VIRTUAL AND AUGMENTED REALITY TECHNOLOGIES
FOR PRODUCT REALIZATION

S. C-Y. Lu (2), The IMPACT Laboratory, University of Southern California, USA
M. Shpitalni (1), R. Bar-Or, CAD Laboratory, Mechanical Engineering, TECHNION, ISRAEL
Rajit Gadh, The I-CARVE Laboratory, University of Wisconsin-Madison, USA

Abstract

Our society expects engineers to develop products that are affordable, functional and sustainable. Effective product realization methods and tools are the answers to these societal expectations. In this paper, a new type of CAE tools, called virtual and augmented reality technologies, is introduced, reviewed and examined to reveal their great potentials in product realization. Specific areas where these emerging technologies can make a big difference are highlighted to illustrate the possible new paradigms of product realization. Subjects that require continuing R&D efforts to mature the technologies for real-world engineering applications are also identified. Both product development engineers and virtual reality researchers should find this paper valuable to guide their efforts in developing a common road map for joint explorations. It is anticipated that the results from these joint explorations will enable engineers to deliver new products to the society across the time, space and other boundaries with high efficiency and great ease in the future.

Keywords: Design and Manufacturing, Product development and realization, Virtual and augmented realities.

1 INTRODUCTION

Product realization is one of the ultimate challenges in the engineering profession, which is largely responsible for the creation of wealth in our society. As society develops, the complexity of product realization tasks in terms of their overall quality, costs and lead-time also increases rapidly. Meanwhile, our society has evolved into a more holistic and life cycle oriented view toward the environmentally sustainable creation, usage and recycling of engineered products. All these new societal trends have added to the demands on constantly searching for better methods and tools to support product realization tasks in the engineering profession.

Digital computers have become an indispensable tool in product realization to date. Engineers use them to aid decision-making and process control in design, planning, production and distribution phases to improve quality, reduce costs and shorten lead-time. As a result, the interaction between engineers and computers has become a critical factor in determining the overall effectiveness of product realization [1]. Current computer-aided engineering (CAE) tools offer users 2-D textual and graphical interfaces, which are very cumbersome for engineering practice that needs a high fidelity human-computer interaction. Recent developments in multimedia [2] and virtual and augmented reality technologies offer some very interesting potentials to meet this critical need.

This paper introduces the great potentials of virtual and augmented reality technologies in product realization to the engineering communities. We first highlight the disciplinary, temporal and geographical challenges of product realization, and then introduce the basics of these new technologies with a brief overview of their hardware and software components. The focus of this paper is on the use of these technologies to solve product realization problems, emphasizing the great potentials that these applications can lead to many exciting new paradigms in engineering profession. The paper also identifies areas where more joint R&D efforts are needed from the engineering and computer science communities to make virtual reality technologies a true reality for the real-world practice in the near future.

2 TECHNICAL CHALLENGES OF PRODUCT REALIZATION

Product realization, in its broad sense, refers to the process by which the concept of an engineering product goes through several stages of its complete life-cycle, including design, manufacturing and planning, delivery, maintenance, and recycling and reuse, as shown in Figure 1. The design stage involves making the decision on the forms, structures and materials of the product. The planning stage determines a production plan for the product, which is based on the product definition generated from the design and the real-world manufacturing constraints of the factory. Delivery refers to the actual distribution of the product from the factory floor to the sales channels and finally on to the customers. The servicing stage requires the product to be maintained so as to keep it under good operational conditions until the end of its designed life. Subsequent to the end of the product's life, a product needs to be recycled, and issues such as recyclability and disassemblability become very important. As illustrated in Figure 1, the thicker cycle of arrows represents the flow of product realization activities from one stage to another; whereas the thinner cycle of arrows represents the reverse flow of information/knowledge which is needed from the downstream to the up-stream of the product development cycle.
For example, knowledge of manufacturing and planning must be accounted for earlier in the design stage so that manufacturing and planning can be time efficient and economic. Each of these stages/phases presents unique technical challenges to different engineering professionals and/or end-users who are involved with the various life-cycle concerns of product realization [3] [4]. More details of these challenges at different stages of product realization have been discussed in [5] [6].

![Figure 1. Life-Cycle Concerns of Product Realization](image)

**Figure 1. Life-Cycle Concerns of Product Realization**

A key to any successful product realization activity is the early incorporation of knowledge flows from downstream to upstream, as indicated in Figure 1. The incorporation of downstream knowledge allows various life-cycle product realization concerns to be fully incorporated, evaluated, analyzed, compared and optimized at the early stages when costs for changes are still low. This is unfortunately not an easy task in practice, due to the difference between and separation of involved activities and personnel.

Regardless of their specific contexts, the technical challenges of product realization can be generally categorized as belonging to one of the three major categories, namely **disciplinary**, **geographical**, and **temporal**. These three categories of challenges are the key areas where virtual and augmented reality (VAR) technologies can make significant contributions, as will be explained in this paper. Here, we briefly summarize the technical challenges of product realization in terms of these three categories, before introducing the possible solutions arising from VAR technologies.

2.1 Disciplinary Challenges

Product realization, at its minimal level, requires individuals from different disciplines of an engineering organization to collaborate and come to a design decision on what a complete product definition (i.e., model) should be. However, each individual or department involved in the product design has its own vocabulary and perspective on the issues that are important to them. For example, a tooling engineer regards the draft angle as an important feature, while a design engineer emphasizes the form and functional features of the product definition. While both are looking at the same geometry, the issues of interest to them are quite different because they are from very different disciplines. This gap creates many communication difficulties, and results in a large number of time delays and wasteful changes in product realization practice. Therefore, there exists a need for tools that can help to overcome this disciplinary gap by facilitating effective interaction and collaboration between engineers from multiple specialties who are trying to achieve competing goals during product realization.

2.2 Geographical Challenges

In the global market of today, the different stages of the product development process do not always take place at a given central location. Rather, they are more often performed by perhaps a designer at one place, with collaborating manufacturing and process planning person located at yet another location. The complexity of global logistics requires different stages of product realization to be carried out at different locations so that the parties can better utilize local resources. However, by not being located at the same place, collaborators within the product design team often miss important subtle signals, body languages, voice intonations, and many other implicit expressions, that are available when collaborating face-to-face. This distance separation, which is the norm in product realization practice today, poses major challenges to the engineering community in terms of product development quality, lead-time and costs. Computer tools that enable the tele-presence of remote participants can help to overcome this geographical gap, and hence increase the productivity of product development teams.

2.3 Temporal Challenges

Not every disciplinary expertise required for different stages of product realization will be available at the same place at the same time when they are most needed. Achieving collaborative product realization in today’s setting requires much synchronized coordination of activities between companies and their suppliers, which are often distributed globally across different time zones. For example, a combustion engineer in Detroit, USA, working on the design of a new automotive engine may have to collaborate simultaneously with a structure designer in Stuttgart, Germany, working on the hood design of the car. However, because the two designers do not work at the same time zone, the result could be difficulties in real-time on-line communication, interaction, discussion, etc. An immediate consultation between the engine designer, who needs to make a critical design decision at work at that moment, with the structural expert, who is off work at his local time, would make a big difference in design, possibly eliminating much wasteful iteration downstream. The CAD and e-mail systems of today are not well suited to overcome the asynchronous transfer of information and knowledge caused by design being performed in different time zones. Better communication tools with much higher fidelity and bandwidths are needed to overcome the temporal gaps in product realization. As will be explained later, if properly developed and effectively utilized, these tools could transform this temporal difference between product teams from a hindrance into a benefit.
3 WHAT IS VIRTUAL AND AUGMENTED REALITY TECHNOLOGY

In the past decade, the word “virtual” has rapidly become one of the most over-used adjectives in the English language. For example, engineers today frequently hear such catchy terms as virtual factory, virtual machines, virtual prototyping, virtual engineering, virtual organizations, etc, in the course of their work. At the core of all this fresh terminology is a new technology called “virtual reality” that has gradually evolved from its infancy in the mid 1960s to its current state of realized and potential business applications in many professional fields, including product realization.

