Virtual Prototyping in Mechanical Product Development - a review

A Chatterjee, A Mahapatra, S.S. Roy, N.P. Mukherjee
Virtual Reality Laboratory
Machine Design and Development Group
Central Mechanical Engineering Research Institute
M.G. Avenue, Durgapur-713209 (West Bengal)
Phone: (0343) 2546818, Fax: (0343) 2546745
E-mail: avik@cmeri.res.in; abhi_mahapatra@yahoo.co.in

ABSTRACT

This document provides an insight into the technology of virtual prototyping (VP) and its application in the field of design, engineering, manufacturing and product development. It reviews the concept of virtual and digital prototyping and its fusion with virtual reality (VR). It discusses the technology, its integration aspects, explores some of the wider implications and benefits of the technology. Details specific industry applications of VP, has been discussed and comments on the available prototyping systems and interfacing and customization has been made.

Key-Words: virtual prototyping, virtual reality, design, manufacturing, product development.

I. INTRODUCTION

Markets are becoming more and more dynamic and quick paced. Pressure on crashing product development cycle time, in its initial design phase, with out compromising on product functionality is increasing rapidly. It has been pointed out by Pratt [1] that up to 70% of the total life cycle costs of a product are committed by decisions made in the early design stage. In order to stay competitive, companies must deliver new products with higher quality and a broader variety of customer choice in a shorter time and minimum costs. Therefore, Rapid prototyping (RP) and VP are quickly becoming interesting tools for product development [2].

Automotive and aerospace industries seem to be among the leaders in applying VR and VP for real-world, non-trivial problems. It is not surprising that many organizations, particularly smaller companies, are confused over the application of VP (digital). It is still the case that many companies are unaware of what VP technology has to offer; many also do not think that it has any applicability to their business needs or simply believe that the technology is too complex and expensive. However, as hardware and software prices continue to fall and technologies converge, we are seeing the development of digital and VP systems specifically optimized in terms of cost and capability for the needs of small and medium enterprises.

While some automotive and almost all the aerospace companies have already begun to routinely use VR as a tool in styling and design reviews in the concept phase, it has not been clear that VR can be an efficient tool in assembly/disassembly simulations and maintenance verifications. Assembly simulations are much more difficult in that they involve a lot of interaction and real-time simulation. However, Boothroyd and Dewhurst [3] revealed that the assembly process often drives the majority of the cost of a product in the early stages of design. Although there are already several commercial 3D engineering tools for digital mock-up (and the number continues to grow), all of them lack one thing: intuitive direct manipulation of the digital mock-up by the human. Therefore, they are inherently inferior to VR [4].

2. Virtual Prototyping-Genesis

To appreciate what VP has to offer for Small and Medium Enterprises (SME) as on today, it helps to converge the individual technologies to form the current generation of product development tools. The evolution and integration of these technologies illustrated in the Figure 1 results the development of the concept of product lifecycle management (PLM) which acts as a new paradigm of digital product design and development [5,6]

