Adv. Manuf. (2014) 2:289–294
DOI 10.1007/s40436-014-0085-y

Virtual engineering in design and manufacturing

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Received: 12 January 2014 / Accepted: 13 June 2014 / Published online: 19 July 2014

Abstract Manufacturing systems of the future highly demand that the product data are built into the product model, and smooth data transfer to other computer-aided technologies are enabled. Depending on the type of the manufacturing system, it is envisaged that virtual engineering (VE) technologies play a significant role in integrating the computer-based technologies involved in the product's life cycle. Simulations in a virtual world and exchange of real time product or design data are among the benefits for today's global oriented manufacturing business. To highlight the significance of design as carrier of product data and the key role played by VE technologies to inter-link design, manufacturing and associated components, this paper presents an overview and analysis of the state-of-the-art VE technologies to indicate potential applications and future research directions.

Keywords Virtual engineering (VE) · Product model data · Intelligent manufacturing · Web-based virtual engineering

1 Introduction

Within computer-aided engineering (CAE) field, using 3D simulations that are provided by virtual engineering (VE) technologies is a progressively developing direction. This involves interaction of diverse computer-based engineering tools such as computer-aided design (CAD) in geometric modelling, finite element analysis (FEA) in analysis and other mechanical and process simulation systems. The aspiration to create smooth communication among the diverse CAE tools demands a collaborative engineering work where VE and the interface standards play a key role. Starting from design, VE enables simulation of various activities in design and manufacturing of components, assembly process, quality control and servicing. In short, VE technology is a means to realize simulation-based engineering, and design is the cornerstone of this goal.

In brief, VE is a simulation of the real-world system using another model. Hence we can refer to a computer-based model, in order to manipulate and study the behaviour and performance of the system in a virtual world. In other words, application of VE technologies is a process of experimenting or virtual prototyping on a representative model. Engineering companies of today are highly interested in implementing virtual prototyping in their design and manufacturing processes because VE reduces the product life cycle cost significantly. The drive for the interest to implement VE technologies emanates from the fierce competition in a global market. Nowadays this competition is characterized as innovation-based because the classical competitive factors such as better performance, short time-to-market and low or competitive pricing should be reconciled with other challenges such as new product brands, ecological, safety and legislation aspects [1]. The solution to this challenge lies in using the design engineering data in other processes used to realize the product. Within engineering design, the main role of VE is to contribute in reducing the product development time, assisting engineers in decision making, simplifying generation of alternative design solutions, providing interfaces that allow 3D model manipulation in a virtual world, making necessary changes and design optimization at low

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cost, etc. It is necessary that VE technologies have the above-mentioned capabilities because testing using physical models is expensive and requires long development time, and products are extremely complex [2].

Due to the fact that VE is relatively new, diverse concepts and technologies have recently emerged. It is true for all other emerging technologies that the terminologies and definitions used in this area are not fully established [3]. In an effort to make an interactive assessment of virtual prototypes, Stark et al. [4] reported an analysis of the key elements involved in modern virtual product creation process including 3D CAD modelling using parametric modelling techniques, CAE technologies for analysis and simulation, numerical controlled production systems and validation of design concept by simulation and prototyping.

The role of VE in design, as seen from current developments, is quite immense and important specially in establishing communication among design engineers as well as among project teams located at different parts of the globe. This is particularly crucial in the context of globalization where companies are operating internationally and sharing data is a necessity. To highlight the recent research activities in application of VE technologies in design, this paper presents the state-of-the-art study, development trends, application benefits and future research directions of the technology. The paper covers short overview of some VE technologies and gives analysis of selected application areas.

Section 2 presents overview of selected VE technologies, and the example applications of the technology are discussed in Section 3. Prospective research areas are highlighted in Section 4. At last, conclusions are given in Section 5.