Unfortunately, the true definition of virtual reality technology has often been lost in the midst of these buzzwords. Therefore, before we can develop a systematic road map to derive benefits from its application potentials in product realization, we must first understand the term’s correct and precise meaning.

The word “reality” refers to our connotation of the external physical world. This reality is mainly describable by, and experienced through, human sensory capabilities [7]. One of the dictionary definitions of the word “virtual” is “being something in effect but not in actual name or form”. When combined, therefore, the words “virtual reality” (VR) suggests a realm that is believably experienced through our sensory skills, yet does not physically exist in the world. In order words, VR is about creating substitutes for real-world objects, events or environments that are acceptable to humans as real or true. The terms “virtual environments”, “artificial environments” and “synthetic environments” are often used interchangeably when the subject of VR is discussed.

Specifically, “virtual reality technology” is often defined as “the use of real-time digital computers and other special hardware and software to generate a simulation of an alternate world or environment, which is believable as real or true by the users”. In other words, VR technology creates an environment in which the human brain and sensory functions are coupled so tightly with the computer that the user seems to be moving around inside the computer-created virtual world in the same way people move around the natural environment [8]. This definition points out that the key advancement and challenges of VR technology lies in the human-computer interface. As will be explained in more details later, this interface must be immersive, interactive, intuitive, real-time, multi-sensory, viewer-centered, and three-dimensional.

Because of differences in human sensory capabilities, and, more importantly, variations in application needs, the measure of “real or true” is certainly not absolute for all people in all cases. Therefore, it is only meaningful to define VR technology based on a limited, measurable set of human sensors, and to focus the discussion on particular applications. Because the application domain of our interest in this paper is product realization, the VR technology users we will discuss will be mainly design and manufacturing engineers. Consequently, in this paper the human sensory capabilities under scrutiny will be limited to those that are essential for engineers during product development, such as visual, auditory and haptic.

Depending on the relationship between the alternate environment and the real physical world, VR technology can be further broken down into two types, both of which have significant application potentials in product realization. If the computer-generated environment is completely detached from the real world and the user is fully immersed within the virtual world, this is commonly called “virtual reality (VR) technology” (Section 3.2). However, if the virtual environment is only a partial representation of the real world upon which it is projected, and the user does not experience a full immersion, it is commonly called “augmented reality (AR) technology” (Section 3.3). Except for the difference in immersion, VR and AR use the same technological principals. Their different application potentials in product realization will be elaborated in Sections 6 and 7 of this paper.

3.1 A Brief History of Virtual Reality Developments

Since digital computers play a central role in VR technology, the early advancements of this technology paralleled that of many computer-related technological developments. These include computer simulations, three-dimensional interactive graphics, computer-human interfaces, etc.

As early as 1929, Edwin Link designed a carnival ride that made the passenger feel that he/she was flying an airplane [9]. In the early 1960s, the Sensorama ride designed by Morton Heilig used light, sound, motion, and even smell to immerse the participant in a motorcycle ride through Brooklyn and other sites. This ride later evolved into the flight simulator technology that is commonly used as a training device for modern aviators. The obvious benefits of flight simulators are they do not risk lives and equipment, and can be upgraded to accommodate new generations of airplanes and spaceships in a cost-effective manner. These flight simulators, such as the Super-cockpit at Wright-Patterson Air Force Base, are often regarded as the parents of modern-day VR.

Several significant inventions in the 1960s and 1970s contributed to the development of current VR technology. In 1965, Ivan Sutherland published “The Ultimate Display” [10], a paper that described how a computer would one day provide a “window” into virtual worlds. In 1968, he built a head-mounted computer graphics display that also tracked the position of the user’s head movements. This device, which couples computer simulations with human factors, allowed the user to view simulations rendered in wire-frame graphics in the left and right views. The immersion experience was created by changing the viewpoint of the scenes according to the movements of the user’s head. As a result, when the user’s head moved, the virtual scenes remained stationary in space, creating the impression of looking at a solid 3-D object in space. Viewer-centered graphics, as it is called, is a key to VR technology.

At about the same time, a research team at the University of North Carolina began the Grope project to explore real-
time force feedback [11]. Computer-generated force feedback directs physical pressure or force through a user interface so that the user can experience some sort of tactile sensation within the virtual world. Such integration between computer simulations and human haptic sensors further advanced modern VR technology.

Although they provided the foundation for VR technology, these early research projects did not immediately result in useful practical applications, nor did they raise much commercial interest in industry circles. This was mainly due to the limited computing power available at the time, a hindrance that made real-time simulation and interactive graphics difficult to execute, and high equipment costs that prevented widespread experimentation and utilization.

In the mid 1980s, the Ames Research Center at NASA started developing relatively low-cost VR equipment from off-the-shelf LCD, TVs, and other electronic components to offset the exorbitant cost of the equipment used in flight simulators. Many start-up commercial companies also began to offer simplified hardware and software for limited VR developments and applications. At the same time, computing power increased considerably in the late 1980s and early 1990s, which made real-time simulations and interactive graphics a possibility, even with desktop computers. All these developments helped make commercial applications of VR feasible toward the beginning of the 1990s.

Early VR systems consisted of a real-time computer system, a head-mounted display, and an interactive glove. Such VR systems are still used by the entertainment industries today. As VR hardware and software become more powerful and affordable, other professional fields, such as education, medicine, e-commerce, architecture, art, etc., have also started to embrace the technology and develop more applications. The application of VR to product realization represents one of the most important areas where this creative technology holds great potential to have a revolutionary impact on the industry as a whole. These potentials will be further discussed in later sections of the paper.

Since the development of VR closely parallels that of interactive computer graphics, it is important to note their differences. Both technologies deal with the creation, storage, and manipulation of object models via computers [12]. The main differences lie in their interfaces with human users. While computer graphics enable users to view computer-generated pictures from the “outside”, VR attempts to immerse the user “inside” an environment containing 3-D objects with 3-D locations and orientations in 3-D space [13]. More importantly, the interaction with the environment in VR must be user-controlled and user-centered (and hence tracing the user’s viewpoint is a critical task in VR, but not in traditional computer graphics). Multi-sensory is yet another difference between the two. Unlike computer graphics, which mainly deal with the visual interface, VR often adds auditory and haptic sensory inputs to enhance the user’s experience.

3.2 Virtual Reality Technology

There are four key characteristics -- immersion, presence, navigation and interaction -- that can be used to measure and classify different VR systems and their applications. Immersion refers to the VR user’s feeling that his/her virtual environment is real, whereas presence denotes a self-representation and association of a VR user within the virtual environment. By navigation, we refer to the user’s ability to move around and explore the features of a 3-D scene, such as a new automobile, whereas interaction implies the ability to select and move/modify objects within that scene, such as a car door. Navigation can be viewed as the simplest form of interaction in VR applications. Real-time responses are implied in both navigation and interaction, which post a high demand on VR computing power.