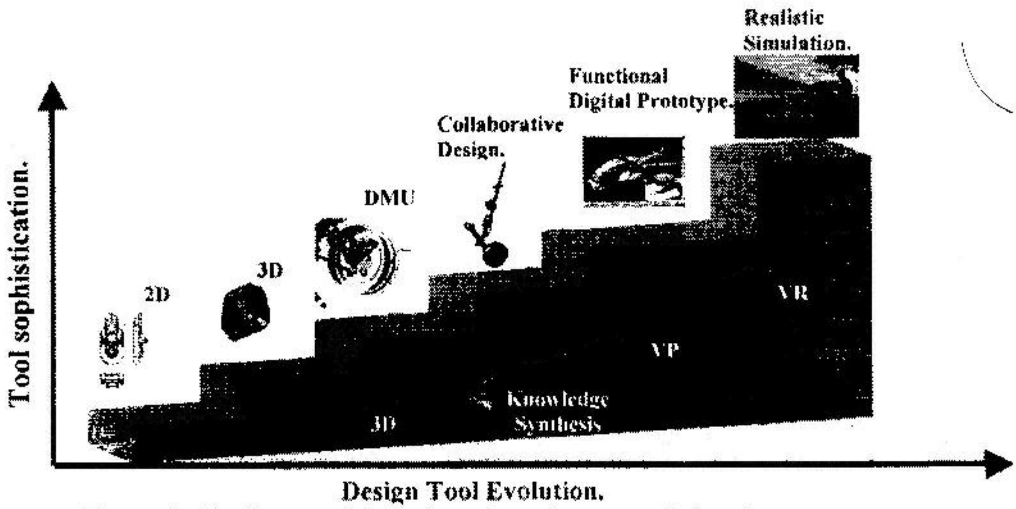

Figure 1: Evolution of digital product design and development

3.0 Specific Industry Applications of Virtual Prototyping

The application of VP tools is very closely aligned to VR. The benefits of VP- VR extends over a wide range of industry and basic science, so it is important to look beyond the general benefits, to assess what VP may offer in the particular industrial sector.

3.1 Automotive Industry

Automotive companies globally have invested very heavily in CAD/CAM systems and in computerized design analysis tools because they are in constant pressure to develop and produce high quality vehicles with lower development and design costs. However, as these industrial design tools and automated systems became industrial standard, automotive manufacturers have had to look elsewhere, to maintain their competitive edge. It is in this area VP- VR is enabling the manufacturers to bridge the gap between design tools and automated manufacturing systems, through the creation of full action mockups of vehicle bodies, functional simulation of vehicle sub assemblies and even the creation of virtual production system to validate and improve the product manufacture. In this direction they have reaped significant benefits and not only the development cycle for modern production cars has came down from 5 years to 2.5 years but also there is drastic reduction in engineering changes made after production [7] .

New simulation tools fundamentally based around VR are also being adopted by automotive industry for their design and development of assembly lines. General Motors (GM) is the prime example of this migration from physical to virtual testing." In 1991, we crashed about 80 vehicles when doing front and rear barrier tests for the Caprice," says Steve Rhode, GM's technical director of vehicle synthesis, analysis, and simulation, and keynote speaker at the Daratech conference. "Ten years later, for the 2001 Impala, we were down to 28 hardware tests. The tests were done virtually." Meanwhile, the number of regulations for testing was expanding geometrically. "The only way we could contain this," he says, "was through the use of simulation technology." (*Computer Graphics World* , December, 2001). Engineers of Ford Powertrain (Dearborn, MI) realized a reduction from 2 weeks to 3 days for full virtual engine simulation, through LMS Virtual Lab, a propertory software of LMS International [8]. A Ford engineer uses a Powerwall from Silicon Graphics to examine a full-scale stereoscopic view of the aerodynamic flow for a Formula One car calculated with a proprietary CFD code. Many other multinational companies have also successfully explored the use of simulation tools to enable engineers to design and develop a dedicated new manufacturing facility like Land Rover UK, Nissan etc.

3.2 Aerospace

The aerospace industry is marked with very large-scale projects involving highly complex sub- systems and relatively low volume products. Apart from these most of the design and development activities are distributed across the world and the issues of communication and design co-ordination are paramount. This requirement of the industry basically drive the development work in CAD/CAE systems and today almost all the aerospace giants are compelled to invest and use the VP- VR technology to cope up with their design and development complexities [9].

Boeing invested more than $1 Billion (and insiders say much more) in CAD infrastructure for the design of the Boeing 777. Boeing based their CAD system on CA TIA (Computer-Aided Three-dimensional Interactive Application) and ELFINI (Finite Element Analysis System), both developed by Dassault Systems [10] of France and licensed in the United States through IBM. Designers also use EPIC (Electronic Preassembly Integration on CATIA) and other digital pre-assembly applications developed by Boeing. A virtual mock up of Boeing 777 can be made from millions of parts and interconnection list so that can "fly through" the design to check for unwanted interconnections. The computer can also automatically check for such interferences so that these can be identified and redesigned before they are discovered (more dramatically and at much greater expense) during physical assembly. If there are n components we can think of an n by n matrix of pairs of potential collisions, so 3,000,000 parts would have approximately n*(n-1)/2=4.5x1012 possible intersections to be checked. Although this grows only quadratically with the number of parts (not the exponential growth generally concerned elsewhere) just the sheer number of parts makes brute force enumeration unattractive. Fortunately, there are quite standard ways to reduce the search.