2 VE technologies

2.1 Virtual design

Mechanical design is, by its nature, multidisciplinary work involving competence and knowledge from diverse fields, for instance, solid modelling, creativity, material science, production technology, control techniques, marketing and economics. In addition, the classic design process of a mechanical part or system has been characterized by sequential activities as depicted in Fig. 1. This sequential process is known to make the time to market of the product very long, which does not fit today's production philosophy. It is also a well-established fact that design work is characterized by cross-company collaboration involving intensive exchange of product data, where sequential processes such as the one depicted in Fig. 1 are no longer applicable.

Today, engineers typically use diverse digital engineering tools and operate in multidimensional engineering processes. This has initiated research ideas in collaborative product development where investigating the way engineers currently work and how the newly emerging global oriented working environment influence the main engineering roles such as design, analysis and design validation [5].

In other works, it has been reported that current research in the application of VE technologies using design data [6] has focused on the usability and benefits of the technology by interfacing with standard simulation software such as FEA and multi-body systems [7–9]. As a result, 3D models based computer simulations are now common practices in industry, while research on exploration of the analytical aspects of design process and how the design data are integrated to serve in various stages of the product life cycle is lacking. The 3D simulation capabilities have for sure served in creating design visualization easier through computer graphics. The possibilities to make design modification based on real-time virtual simulation can be achieved, particularly in making significant added value for complex applications [10, 11], when virtual design technology is fully utilized.

2.2 Multibody dynamics simulation

Multibody dynamics (MBD) simulation is a multidisciplinary field involving, among others, modeling techniques, mechanics, computer science, numerical methods and CAD. The simulation technique focuses on mechanism

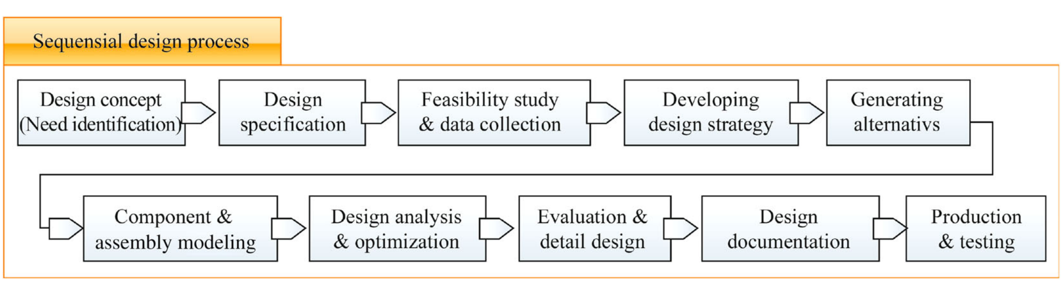

Fig. 1 A typical sequential design process for part/system design

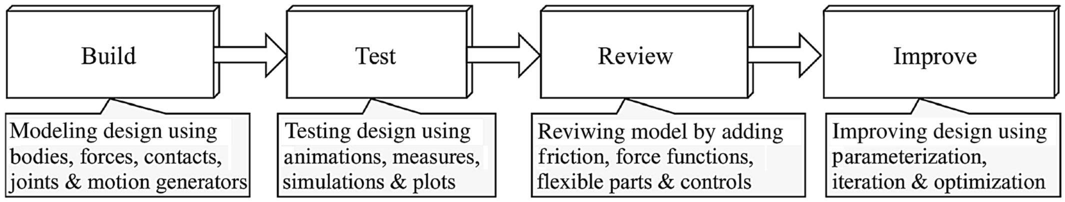

Fig. 2 Virtual prototyping process in ADAMS

simulation of multibody mechanical systems consisting of two basic elements: rigid bodies and inter-connections. It is a discipline of current active research for mechanical interaction of complex mechanisms. MBD simulation enables to study none existing objects, of course at low cost, and supports the designer in decision making by exploring "what if?" scenarios [12]. Due to the potential to reduce life cycle cost of a product, more and more MBD simulation packages such as automatic dynamic analysis of mechanical systems (ADAMS) from MSC software [13] are getting their way into the industry. The basic code of ADAMS was developed at University of Michigan with Adams/solver to solve nonlinear numerical equations from models in text format. Further developments included other modules that allowed users to build, simulate and examine results in a single virtual environment, as illustrated in Fig. 2.