3.2.1 Immersion and presence in virtual reality

In a practical sense, if a user cannot tell which reality is “real” and which one is “virtual”, then the computer-generated environment is totally immersive. A high degree of immersion is equivalent to a realistic or believable virtual environment from the users’ point of view. The degree of immersion experienced is affected by several factors. First, feedback lag due to tracking and rendering delays is the main reason for users to feel a less-than-complete immersion. Second, narrow fields-of-view, which produce “tunnel visions”, and mono-scopic views, which lack range depth, degrade the immersion effects in visual feedback. Immersion can be enhanced by adding audio, tactile and force feedback.

While immersion can be an objective measure, presence is often the user’s subjective sense of being in the virtual environment. Presence requires a self-representation of the user’s body or hand (depending on which is tracked by the system) within the virtual world. It also requires the user to identify and associate with the “virtual self” represented in the system and to feel that its movements in the virtual environment are corresponding to the user’s movements in the real world. Real-time responses and minimum latency are important for realistic presence.

It is clear that both immersion and presence are important for VR applications. Unfortunately, achieving both simultaneously is extremely expensive with current technologies. Furthermore, the degree of immersion is almost reciprocal to the degree of presence in practical applications. For example, a head-mounted display gives a full immersion but without any presence. A virtual table provides almost no immersion, but offers users a full presence. This indicates that there can not be a perfect VR input/output device – they must be individually determined according to the immersion and presence requirements of particular applications. For example, an augmented reality system requires a high level of presence of users in the real world, while there is not much of a self-presence in the virtual environment at all.

3.2.2 Relationships with the real-world in virtual reality

Based on combinations of hardware/software, different degrees of realism, and modes of user interactions, VR
systems can be classified into distinct types by different means. One useful way of distinguishing VR systems is by examining the relationship between the virtual environment (VE) they represent and the real world of the user [14].

1. The VE is actually a full projection of some real environment, which might be of very different physical scales or at some distance from the users. The latter case is often described by the term tele-presence. With this type of VR systems, the user can manipulate existing real objects remotely through the aid of their corresponding virtual objects (i.e., tele-operation). Some examples are modifications of the structure of materials at atomic scale and steering a vehicle on the moon or polluted terrain.

2. The VE does not exist (i.e., does not have its real-world counterpart yet), but is otherwise fairly realistic. It might have existed in the past (e.g., the re-creation of Titanic), or it might exist in the future (e.g., an automobile under design). With this type of VR systems, the user manipulates non-existent objects directly. For example, a design can examine the interior of a future car design, and a manufacturing engineer can visualize the fabrication processes being planned. Such VR systems are commonly used as virtual prototyping tools in product realization.

3. The VE is quite unreal from the viewpoint of the actual physical world. This is commonly the case in creative entertainment applications that strive to provide the audience with an exciting, exotic and imaginary world. The unreal phenomena are created by so-called "cartoon-physics" which lends special effects to objects that are not possible according to physical laws. Certainly, the user can only interact with non-existent objects in this type of VR system.

There are some VR systems that are a combination or mixture of the above three types. For example, augmented reality (AR) systems are a hybrid of types 1 and 2. More details on AR systems will be provided in Section 3.3.

3.2.3 Types of virtual reality systems

After explaining the concepts of immersion and presence and the different relationships of VE with their real-world counterparts, we can classify different VR systems and applications in the following table (Table 1):

<table>
<thead>
<tr>
<th>Relationships with the Real-world</th>
<th>Unreal</th>
<th>Not Existing</th>
<th>Existing</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Immersion</td>
<td>Entertain -ment</td>
<td>Functional simulation</td>
<td>Tele-presence</td>
</tr>
<tr>
<td>In-between</td>
<td>Training</td>
<td></td>
<td></td>
</tr>
<tr>
<td>High Presence</td>
<td>Ergonomic</td>
<td>AR</td>
<td></td>
</tr>
</tbody>
</table>

Table 1. Types of virtual reality systems [14]

3.3 Augmented Reality Technology

As explained above, augmented reality (AR) is a variation of virtual reality (VR). The components of AR systems are similar to those of VR systems. AR systems, however, are not aimed at immersion of the users in a virtual environment. Rather, the goal of AR systems is to superimpose (i.e., augment) computer-generated graphics over real objects in the user’s field of view as if they appear in the real world. Thus, a STD (see through device) is used by the user, which eliminates the need to model the environment. This saves not only a lot of modeling effort but also reduces by factors the information needed to be generated and transferred in real time (which is the main technological drawback of VR). Therefore, AR systems exhibit more application potentials than do VR systems at the present time.

3.3.1 Characteristics of augmented reality technology

Augmenting necessary information can enhance the user’s perception and improve his interaction with the real world by supplying him with necessary diagrams, step-by-step instruction, real-time animations, and other data that is essential for his work. These augmentations should be correctly aligned (registered) with the real objects they represent. Due to the relatively simple graphics displayed in AR systems, a complete 3-D model of all objects in the field of view is not necessary as in the case of VR systems. Some objects might be modeled in detail, while others appear only as a wire-frame. Typically, most of the user’s view would be from the real world. For this reason, AR systems do not need to be driven by the same graphic engine used in a VR system in order to supply a sufficient frame rate. 3-D manipulation of smaller models can be handled by much cheaper equipment in AR systems.

With AR systems, the physical model also requires less computational power, since only a few entities might need modeling. However, since the user can see both the graphics and the real environment at the same time, it is quite easy to sense any slight misalignment between the two. This is because misalignments create a visual - visual conflict, which is much stronger than other human sensory conflict [15]. If the computer-generated graphics are not properly placed with respect to the real world, or if they appear to “swim” around the real world objects, the augmentation may be useless and confusing, as the human visual system is sensitive enough to pick up even small misalignments.

For this reason, registration is by far the most crucial technical issue in AR systems. A complete registration error analysis can be found in [16]. There are numerous sources of registration errors. In general they can be divided into two categories: static errors and dynamic errors [15] [16]. According to [16], the major contributor to static errors is tracker system error. However, dynamic errors, which are caused by system lag, are the single highest contributor to the overall registration error.

Figure 2. illustrates the event flow of an AR system loop for updating visual displays.
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In video AR systems, the user sees the real world indirectly through a set of video cameras. Both the real and virtual objects exist as separate video streams, and augmentation is achieved by using some video blending technique, such as chroma keying. As in the case of optical systems, both fixed and portable AR systems are possible.

A portable system uses a regular closed-view HMD with a pair of video cameras mounted on top. After the camera video streams are blended with the virtual objects, they are fed back into the helmet’s monitors, giving the user a view of both. In a fixed video system (monitor-based), the mixed video stream is displayed on a standard computer monitor rather than in an HMD. Stereoscopy is also possible in this method by using a pair of shutter glasses.

Each of these technologies has its strengths as well as its weaknesses, and a design choice should be made according to the specific application needs. A detailed comparison can be found in [11]. Advantages of these video systems include:

- Better registration: since both real and virtual images are video streams, the system can synchronize both streams in time, reducing mis-registration caused by system delays. The video data can also be used as an additional tracking sensor.
- More convincing augmentation: video systems can completely obscure real world objects with virtual ones, thus creating more realistic augmentation.

### 3.3.2 Types of augmented reality systems

Several methods can be used to achieve augmentation of computer-generated graphics over real world images. These methods divide AR systems into two main categories: optical AR and video AR [15].