Boeing has opened a new VR lab that allows designers and maintainers to evaluate and test the Joint Strike Fighter (JSF) supportability in a virtual environment using the same three-dimensional modeling data used to design the aircraft [11].

3.3 General Manufacturing

Perhaps one of the most interesting and important of these recent developments is called "Virtual Manufacturing (VM)" [12,13]. Often termed "The next revolution in Global Manufacturing", VM involves the simulation of a product and the processes involved in its fabrication [14,15]. Simulation technology enables companies to optimize key factors directly, which includes manufacturability, final shape, residual stress levels, and product durability .They directly affect profitability by reducing the cost of production, material usage, and warranty liabilities.

At the core of virtual manufacturing lies nonlinear Finite Element Analysis (FEA) technology [16]. This technology has enabled companies to simulate fabrication and testing in a more realistic manner than ever before. Nonlinear FEA uses an incremental solution procedure to step through the analysis. In contrast to linear FEA, where a solution is achieved in one step, nonlinear FEA may require hundreds, even thousands of steps. There are three major types of nonlinearites:

- Material- plasticity, creep, viscoelasticity
- Geometric-large deformations, large strains, snap-through buckling
- Boundary-contact, friction, gaps, follower force.

A nonlinear analysis can include any combination of these. Nonlinear FEA software, MSC. Marc, is used to simulate the metal-forming process. For example instead of implementing the trial-and error procedure on the real model, FEA is used to find the optimal die shape. The spring-back can be accurately predicted before the real die is built.

In order to speed up tool design, VM based techniques are required to aid in planning of the pass sequence development, calculation of the spring-back angle, and estimation of the strip edge elongation. In short, digital simulation and 3D visualization allow you to predict how products and materials will perform in real-world environments-enabling engineers to rapidly explore multiple design and process alternatives without having to build costly and time-consuming physical prototypes. Even the factory layout, tooling, and processes can be simulated, preventing costly delays and inefficient processes.

4.0 Advantages of VP-VR

Academic exploration of VP tools [17] has indicated that for many years the technology has the potential to revolutionize both new product and new manufacturing-process developments (Schmitz 1998). An assessment of VP tools, through published academic research, Internet publications and a number of leading industry case studies highlights a clear number of advantages.

4.1 Reduce Time to Market

Overall, the market demands for customization are now entrenched in almost all sectors where the philosophy is increasingly to replace old products with new or revised models over shrinking product life cycles. Such developments demand that companies become more efficient in developing rapid time-to-market capabilities if they wish to preserve their profit margins.

4.2 Early Testing

The starting point for the utilization of VP tools is their capability to import product data created in CAD. Once a functional, virtual product model has been created using a conventional 3D CAD system, it can then be tested in a number of ways, obviating the usual need for a physical model. For examples, if a full 3D virtual prototype of an assembly exists, then it is possible to apply an assembly simulation package to obtain a full mechanical and dynamic simulation of the proposed assembly sequence, allowing potential insertion paths to be checked for access clearance and clashes [18,19] .VP testing has also been applied to the ergonomic design of automobiles, aeroplanes and assembly workstations.

4.3 Reduction of Physical Prototypes

For many organizations the production of a physical prototype is an essential step in the process of developing a new product. However, a physical prototype often requires manual tooling, skilled hand assembly, delicate testing instrumentation and time spent interpreting prototype data. As such it represents a necessary but ultimately time-consuming step in the development cycle. The time associated with making more than one prototype, especially with design revisions between each prototype, can tie up engineers and equipment for days or weeks at a time. VP-VR allows multiple prototypes to be constructed and optimized to ensure that the physical prototyping should hold no real surprises.

