access. However, what good is data if it is coming from so many sources at once, and it is so voluminous that it cannot be used? VAs may provide the ability to digest the data in a meaningful way to empower humans to make intelligent decisions in response. Ultimately, the VA may be the application that enables application specialists to cognitively integrate RRM data so it can be put to good use.

REFERENCES

[AutoCAD88] Autodesk, Inc., *AutoCAD Reference Manual* , Appendix C, "Drawing Interchange and File Formats," Sausalito, CA, January 1988.

[AVSUsers93] AVS Users' Group Meeting, SIGGRAPH 93, August 1993.

[Bailey93] Bailey, M., et al., *Course Notes 2: Introduction to Scientific Visualization Tools and Techniques*, SIGGRAPH 93, August 1993.

[Brodlie92] Brodlie, K. W., et al. (eds.), *Scientific Visualization, Techniques and Applications*, Springer-Verlag, New York, NY 1992.

[Bryson91] Bryson, S., and Levit, C., "The Virtual Windtunnel: An Environment for the Exploration of Three-Dimensional Unsteady Flows," included as paper in [Bailey93], originally published in IEEE in 1991.

[Butler92] Butler, D. M., et al., "Visualization '91 Workshop Report: Scientific Visualization Environments, *Computer Graphics*, Volume 26, Number 3, August 1992.

[Chernoff73] Chernoff, H., "The use of faces to represent points in k-dimensional space graphically," *Journal of the American Statistical Society*, vol 68 (342), 1973, pp. 361-368, cited in [Brodlie92].

[Dickerson93] Dickerson, H., "Software Product Survey," Microsoft Corporation, usenet article comp.graphics.visualization:3052, June 16, 1993.

[Fuchs89] Fuchs, H., Levoy, M., and Pizer, S. M., "Interactive Visualization of 3D Medical Data," *IEEE Computer*, August 1989.

[Good93] Good, M., Digital Equipment Corporation, comment made at [AVSUsers93].

[GIF87] "Graphics Interchange Format—A standard defining a mechanism for the storage and transmission of raster-based graphics information," CompuServe Incorporated, 1987, cited in [Brodlie92].

[Ginsberg93] Ginsberg, M., "Challenges to the Use of Supercomputers and Scientific Visualization for Automotive Applications," *Computers and Graphics*, Vol. 17, No. 5, 1993.

[Gough88] Gough, M. L., *NSSDC CDF Implementer's Guide (DEC VAX/VMS) version 1.1.*, National Space Data Center 88-17, NASA Goddard Space Flight Center, 1988.

[Haber90] Haber, R. B. and McNabb, D. A., "Visualization Idioms : A Conceptual Model for Scientific Visualization Systems," *Visualization in Scientific Computing*, 1990, cited in [Brodlie92].

[Hagen93] Hagen, H., Muller, H., and Nielson, G. M. (eds.), *Focus on Scientific Visualization,* Springer-Verlag, New York, NY 1993.

[Harary93] Harary, H. and Rushmeier, H., National Institute of Standards and Technology, Gaithersburg, MD, conversation concerning their work, October 1993, unpublished.

[Heirich93] Heirich, A., California Institute of Technology, CA, conversation concerning his work, October 1993, unpublished.

[IGES90] Initial Graphics Exchange Specification, Version 5.0, IGES/PDES Organization, NTIS PB88235452, National Technical Information Service, Springfield, VA, June 1990.

[ISO 8632] ISO 8632, Computer Graphic Metafile, International Organization for Standardization, 1987. (Also approved by the American National Standards Institute as ANSI/X31.22.)

[ISO 10303] ISO/DIS 10303-1, Industrial Automation Systems and Integration—Product Data Representation and Exchange—Part 1: Overview and Fundamental Principles, International Organization for Standardization.

[Jenter] Jenter, H. L. (U.S. Geological Survey, Reston, VA 22092) and Signell, R. P. (U.S. Geological Survey, Woods Hole, MA 02543), "NetCDF: A Public-Domain-Software Solution to Data-Access Problems for Numerical Modelers," available by FTP from crusty.er.usgs.gov/pub/netcdf.asce.ps.

[Jurrens] Jurrens, K. K., *An Assessment of the State-of-the-Art in Rapid Prototyping Systems for Mechanical Parts*, NISTIR 5335, National Institute of Standards and Technology, Gaithersburg, MD, December 1993[29].

[Kay] Kay, D. C. and Levine, J. R., Graphics File Formats, Windcrest Books, ISBN 0-8306-3060-0.

[Kerlick90] Kerlick, G. D., "Moving Iconic Objects in Scientific Visualization," in [Bailey93], article originally published in IEEE, 1990.

[Kessler93] Kessler, M., University of Michigan, Ann Arbor, MI, comment made at [AVSUsers93].