**Optical Augmentation**

Probably the most well known optical AR system is the head-up display (HUD) used in military jet fighters. In a HUD system, the pilot views the world through a semi-transparent semi-reflective glass called a “combiner”. A monitor is placed under the combiner, which in turn is positioned at an angle that gives the pilot both a view of the real world and a reflection of the monitor graphics. An aircraft’s HUD is an example of fixed AR systems, also known as monitor-based AR.

Another possible version is portable AR, using an HMD (Helmet Mounted Display). The technology used by HMDs is similar to that of the HUD, except that the combiners and monitors are placed in the helmet directly in front of the user’s eyes. Advantages of these optical systems include:

- Simplicity: there is only one video stream to deal with
- Direct view of the real world: the real world view is unaffected by monitor resolution, optic distortion, system delays and camera offset from the actual eye location

**Video Augmentation**

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### 4 BACKGROUND OF VIRTUAL AND AUGMENTED REALITY SYSTEMS

Having been introduced to the general concepts of VR and AR technologies, the reader needs to be equipped with some background of VAR hardware and software in order to appreciate the application potentials of these new technologies in product realization. This section is provided as an introductory overview for those readers who are unfamiliar with the subject.

#### 4.1 Components of a Generic VAR System

At the center of all VAR systems is a digital model of the alternate world, virtual objects and/or events that the systems try to represent. In architecture engineering applications, for example, this digital model could be a realistic representation of a building interior under conceptualization. In tele-presence and tele-operations scenarios, the model could be a digital mock-up of the moon or an underwater terrain being explored. In the medical domain, this model could be a digital mock-up of a patent’s heart or brain on which a surgeon is operating remotely. For product realization applications, this digital model is commonly referred to as the “integrated product model” of a new product or process under development.

Components of a complete VR system are, therefore, all related to the creation/storage, manipulation, simulation and presentation of this digital model. They include:
1. a computer-aided design environment to create and store all necessary information about the model on computers,
2. an input device system to enable the human user to manipulate and interact with this digital model naturally,
3. a dynamic simulation capability to generate physically realistic responses of the model under different interactions, and
4. a high-fidelity multi-sensory output system to render and feedback what has been created and manipulated in real time.

In actual operations of a VAR system, these components are used iteratively in a tightly coupled manner to create realistic, real-time sensations for users. Notwithstanding the fact that AR systems generally have less stringent computing requirements than VR systems, we will discuss interactivity, realism and real-time issues such as generic requirements for all VAR systems in the following sections.

4.1.2 Real-time physical simulation

The digital model being created on computers must behave, as much as possible, like their real-world counterpart in order to give users realistic sensations. For example, when a virtual object is being dropped from the air, it must fall naturally according to the law of gravity and bounced realistically according to the law of reacting forces. Should the object be broken during impact, it must break practically the same way as a real object would break. When a user touches an object, he/she must experience the tactile sensation as if a real object were being contacted. Much other related contact issues, such as collision and interference between solid or deformable objects, should also be represented on computers in a realistic manner. All these realistic responses from the virtual objects/events are critical for VAR to be useful in real-world engineering applications.

In theory, computer simulations based on physical principles are the solutions here. However, due to the demands of realism and interactivity, this is a much more difficult task in VAR systems than those traditional simulation technologies can offer. Realism calls for a complete and detailed modeling of the objects/systems and their surroundings, which is very difficult due to our lack of understanding of the physics involved in many real-world phenomena. Interactivity calls for real-time, dynamic simulations of complicated interactions between objects and events, which is not practical in many engineering scenarios even with the most powerful supercomputers available to date. New simulation capabilities, which can balance the realism and interactivity requirements in a highly flexible manner according to domain requirements, are needed in VAR applications.

4.1.3 Natural input device

Compared with traditional CAD/CAE applications, VAR systems must offer users a much higher degree of interface possibilities (e.g., immersive, interactive, intuitive, multi-sensory, real-time, and 3-D) to interact with virtual objects/events within the computer-generated world. Input devices that can interactively, accurately and non-obstructively capture users’ instructions, and then intelligently interpret their intentions, play an important role in any useful VAR systems. Traditional computer input devices, which are based on manual-driven instructions and treat visual, auditory and haptic inputs separately, are inadequate for VAR applications.

The challenges of VAR input devices are many. First, immersive and 3-D requirements of VR suggest that input devices must allow, as much as possible, 3-D input instructions from users. Many traditional input devices, which are mostly 2-D and 2½-D, are inadequate for VR applications. Second, intuitive and interactive VR calls for non-obstructive input methods, such as natural voice, body postures, and even facial expressions, which are difficult to achieve accurately with current computing technologies. For example, automatic gesture recognition (e.g., thumbs-up or thumbs-down may signal certain pre-defined user instructions) enables humans to express their desires within the virtual world in a very natural manner; but this technology is still at its infant stage at the best. Third, multi-sensory requirements of VAR demand that input devices handle visual, auditory and haptic queues simultaneously, which is far beyond the limitation of current technologies.
4.1.4 High fidelity output system

During actual operations, a high-fidelity output system is the critical linkage among all other VAR components outlined above. The general requirements of VAR output systems are similar to those of input devices, namely immersive, interactive, intuitive, real-time, multi-sensory, viewer-centered and 3-D. They must offer realistic graphical, audio and/or tactile feedback of human interactions with the virtual world that generated by computer simulations in a highly interactive manner. Here, high fidelity refers to the ability of VR systems to provide a high degree of human sensation in terms of interactivity and realism. For graphical feedback, this requires a high quality 3-D display device that can render photo-realistic images in real-time. For auditory sensation, 3-D sounds that center on user movements are required. For tactile feedback, it needs output devices to exhibit force, vibration, or even textural feedback from the system. All these requirements are beyond the capabilities of traditional computer output systems that are mostly graphically based.

User-centered, which is the key to immersion, is the most important requirement in VAR output systems. In visual feedback, for example, this requires special devices that can automatically track users’ movements in order to update the viewpoints of VAR images for immersion experiences.

4.2 Overview of VAR Hardware and Software

Because human-computer interaction is the central issue for any VAR applications, all VAR hardware and software are aimed at managing this critical interface between humans and computers. In order to appreciate their potentials and limitations in product realization applications, we include here a brief overview of hardware (computer, tracking, input, and output) and software commonly used in VAR systems.

First, three terms, namely refresh rate, update rate and latency (or lag), which are commonly used in describing VAR system performances, must be explained. The refresh rate defines how often the screen of the display device is refreshed with the same or a new image. Typically, a refresh rate of 72 Hz is required for human eyes to view the images without flickers – an important requirement for VAR realism. The update rate defines how frequently the content of the image is updated on the display device. The update rate is determined by the computing speed at which software is executed. The latency or lag is the time delay between an event occurring and its observation. In a VAR system, the latency can be the time elapsed between a tracker detecting a new head position and a user seeing an updated image rendered on a display.

4.2.1 VAR graphics computers

VAR computers come with all different processing powers and storage sizes, ranging from desktop PCs to graphical workstations to supercomputers. Their processing limitations, however, ultimately determine the scope and complexity of VAR applications they can support.

VR-based interactive games from entertainment industries commonly work on powerful PC-based game machines equipped with multi-media capabilities. These PCs are optimized for interactive graphics, 3-D sounds, and limited 3-D input/output devices. However, their limited processing powers can only give partial immersion with limited realism and interactivity that restrict their applications in product realization. Most VR-based systems in the product realization domain require the power of high-end graphics workstations or supercomputers often used in the simulation industries. These high-power machines are often equipped with specialized multi-channel image generators to produce real-time, panoramic views at high update rates.