4.4 Reduce Development and engineering changes

It is argued that the current manufacturing environment is unforgiving of products that are late to market, as much as 50% to 70% of the potential profit margin from a new product is lost when it is introduced late. Also, the costs associated with finding defects in industrial products are a function of where in the design-to-production process the problems are found. Often the "rule of 10" law is applied: the cost of fixing a problem that should have been avoided in the design phase is increased 10 times if found in the physical layout stage, 100 times if found on the shop floor, and 1,000 times if found by a customer. It is clear that these are the most powerful arguments for the adoption of VP tools.

4.5 Unravels Design Complexity

Design complexities are growing every day, product life cycles are shrinking and the time available to finish a working design is being compressed. Design tools developed for the 1980s or even the early 1990s were built around the "find and fix" mentality .This approach may have worked for the product life cycles of the 1980s and early 1990s, but it is not adequate for the more time-critical products being designed and built today. VP is representative of an evolving new generation of tools that enable the "predict and prevent" approach to design. They are not a luxury; they are a requirement. These tools help reduce frustration among design-team members, shorten the time to finish a design, and improve the quality of the design by allowing exploration of design alternatives and engendering a right-first-time attitude to product manufacturing.

5.0 Availability of VP-VR Tools

The selection of a suitable VP- VR tool or VP- VR enabled CAD system is business-critical. The decision also depends on many factors that are unique to individual enterprises, such as available operator skills, legacy systems, network requirements and budget. In seeking to identify and implement a VP approach to design and process it is essential that a methodical effort be adopted to obtain the right system at the right price -one that will deliver the functionality required and achieve rapid organization-wide acceptance.

The pace of technological change within the CAD and VP sectors is significant and it is accelerating. In undertaking this study, information has been sought on some of the leading VP tools available on today's market. The system functionality areas, as identified by the survey, cover the following applications: (i) computer-aided industrial design (ii) design review and motion simulation (iii) ergonomics, maintainability and assembly sequencing (iv) factory layout, simulation and robotics (v) Manufacturing process simulation (vi) CAE visualization (vii) virtual training. Some of the leading industrial VP-VR Tools have been mentioned. They are CATIA V5 with Enovia DMU (Digital Mock-up Unit) [10]; Msc.ADAMS (Advanced Dynamic Analysis of Mechanical System) [20];LMS[9]; LS-Dyna [21]; Ensight Gold (Generic post processor in immersive environment) [22]. Please note that the list is not exhaustive.

6.0 System Selection and Configuration Guidelines for VP-VR in Manufacturing

In selecting suitable VP-VR tools, companies should seek to apply the lessons learned during the purchase and procurement of their CAD and associated design technologies. The sales routes, major procurement steps and hardware requirements are identical to purchasing today's mid-to high-end CAD systems. However, given the evolutionary nature of VP tools, key consideration should be given to the following system elements (Tuikka & Samela 1998). (i) System should be easy to use-with open menu structure and customizing interface (ii) Full computer integration with the design work (iii)The concept should be visualized well (iv) Easy file transferable (v) Heterogeneous CAD Data migration facilities (vi) Advanced system should be user interactive and immersive.

To meet the compute and graphics power required for this purpose two new alternatives have emerged based on two different graphics & processing architectures-

- Hybrid grid type architecture, which exploits, leverage the economics of the Personal Computer (PC) world while addressing the requirements of a multi-disciplinary collaborative environment
- Technology, known as scalable graphics, which leverages industry-standard computer processing units (CPU) and GPU (Graphics Processing Units) in a high-performance shared memory architecture.

The key difference between these two hybrids is in the supporting system architecture, with the first built on a networked cluster of PCs and the second built on a modular, high-performance architecture where the system memory is shared between all computational resources. Detail discussion on these systems are beyond the scope of this report , but the reader is free to contact the author if there is a necessity. In the case non-linear FEA simulations for manufacturing processes soft wares supporting the "Domain Decomposition Method (DDM)" or capable of using multiple simultaneous processors will have clear advantage.