Multibody systems are often modeled using graph-based theories where the rigid bodies and connections are mapped to vertices and edges, respectively in a system graph. This is referred to as component-based modeling [14]. On the other hand, recent advances in modeling have resulted in several other modular and object-oriented languages that satisfy the requirements for multibody simulation [15]. Several softwares including ADAMS are using these modeling and simulation techniques.

Studies in the area also show that having the design and simulation processes within a single domain can further simplify the modeling process and avoid unnecessary duplication of data entry for analysis, virtual simulation and other VE based processes.

2.3 Integrating VE technologies

One important method to realize the integration of engineering activities and thus establish an intelligent manufacturing system is to be able to integrate VE technologies. The developments of advanced computer-based technologies open better opportunities for inter-linked VE environment because digital models and simulations are used instead of physical objects and operations on them. Compared with physical objects, virtual/digital models better

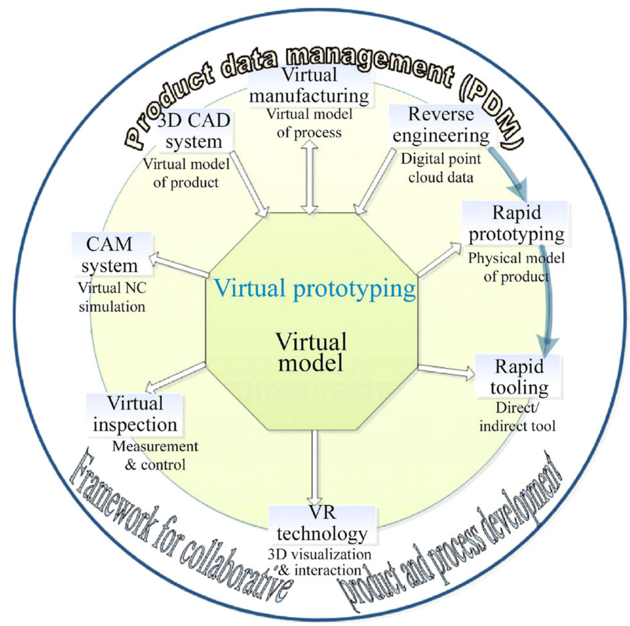

Fig. 3 Components and interactions of VE technologies

facilitate communication and collaboration among engineers and other stakeholders that are located at different locations. Thus, integrated VE environment enables work collaboration on a single design regardless of geographical location.

In a study on integrated product and process development in collaborative VE, Mandic and Cosic [2] worked out an overview of VE system components. Figure 3 shows an adapted overview of the components in this collaborative system. This simplified overview shows that the virtual model is the basis of the interaction and plays the central role in integrating the engineering functions involved in the product's life cycle. The CAD model feeds the virtual model with complete product description in a digital form, and these digital data are carried forward and distributed to all other components of VE technologies. This form of interrelation based on CAD data is expected to make smooth flow of data and simplify exchange of information.

2.4 Web-based VE

Web-based simulation technologies [16] integrate the Web technology into the field of simulation [17] and currently are seen as the useful tool in engineering field particularly within engineering education. Together with the developments of computer-based design, educating design engineers using the Internet system will provide a new networking approach. In design and manufacturing environment, web-based solutions can enhance the competitiveness of products by providing an interactive system that reduces the time-to-market and thus reducing cost and increasing the quality of the product. However, design and manufacturing are normally sophisticated engineering operations and thus certain challenges should be addressed before being able to utilize this approach effectively. This primarily includes the possibility of exporting the geometric model into a format compatible with the web browser. A standard file format known for 3D model transfer is the virtual reality modeling language (VRML) that is also accepted by the web browser. This format is designed to cover all aspects of web-based display and interaction and it allows multiple participants [18]. The possible limitations of the file format mentioned in Ref. [18] include security issues, difficulty for reverse-engineering purposes due to the fact that the VRML format is no longer a CAD data and large model size [19]. Formats like computer graphics metafile (CGM) and autodesk's drawing web format (DWF) can also be used for 2D models and require special plug-ins to view the model in the browser.