4.2.2 VAR tracking devices

The realism of VR comes largely from the system’s ability to update computer images automatically according to changing user viewpoints. This requires tracking technologies to continuously monitor the real-time position and orientation of the user’s head and hands, and sometime the entire body for some applications. The tracking technologies currently used in VAR applications include mechanical, optical, ultrasonic, inertial, and magnetic types each has its strengths and limitations. Latency (or lag) and update rate, which determine the time taken between measuring a position and its availability to VAR software, are most important to trackers. If too much delay is encountered, navigation and interaction with virtual objects could become very cumbersome. An example of an electromagnet type tracking device is Ascension Flock of Birds™, as shown in Figure 3.

Figure 3. Motion tracker - Ascension Flock of Birds™

A typical mechanical tracker is a reverse robotic arm jointed at the shoulder, elbow and wrist. When one end is fixed in space, the position and orientation of the other end is calculated by measuring the joint angles using suitable transducers. This type of tracker has high accuracy and low latency, but its active volume is restricted and its operation is quite intrusive.

Optical trackers use video cameras to record the movement of users by tracking pre-placed markers on their bodies. This type of tracker is not intrusive; but the placement of markers, so that they are always visible from the camera, is not an easy task when complex motions are performed. This type of system can also be used to
trace facial expressions by monitoring the motion of small markers attached to the user’s face.

Ultrasonic trackers employ ultrasonic sound to locate the position of the user’s head and its movements. This type of tracker is simple, effective, accurate and low cost. But it is restricted to working within a small volume (much like seeing a volume of space in the form of a fish-tank inside the monitor), sensitive to temperature changes, and dependent upon line of sight.

Electromagnetic tracking technology is the most popular type in VAR systems to date. It uses a device, called the source, that emits an electromagnetic field, and a sensor that detects the radiated field to determine the position and orientation of the user’s head and hands. The source is often attached to a fixed place in space and the sensor is attached to a head-mounted display or fitted with a 3-D mouse. This type of tracker is non-intrusive, has low latency and no line of sight restrictions. However, its active volume is small (a few cubic meters), and large metallic objects readily distort the magnetic fields, resulting in erroneous head position and orientation readings. As described before, this problem is of great concern to AR applications in product realization where computer-generated images must accurately be projected onto real objects.

Inertial trackers such as gyroscopes can be used together with other motion sensors to make head motion predictions, thus reducing the effective system lag.

### 4.2.3 VAR input devices

A VAR input device must be able to measure all six degree-of-freedom (DOF) movements in space in order to completely control the position (i.e., X, Y, Z displacements) and orientation (i.e., pitch, roll and yaw angles) of virtual objects during interaction and navigation. The input devices commonly used in VR systems are 3-D mouse and data-glove, as shown in Figure 4 (a) and (b). Other more advanced input methods, such as gesture recognition, remain as experimental research tools to date.

![Figure 4. VAR input devices](image-url)

Like 2-D mice commonly used for computer inputs today, a 3-D mouse is a hand-held device with a tracker sensor and some buttons. It is used for navigating or picking objects within a virtual environment. Although most 3-D mice are used for controlling spatial movements, there exist more advanced devices that enable tactile and audio instructions and feedback. 3-D mice exist in different forms such as flying mice, wands, and force balls, each with different design features for various application needs.

With a 3-D mouse, it is hard to accurately capture hand gesture, such as pointing or grasping, which are very natural for human inputs. Data (or digital) gloves are designed for this purpose. A simple interactive glove is made of a lightweight material into which small transducers (e.g., strain gages or fiber optics) are sewn to measure finger joint angles. An additional tracker on the wrist also monitors the position and orientation of the hand. Together, these represent a complete virtual hand within the virtual environment for various manipulation actions. They can accurately communicate hand gestures and, in some cases, even return tactile signals to the user’s hand.

### 4.2.4 VAR output devices

Three main types of output devices, namely visual, audio and haptic, are needed in VR systems. Visual output devices are 3-D graphical displays, which are most popular in VR applications to date. Haptic devices that provide force and tactile feedback are the least developed types of VR output devices. An example that uses mechanical robot arms to provide force feedback is PHANTOM™, as shown in Figure 5.

![Figure 5. Force feedback device - PHANTOM™](image-url)

Display technologies, ranging from 3-D screens, head-mounted displays (HMD), BOOM displays, CAVEs, virtual tables and panoramic screens, are central to any VR system. They offer users different degrees of immersion experiences, and hence have their different application focuses. 3-D screens often require users to wear a pair of polarized glasses to see a sequence of corresponding left and right views of a scene. A typical HMD contains two LCD screens, one for each eye, viewed through infinity optics (i.e., they are collimated to infinity). Since users are completely enclosed within computer-generated scenes that are updated through tracking devices mounted on HMDs, full immersion is achieved. The BOOM display is
a high resolution CRT stereo device supported by a counterbalanced arm. As the BOOM is moved about, joint angles in the articulated arm are measured to compute 3-D position and orientation.

Panoramic screens, which are spherical, are often used in the domes of modern simulators. They enable a group of VAR users to share the same visual experience. However, it is hard to maintain a consistent image quality across the entire screen. Virtual tables use projectors, hidden inside the table, to display the VAR image onto a glass or plastic screen that forms the tabletop. With the aid of shutter glasses and head trackers, a user can get excellent 3-D views. Although two or more people can stand by the table to share a common view, the system is strictly a one-person system. The CAVE display uses several rear projection screens in a 10x10x10-foot cube space that gives a high degree of immersive experience. Although a CAVE is big enough to allow up to 10 people to be fully immersed in a virtual world, only one user is head tracked and wears shutter glasses for stereoscopic views.

The output devices that return force information to users are called haptic devices because they provide some sort of sensory feedback through the tactile senses. Through these devices, it is possible to touch, weight and grasp virtual objects with sensation close to that of real objects. In order to create a sense of touch between the user’s hand and a virtual object, contact or restoring forces are computed to prevent penetration into the virtual model. This involves contact determination, penetration detection and computing the restoring forces. Such haptic feedback is very important for many engineering applications where fine manipulations of virtual objects are often required. These devices should also support natural dexterity, human-scale workspace, and full interoperability with CAD modeling systems. Compared with visual displays, haptic devices are less developed to date.

4.2.5 VAR software
VAR software packages are often called world-building programs, which enable VAR programmers to design the whole environment and objects that a user encounters in a virtual world. A VAR software must take into account, not only the geometric aspects, but, more importantly, the behavioral characteristics of the environment and objects that exist in that world. CAD modeling programs are used to create objects, adding and integrating necessary shape and functional information. Rendering programs are then used to add textures, colors and shadows to enhance the realistic appearances of objects. VAR toolkits, often available as modular libraries of preexisting codes, are used to link these objects and their environment by adding behavioral characteristics such as two objects colliding in space, a car door opening, etc.

Many world-building toolkits are now available with advanced graphical user interfaces (GUIs), enabling people without programming experience to create virtual environments and VAR applications. The user can insert predefined objects, drawn from libraries of 3-D clip art or imported from other CAD programs, and then assign necessary behaviors to the objects. Sound and portals are the two important aspects of interactivity in VAR software. Adding sound to a particular event at a specific time can result in an enhanced authenticity to a VAR experience. Portals allow transitions between multiple environments – an important aspect for navigating through the VAR world. When the user traverses one programmed portal, he/she passes through another connected environment or level within the simulation.