[Kramer92] Kramer, T. R., et al., *Issues and Recommendations for a STEP Application Protocol Framework*, NISTIR 4755, National Institute of Standards and Technology, Gaithersburg, MD, January 1992.

[Lang93] Lang, U. and Grave, M., "Data Structures in Scientific Visualization," in [Hagen93].

[McNab93] McNab, D., Advanced Visualization Laboratory, University of Maryland, College Park, MD, comment made at [AVSUsers93].

[NCSA89] *NCSA: HDF Calling Interface and Utilities, NCSA HDF Version 3.1*, National Center of Supercomputer Applications, University of Illinois at Urbana-Champaign, 1989.

---

[29]All reports from the National Institute of Standards and Technology are available from the National Technical Information Service, Springfield, VA 22161.

[Nies93] Nies, P., Texas Instruments, Dallas, TX, conversation concerning his work, September 1993, unpublished.

[Poskanzer89] Poskanzer, J., "Extended Portable Bitmap Toolkit," public domain software available on X11.4 release tape from MIT, 1989, cited in [Brodlie92].

[Puttre93] Puttré, M., "Picture this: visualization tools for CAD drawings," *mechanical engineering*, Volume 115, Number 12, December 1993.

[Post92] Post, F. H. and Hin, A. J. S. (eds.), *Advances in Scientific Visualization*, Springer-Verlag, New York, NY 1992.

[Ressler93] Ressler, S., *Applying Virtual Environments to Manufacturing*, NISTIR 5343, National Institute of Standards and Technology, Gaithersburg, MD, January 1994.

[Rew90] Rew, R. K. and Davis, G. P., "The Unidata netCDF: Software for Scientific Data Access," *Proceedings of the Sixth International Conference on Interactive Information and Processing Systems for Meteorology, Oceanography, and Hydrology*, Anaheim, California, 1990.

[Rew93] Rew, R., netCDF Frequently Asked Questions (FAQ) from sci.data.formats usenet news group, June 16, 1993, archived in pub/netcdf/FAQ on unidata.ucar.edu.

[Robertson91] Robertson, D., Ulrich, K., and Filerman, M., "CAD and Cognitive Complexity: Beyond the Drafting Board Metaphor," Manufacturing Review, Vol. 4, No. 3, American Society of Mechanical Engineers, September 1991.

[Rodriguez90] Rodriguez, Walter, *Visualization*, McGraw Hill, Inc., 1990.

[Rodriguez92] Rodriguez, W., *The Modeling of Design Ideas, Graphics and Visualization Techniques for Engineers*, McGraw Hill, Inc., 1992.

[Russ90] Russ, R. and Davis, R., "NetCDF: An interface for Scientific Data Access," *IEEE Computer Graphics and Applications*, 1990.

[Rushmeier92] Rushmeier, H. E., "Synthetic Images for Cost-Effective Machine Vision/Illumination Design," Applied Machine Vision Conference, ASME, Atlanta, Georgia, June 1992.

[Schlesinger93] Schlesinger, B. M., "NOST FITS Definition Accredited as NOST Standard," sci.data.formats usenet news group, July 14, 1993.
Note: printed copies of the standard can be obtained from the NOST Librarian at NASA/Science Office of Standards and Technology, Code 633.2, Goddard Space Flight Center, Greenbelt, MD 20771.

[Stern93] Stern, I., Frequently Asked Questions (FAQ) for the sci.data.formats usenet news group, September 15, 1993.

[Stolk92] Stolk, J. and van Wijk, J. J., "Surface-Particles for 3D Flow Visualization," in [Post92].

[Todd93] Todd, T. T., *Course Notes 11: Introduction to Volume Visualization: Imaging Multi-dimensional Scientific Data*, SIGGRAPH 93, August 1993.

[Treinish91] Treinish, L., "SIGGRAPH '90 Workshop Report: Data Structures and Access Software for Scientific Visualization," *Computer Graphics*, volume 25, number 2, 1991.

[Treinish93] Treinish, L., "Unifying Principles of Data Management for Scientific Visualization Tools and Techniques," in [Bailey93].

[Unidata91] *NetCDF User's Guide: An Interface for Data Access*, Unidata Program Center, Boulder, Colorado, 1991.

[Wallace91] Wallace, G. K., "The JPEG Still Picture Compression Standard," *Communications of the ACM*, April 1991.

[Wendorf93] Wendorf, G., "Scientific visualization grows in acceptance," Workstation (An independent newsmagazine for HP/Apollo workstation & server users), Volume 9, Number 9, September 1993.

[Wessel91] Wessel, P. and Smith, W. H. F., "Free Software Helps Map and Display Data," *Eos*, volume 72, number 41, 1991.