To utilize the web-based technology in establishing networks of engineers and be able to share design data over the Internet, the concept of interactive design visualization (IDV) was also used by many companies [20]. This may facilitate an immediate sharing of product data by uploading CAD data to the company's server and communicate with the clients [21]. However, the current status indicates that a true real-time interaction among engineers and clients is far from reality due to some bottlenecks such as questions related with company data security issues as well as establishing user-friendly user interfaces that can be used with little or no training.

As of today, the multi-user functionality of web-based VE technologies has got the most attraction as a medium of education [22, 23]. Using this principle, many online trainings and virtual lectures are possible to involve participants located at various parts of the globe.

3 Example applications

3.1 VE based design visualization and validation

It is well documented in the literatures that the traditional design process (see Fig. 1) follows the line from design works to prototype development, testing prototypes, design analysis and simulation, and redesign is time consuming and leads to high production costs [24, 25]. VE based design is widely considered to improve the above-mentioned drawbacks of the traditional design process in designing a new product and prototyping. At the early product development phases in particular virtual design simulation and prototyping are essential tools to, among others, experiment functionality of mechanical motions and features. Rapid prototyping (RP) technology was primarily intended to assist the product development phase of design works to improve design concept visualization and hence reduce the time consumed in developing physical object, in most cases scaled prototypes. This is because RP technologies can develop prototypes for diverse purposes such as design object visualization and verification within a relatively short time. The function or application of such prototypes is highly dependent on the type of technology used to build the prototype whose process depends on the material used. Based on the material type, RP processes are classified into four main groups as depicted in Fig. 4.

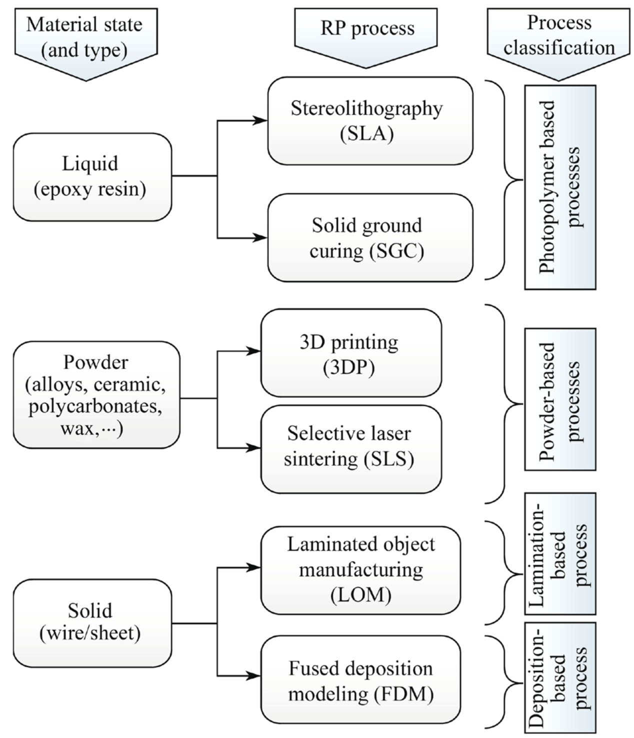

Fig. 4 Process material based classification of rapid prototyping technologies

Using a digital model for testing and design evaluation within a virtual computational environment, the concept of VE is expected to improve some of the shortcomings of current RP technologies. This is because the concept allows getting the physical "feeling" in virtual environment and errors can be detected before high costs are committed.