4.3 Human Factors in VAR Applications
Since all VAR systems deal with the human-computer interface, a discussion of VAR technology is not complete without looking into some critical issues of human factors. The brain allows us to perceive the world through our senses, which are the data channel between the physical environment and the brain. All the senses rely on specialized receptors that translate physical phenomena, such as sounds, lights or heat, into nerve impulses that move along the pathways of the nervous system to specific areas of the brain. The visual cortex, for example, is one area of the brain that acts as a complex information processor that transforms nerve impulses into information for the brain to interpret.

A VAR system generates a fully or partially simulated virtual world, presenting it to VAR output devices that change electronic signals into physical phenomena. VAR input devices measure and record physical phenomena electronically, creating digital signals that the computer can process. Together, these VAR devices seek to couple the processing of digital data on computers with the sensory perceptions of the brain.

There are two reasons why human factors are important in VAR applications. First, the sensory input/output signals generated by VAR devices must match well the capabilities and capacities of human sensory systems in order to create a high degree of sensation required by VAR applications. Second, both the positive and negative physiological, cognitive and even social effects of VAR devices on human beings must be carefully understood in order for VAR applications to make useful impacts. Since VR systems require a full immersion of users into the virtual world and a total separation of users from the real world, the human factor considerations of VR are more important than that of AR in practice.

A complete understanding of this subject requires a very deep study into medical physiology that is beyond the scope of this paper. Here we only briefly review three human senses, namely seeing, hearing and touching, which play the most important role in product realization tasks. We then summarize their implications on VAR systems and applications.

4.3.1 Engaging human senses for product realization
To provide the necessary visual sensation, VAR systems use 3-D displays, shuttled glasses and graphical illustrators to mimic critical visual information such as stereoscopic, colors, shadows and shapes. Their basic task is to transform a computer-generated signal into visible light, and to direct and focus that light into the eyes the same way as if the light were reflected from the
physical world. The immersive type of displays cut out all extraneous visual information, helping users to focus on the subject to enhance the visual sensation.

Audio sensation is important to enhance the immersive experiences of the users. VAR systems have high quality stereo sound (i.e., multi-channel sound) devices that use electromagnetic speakers to generate sound waves for human ears. 3-D realism comes from the devices’ ability to carefully track the time delay between sounds for each ear, a difficult task when the users are moving around in space. Headphones provide good sound reproduction while insulating the ear from other distracting sounds from the real world. Automatic voice recognition is also gaining popularity these days as a natural VAR input method.

The tactile ability to touch virtual objects, to feel them vibrate, and to react to their weight, for example, is very important for product realization tasks. Some of the more advanced VAR systems have just begun to explore this type of haptic sensation. Most of the current technologies are being focused on human somatic senses through touch, pressure and vibration receptors. More delicate human senses, such as surface textures, are not exploited yet by VAR systems. Simulation of these tactile sensations is very difficult because it requires a complete understanding of our skin and deep muscle tissue.

In summary, if a VAR system is to be useful in practical applications, it must:
1. Be easy to use from the human factor point of view
2. Accommodate a wide variety of human sizes
3. Not cause fatigue (see next section)
4. Not induce nausea (see next section)
5. Not require long periods of adaptation

4.3.2 Implications for VAR technologies

In a way, VAR systems attempt to use digital devices to trick, fool and cheat human senses. As can be expected, such artificial manipulations of human senses could result in some negative impacts on human physiology, psychology, and even sociology. The effects of these impacts can become more serious as users become more detached from the real world and completely immersed in the virtual world. While researchers have just begun to look into the psychological and sociological effects of VAR systems, physiological impacts on human are known from application experiences.

Motion sickness, for example, is the most common complaint among VAR users. People, who spend too long in flight simulators, especially those systems with panoramic displays without motion platform, suffer similar problems caused by the loss of equilibrium within the vestibule system in our inner ear. VR systems that use fully immersed head-mounted displays can cause the same motion sickness effect because they isolate the users from real world fixed landmarks such as the ground and the horizon. Furthermore, 3-D stereo displays must be aligned correctly. Otherwise, one eye will attempt to resolve these mis-matches, causing eyestrains and headaches and inducing serious nausea. Certain types of images, such as rapid rotations, sudden stops and starts, on immersive panoramic displays can cause motion sickness within seconds. The degree of freedom (DoF) of motion platforms must match that of the visual information presented on the displays of VR systems. Otherwise, our brain will be confused, and nausea will be induced, because the DoF detected by our vestibule system is different from that perceived by our eyes.

The above examples signal the importance of human factors in designing VAR systems for practical applications. From the physiological point of view, visual senses motion platforms are the most important factors to consider because they directly affect human balance. The flight simulator industry has accumulated a wealth of knowledge and experience in this area, and should provide a good base for the VAR industry to consider. The psychological and sociological impacts of VAR technologies should also be studied carefully as we deliver more VR applications to engineering practice.

4.4 VAR Technologies and Internet Developments

The Internet can make the physical distance between anything that can be represented digitally disappear. The next step for VAR developments is networked VAR-based systems that are used by multi-disciplinary teams at two ends. For networked VAR, an important item is latency, which is the delay between the time the action is performed at one end to the time when the action is perceived at the other. No matter how fast we make the networks, the demand for designing increasingly more complex 3-D geometry and increasingly large amounts of data that we would like to transmit will always result in less than desirable performance. The solution must therefore be to look for smarter distributed representations that will reduce visualization latency.

5 USING VIRTUAL AND AUGMENTED REALITY TECHNOLOGIES FOR PRODUCT REALIZATION

Virtual and augmented technologies (VAR) create a virtual environment that can be useful for product realization. In modern manufacturing, a product life cycle consists of the complete cycle of design, planning, manufacturing, delivery, servicing, and recycling. VAR technologies present a new paradigm to affect each of these product life-cycle stages, and to integrate various life-cycle concerns via advanced information technologies. This new paradigm allows interactivity, tele-presence, and collaboration for rapid creation and analysis of virtual product models during the design stage. Planning for manufacturing, the next stage of the product realization process, is made easier through integration of manufacturing knowledge bases and assembly knowledge bases up front into the VAR-based product CAD models. Delivery is greatly enhanced through product data management (PDM) systems that allow companies to work efficiently with their customers [18]. In addition, enterprise resource planning (ERP) software programs allow both the manufacturing planning and the delivery requirements to be tightly integrated. Examples of such software include SAP, BAN, PeopleSoft, etc. Servicing requires activities such as disassembly, which can also be
performed within VAR environments today. Finally, recyclability may also be evaluated and visualized up front within a VAR environment, hence providing the designer with an idea of how the product will be recycled at the end of its life span. Since VAR is applied to the whole life cycle of the product realization process, it allows us to integrate all stages of the product realization process into a centralized CAD database (i.e., the complete product model). While the information-based VAR approach symbolizes the ideal abstraction of a VPR process, this is the holy grail of VPR, the path to which is littered with several daunting research roadblocks.

5.1 Technical Challenges of Virtual Product Realization

The result of applying VAR to product realization is virtual product realization (VPR). VPR involves the virtual generation of product design, product planning, product delivery, product maintenance, and product recycling. The technical challenges within each of these stages are outlined as follows:

Designing – Virtual designing refers to decisions on product shape, product assembly, product material, tolerance, etc., before the product is built, i.e. when the product is still “virtual”. The challenges herein are the representation of product design, creation of a natural interface for interaction between the human and the computer, management of the data and the product definition over the distributed design environments, etc.