7.0 Summary

VP is a computerized design technology that holds revolutionary promise in improving efficiencies within new product-development processes. The technology has evolved from integration of existing design tools such as CAD and VR, and has now reached a level of maturity to warrant serious consideration as a must have design, analysis and visualization capability. In recognition of its maturity, many CAD tools now incorporate VP capabilities as part of their modular construction. The implication for small companies seeking to adopt VP -VR have moved awareness from the cost barrier, as the price of tools has fallen significantly in recent years. What is required is a greater understanding on their part of the potential and usability of VP and the development of a viable business case for adoption. The technology itself, whilst continuing to fall in price, is coalescing around common standards and interface tools such that it ease of use and market acceptance are on the increase.

8.0 Acknowledgement

The authors are thankful to Director, CMERI, Durgapur, for his kind permission to publish this paper.

9.0 Reference

I. Pratt, M. J.: Virtual prototypes and product models in mechanical engineering. *In Virtual Prototyping-Virtual Environments and the Product Design Process* (Eds J.Rix, S. Hass and J. Teixeira), 1995, pp. 113-128 (Chapman and Hall, London).

2. Boothroyd, G., Dewhurst, P.and Knight, W.: Product Design for Manufacture and Assembly, 1994 (MarcelDekker, NewY ork)

3. Burdea, Grigore C. and Philippe Coiffet (1994) Virtual Reality Technology, Wiley, New York, NY.

4. Rooks, B., A shorter product development time with digital mock up. *Assembly Automat*, V 01.18, No.1,1998,pp.34-38.

5. Caldwell, R. D., N. Ye and D. A. Urzi (1995) Reengineering the product development cycle and future enhancements of the computer-integrated environment. *International Journal of Computer Integrated Manufacturing*, Vol. 8, No.6, 441-447

6. Tseng, M.M.; Jiao, J.; Su, C.J., Virtual Prototyping for customized product development. *Integrated Manufacture System*, Vol. 9, No.6,pp.334-343.

7. Stone, Robert J. (1995) The reality of virtual reality. *World Class Design to Manufacture*, Vol. 2, No. 4, 11-17

8. http://www.lmsintl.com/

9. Bennet.G.R, The application of VP technogies m the dvelopment of complex aerospace products. *Aircraft Engng Aerospace Technol*, Vol. 69,No.l, 1997,pp.19-25.

10. http://www.3ds.com/

11. http:/ /www .immersion.com/3d/case_study_gallery/boeing.php

12. Shukla,C.;Vazquez, M.; Frank Chen, F.,Virtual Manufacturing: An Overview, Computer ind. Engng, Vol.31,No.l/2, 1996,pp. 79-82

13. Lederer, Gilad (1995) Making virtual manufacturing a reality. *Industrial Robot*, Vol. 22, No.4, 16-17.

14. Chang, K.H.; Silva, J.; and Bryant, I., Concurrent design and manufacturing for mechanical systems. *Concurrent Engg: Res. Applic.*, V 01.7, No.4, 1994, pp 290-308.

15. Tiruvannamalai, R.S.; Virtual Reality in Design and Manufacturing Applications, 2002.

16. Cook, R. D., Malkus, D. S., Plesha, M. E. and Witt, R. J. : *Concepts and Applications of Finite Element Analysis*, 4th edition, 2001 (John Wiley, New York).

17. Bickel. D, 3D real time simulation and VR tools in manufacturing industry .*Virtual Reality for Industrial Applications*, Berlin: springer, 1988, pp.123-138

18. Jayaram, S., Jayaram,U., Wang, Y., Tirumali, H., Lyons, K.and Hart, P. V ADE: A virtual assembly design environment. IEEE Computer Graphics and Applic., November/December 1999,44±50.

19. Jayaram, S., Connacher, H. I. and Lyons, K. W. Virtual assembly using virtual reality techniques. *Computer-Aided Des.*, 1997, 29(8), 575±584.

20. http://www.mscsoftware.com/

21. http://www.lstc.com/

22. http://www.ceintl.com/