Design iteration on the digital model is cheap and the design optimization is done within shorter time because the number of design iterations using physical models, including those produced using RP technology, is significantly reduced. Most of all, visualization using VE concept is considered to be an effective way to create real scenarios that facilitate effective communication of design idea and to test functionality [26].

It is important to underline here that VE is not an option to completely replace RP technologies. While RP technologies still remain the preferred options for direct production of certain customized parts, virtual prototyping is the best option in areas of small-batch production for instance where making physical prototypes or production of patterns and mould is not economical. It is also envisaged that both technologies can supplement each other because virtual prototyping can be used as a means of validation and quality control while RP technologies are used for direct production of parts.

3.2 VE in process simulation

The manufacturing process is directly related to the design work of a product. Thus, it is one area that benefits from the VE technologies. Computer simulation of processes such as running the CNC part program in virtual environment can assist in detecting possible manufacturing errors and difficulties. Thus, we observe a paradigm shift in the manufacturing engineering area from mass production based to rapid responsiveness and flexibility [27]. To realize virtual manufacturing (VM) many research efforts on process simulation [28], study of residual stress and material distribution in forming process [29], study of the effect of friction on sheet metal forming processes [30] are reported. As part of the knowledge and information-based techniques developed in recent years, VM uses artificial intelligence technologies, virtual models and simulations to mimic real world manufacturing operations.

A number of benefits of the application of VE in process simulation can be mentioned. In a state-of-the-art study conducted to highlight the role of VM in material processing and the research progress in the area, Lee and colleagues [31] listed the following key and attractive applications of VM technologies:

(i) testing and verification of product and process design,
(ii) analysis of manufacturability of products,
(iii) evaluating and validating the feasibility of production and process plans,
(iv) optimization of the production process, and
(v) optimization of the manufacturing system performance.

The end goal of such applications is to improve the competitiveness of companies by shrinking the product development time and enhancing the capabilities to predict possible risks before the part is physically produced.

4 Prospective research areas

VE involves a multi-disciplinary knowledge and the progress in the technology is influenced by the advances in both hardware and software related technologies. While some of the associated technologies such as CAD/CAM systems are relatively matured, there is still need for further research in some areas in order to advance the contribution and optimized implementation of VE in design and manufacturing.

In MBD simulation, for instance, there exist clear outstanding research challenges in understanding the governing mechanics of the physical system and making appropriate choice of the simulation programs and solvers. Furthermore, establishing efficient communication among the virtual modeling and simulation tools needs closer research. Recent reviews of Ref. [8] on trends of MBD research indicated that the core topics such as theoretical and computational methods for both rigid and flexible systems, multibodies involving large deformations and special application areas such as biomechanics and education were potential research areas of the future.

As stated, the current condition shows that VE and RP technologies are to certain extent complementary and further research is needed in both areas. The efficient application of each technology depends on the type and size of manufacturing system as well as product complexity. Thus, research of the future in this area is broad and needs to focus on distinguishing the conditions under which each technology can be used best.

5 Conclusions

This paper assessed current status and application challenges of VM and associated technologies in design and manufacturing area. Understanding that design information lays the foundation of the product data description, the study is intended to give a short overview of the technology and highlight research challenges in integrating design data through VE technologies. The end goal of research in this direction is, among others, to make the manufacturing system intelligent, smart and cost effective by reducing the product development phase. As this demands enabling computer-based technologies involved in the product's life cycle to easily communicate to each other with no or less human intervention, this paper focused on the state-of-the-art assessment and analysis of the VE technologies.

Though some of the technologies in this area are sufficiently matured, there still exists significant research to be done in order to achieve intelligent manufacturing systems. As indicated in the paper earlier, this can be possible if the product data are completely and correctly built in the CAD model and the smooth transfer of these data to other components in the system is enabled through further research.

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