Planning/Manufacturing – Planning for manufacturing using VPR involves virtual manufacturing process plan generation, virtual assembly planning, virtual factory floor planning, virtual cost analysis, etc. The challenges in virtual planning/manufacturing involve acquisition and modeling of manufacturing knowledge from the manufacturing shops, acquiring knowledge of assembly, acquiring knowledge of cost, performing market research, so as to input all sets of knowledge with the VAR systems.

Delivery – This involves planning through information systems, delivery of the product through salespersons and finally to the customers. The challenge here is largely a database and data distribution issue.

Servicing – Ensuring that the product is serviceable requires ensuring that the product is easily dismantled/disassembled, is easy to put together again (re-assemblable), is made of material that can be easily handled, etc. VPR for servicing involves disassembly, re-assembly, etc. of product designs, and such analysis can typically be performed in a VAR-based environment. Virtual servicing involves bringing in a large variety of such software tools into the VAR environment.

Recycling – A product is easy to recycle if it can be disassembled and its material can be reused. Virtual recycling is a significant challenge up front at the product design stage. Challenges involve creating sufficient knowledge bases of materials that interact with the product shape/definition to affect recycling.

In all of the above stages, the real world operation must be evaluated, modeled, and then incorporated within the VAR environments. This would involve integration of geometry, material, manufacturing processes, knowledge bases, etc., within a user-friendly user interface.

5.2 How Can Virtual and Augmented Technologies Help Product Realization

In Section 2, we have summarized the different technical challenges of product realization tasks into three types: discipline, time and distance. Having introduced the VAR technologies in Sections 3 and 4, we are now ready to explain how these technologies can help to overcome these challenges.

5.2.1 Helping to bridge the disciplinary gaps

Conventional product realization has often relied on specialization and full separation of the various individual functional units within manufacturing organizations. Designers who create designs typically do not have sufficient information about the downstream manufacturing and assembly needs, and therefore, have less-than-sufficient concern about such downstream consequences. This results in designs being thrown over the wall from design to manufacturing, from manufacturing to assembly, etc. In addition, this also leads to the product designed being returned to the design table for redesign – resulting in a great deal of time wasted and delays from the product conception stage to the final product definition.

VAR technologies allow product manufacturability and assemblability, etc. to be considered and evaluated while the product is still in the early virtual stage. Large manufacturing organizations such as automotive and aerospace companies have realized significant reduction in time delays and design costs for product release from the applications of VAR technologies. Some examples of these will be presented in the next section.

5.2.2 Helping to reduce the temporal gaps

In recent years, with market globalization, coordination of design activities in different parts of the world in different time zones has become increasingly important. Large manufacturing companies now have access to cheaper labor markets, unique material resources and specialized skill sets in different regions and countries. VAR technologies enable such organizations to coordinate and perform round-the-clock product design and configuration, thereby allowing 24-hours worth of work in a 24-hour time span, rather than the traditional 8 hours of work in a 24-hour period. This leads to a significant, three-fold saving in development time alone.

If one were to extrapolate the effect of this distributed and collaborative design approach around the clock, it could reduce an automotive company’s concept to production time from 2 years to 8 months, a time-saving that most manufacturing firms would find highly desirable. The merger of Daimler and Chrysler, and their partnership with Asian automotive firms, for example, could potentially result in such benefits to the product realization process, if proper VAR technologies were to be employed. The
reorganization of the industry is going to result in new opportunities and challenges, many of which relate to the temporal gaps in product realization. All of them can be facilitated through the applications of VAR, databases, and Internet technologies. The CAD systems of today are incapable of handling such complex design activities and transactions across the temporal boundaries, not only because of limitations emerging from database and Internet issues, but also because of the inherently weak drafting-based product geometry representations. Fundamentally new geometry-based and product-based representations are required for such significant development to take place in VAR environments.

5.2.3 Helping to bridge the distance gaps
While VAR technologies allow simulation of downstream manufacturing and assembly concerns within a virtual environment to evaluate the virtual product model, by virtue of the Internet, they also allow the geographical gaps between collaborators to be greatly reduced. A collaborative virtual environment allows designers that are physically separated to share design data, design information, design decisions, design histories, design knowledge, manufacturing process plans, assembly plans, etc. simultaneously or at different times. This is achieved through integrated product data management (PDM) [19][20] – these are systems that are integrated into the VAR systems. Some examples of PDM systems are Matrix-1, Metaphase, I-Man, etc [21][22][23].

The distance gap presents other unique challenges to the field of VAR. In addition to allowing designers at multiple locations to share data and geometry at the same time, collaborative VAR systems can go beyond the particular activity of virtual product realization and integrate it with physical product realization as well. For example, a designer in San Jose, CA sits in a simulated virtual factory, creates a product design, and plans its virtual manufacturing process, while an identical physical manufacturing cell in Tokyo, Japan follows her work and simultaneously performs a physical manufacturing activity such as prototyping with the same part.

Through such combined physical and VAR environments, designers and manufacturers will actually come closer and be able to work simultaneously within these integrated environments. In addition to allowing them to collaborate, such environments would mitigate entirely the negative effects of the physical distance between them. In a sense, it would not matter where they are physically located, and the collaboration would occur in the non-physical space.

6 EXAMPLE INDUSTRIAL APPLICATIONS OF VIRTUAL REALITY IN PRODUCT REALIZATION
VR provides an innovative way of interaction with the computer. It holds the potential to change the way in which humans communicate with the computer. When VR technologies are applied to product realization in industry, they help the user to create, analyze and verify product designs in a simulated environment of the real world. The immersive 3-D environment and natural input/output interface of VR systems provide the user with the ability to interact with the product both effectively and intuitively.

Some common applications of VR include visualization of existing products, visualization for simulation of analysis, and ergonomic analysis in product design:

1. Visualization of product definition: Large organizations such as automotive and aerospace companies rely heavily on certain VR technologies for visualization of design concepts. For example, reviewing the exterior shape of a car can be effectively achieved in a VR environment.

2. Simulation: Functional characteristics of complex products rely very heavily on simulation. One example is crash analysis [24] in the automobile industry. A crash analysis program provides a user with a large amount of data on how the product behaves under a crash situation. Visualization of such data in VR is a natural application of simulation in industries. Other examples are visualization of vibration modes, factory simulation, thermal analysis, etc.

3. Ergonomics: VR is often used for ergonomic analysis where human beings work alongside or within a virtual product. A fully immersive VR-based model of a car can be used to determine the ergonomic merits of the interior with a virtual driver inside [25]. A virtual human operator can be simulated within a VR factory, in which a human being picks and places certain items. Such an application allows the study of unsafe situations in a factory [26].

Specifically, industrial applications of VR in product realization often focus on the following areas: Virtual Design, Virtual Manufacturing, Virtual Prototyping, Assembly and Disassembly Planning, Maintenance Planning, Factor Planning and Scheduling, and Networked Virtual Design for Collaboration [27][28]. In the following sections, some illustrative examples of these applications are discussed. The discussion is not exhaustive; there are many other significant researchers working in these fields.

6.1 Virtual Design
Geometric specifications of a product are created by using a combination of keyboard and mouse input in a traditional CAD system. While the geometric shape designs are 3-D in nature, these traditional input approaches are limited to 2-D devices, such as mouse or digitizer [29]. In addition, interactive 3-D visualization is very limited with those existing CAD technologies. The designer must have a prior idea about the detailed position and orientation of the viewing objects before he/she can manipulate and review them effectively in the design space. These non-intuitive processes make current CAD systems difficult to use for rapid concept design generation and exploration.

A VR-based CAD (VR-CAD) system allows geometric shape designs to be rapidly created on a computer using natural interaction mechanisms, such as 3-D input devices with voice and hand action/motion. In an advanced VR-CAD system, the designer can create three-dimensional
shapes by voice commands, hand motions, and finger motions; grasp objects with his/her virtual hands and move them around; detach parts from assemblies and attach new parts to assemblies. VR input devices enable such intuitive interactions and thereby allow a designer, with a minimum level of geometric experience in using a CAD system, to create concept shapes quickly and efficiently. This is particularly important at early stages of product realization when ideas can be better expressed and captured by simple shapes, rather than words or detailed drawings.

For example, Weimer [30] uses a DataGlove to track hand positions and speech recognition to create a synthetic visual environment for CAD and tele-operation activities. The environment enables a designer to use a virtual control panel and speech in combination with gestures to create engineering parts. The gestures are used to select items from the menu and the speech inputs are used for invoking system commands. The Media Laboratory at the Massachusetts Institute of Technology [31][32] is using three modes of speech, gesture, and gaze that are combined to allow a user to interact in real-time with a graphics display by pointing, looking, asking questions, and issuing commands. The IVY system [33] developed by Kuehne and Oliver allows a user to interact with both geometric and abstract representations of an assembly using a head-coupled display, six-degree-of-freedom trackers, and an instrumented glove. Another system that focuses mainly on hand gestures for design interaction is the PolyShop [34] environment that allows the use of both virtual hands for various tasks within a VE.

Other significant virtual design applications, such as the DesignSpace system [35], allow conceptual design and assembly planning using voice and gesture in a networked virtual environment. The 3-DRAW system [36] uses a 3-D input device to let the designer sketch out ideas in three dimensions. The JDCAD system [37] uses a pair of 3-D input devices and 3-D interface menus to allow a true 3-D design of components. In [38], a 3-D CAD system which performs solid operations and visualizations to support engineering structural design in the virtual environment is introduced. Yeh and Vance [39] combined VR and engineering design to allow effective analysis and optimization of engineering structures. The optimal design of a cantilever beam is presented to illustrate the interactive sensitivity in a virtual environment. The 3DM [40] system describes a 3-D CAD system for use in a head-mounted display for engineering design. It has supports for multiple navigation models: "growing" and "shrinking" to allow work at multiple levels of details - walking (only within tracker range), flying, grasping the world (dragging & rotating).

A particularly interesting research development in the area of creating the first shapes of a product in the product realization process is described in [41][42]. Dani and Chu present a framework for a VR-based conceptual shape design system. They make effective use of VR hardware and software input/output technology to provide an interactive 3-D environment in which the designer can use a combination of hand gesture, voice input, and keyboard to create and view mechanical components. As shown in Figure 6, the user uses the virtual pointing beam to locate objects in the scene and manipulate these objects interactively with two-handed motions and natural voice commands.

![Figure 6. COVIRDS System [42]](image)

### 6.2 Virtual Manufacturing

Virtual Manufacturing derives its roots from the field of Design for manufacture (DFM) which refers to the early consideration of manufacturing requirements and constraints into the design phase of product development. This allows the evaluation of manufacturability of a part during the design stage. Traditional DFM approaches includes technology such as expert systems, feature recognition, feature-based design, and finite element analysis. For example, expert systems, as applied to DFM, are often rule-based programs that check a database of manufacturing rules to analyze the manufacturability of a part. Then, the analyzed manufacturing processes can be applied to the virtual model to simulate the actual manufacturing processes in order to visualize and validate the manufacturability of the part — this is referred to as virtual manufacturing.

Virtual Manufacturing enables the processes of design and manufacture to be brought close together. VR techniques provide a virtual mechanical engineering workshop that can be used to make virtual prototypes using computer-modeling techniques. This creates a safe, interactive environment for capturing enough information to allow the subsequent manufacturing processes, such as numerically controlled milling, lathe, etc. being performed in the virtual environment before the physical prototype is created. The mechanisms and processes of virtual manufacturing are recorded so that these mechanisms and processes can be carried out subsequently on real computer-numerically-controlled machine tools.

A system for DFM, in which the entire virtual machine shop is available to the designer, is under development at the University of Bath, UK [43][44]. Gadg [45] proposed a system that performs Design-for-Manufacturing (DFM) analysis on virtual geometry models via determining the feature interactions on the parts during the design stages.
The Institute for Systems Research at the University of Maryland is investigating a complete DFM system using feature recognition techniques in a research project called IMACS [46] [47]. In a typical CAD environment, the designer creates a design using solid-modeling software, and uses analysis software to examine different aspects of the proposed design’s functionality. The IMACS project is trying to extend this design loop by incorporating a manufacturability analysis system that can be used once the geometry and/or tolerances have been specified. This will help in creating designs that not only satisfy the functional requirements but are also easy to manufacture. For example, the manufacturing information that is determined for the part shown in Figure 7(a) is: 1) It is machinable by drilling and end-milling operations; 2) The best plan requires 13 operations in 3 different setups; 3) The total time required to machine the socket is 31.13 minutes. The setup and operation plans are shown in Figure 7(b). Systems such as the IMACS allow virtual manufacturing to be achieved as a part of the product realization process. Some other researches on virtual manufacturing may be found in [48] [49] [50].

For example, in the Virtual Reality Laboratory at Clemson University, research is being done on the creation of virtual prototyping and on the use of VR to improve the rapid prototyping process [51]. Ford Motor Company used the Division software to create a virtual prototype to simulate airflow under the bumper and to evaluate the effectiveness of the designs [52]. Tseng [53] proposed an approach by combining virtual prototyping with design by manufacturing simulation techniques to support the mass-customization concept. It allows simultaneous generation of manufacturing, materials, costing and scheduling data at design phase. Krause [54] presented a modeling technique, called "virtual clay modeling", based on conventional methods of clay modeling to support virtual prototyping. The system provides the visualization of highlight-lines for shape evaluation, manufacturing of rapid prototyping models and VR interaction approaches to aid in the guidance of modeling tools. Figure 8 shows such a spline-based tool for applying and removing material on the virtual prototype. Some other research efforts on virtual prototyping can also be found in [55] [56].

6.4 Assembly and Disassembly Planning
Design for assembly (DFA) is the evaluating of different aspects of product assembly considerations during the design stage. These evaluations include assemblability, disassemblability, part accessibility, and part layout [57]. All these are closely related to virtual disassembly as they
share many similar concepts and tools. With VR technologies, the users can interact with the computer models in the same way as they would interact with the real models during assembly processes. The user can "hold" different virtual parts in their hands and take them apart or re-assemble them. Problems and difficulties due to assembly and disassembly tasks will be identified and visualized early in the design process.

For example, the Stanford Assembly Automation Tool, STAAT uses the Non-Directional Blocking Graph (NDBG) for contact-based and extended translation analysis of components [58]. The Disassembly Management System, DMS, generates disassembly plans based on an iterative procedure that involves an input disassembly procedure from a user, and successively checks for its correctness based on trivial collision checks [59]. Archimedes determines assembly sequences based on Complete Disassembly (CD) analysis and uses NDBG as the basic structure [60]. A set of CD sequences are generated based on extended contact-geometry analysis [61]. The constraints [62] specified by the user are modeled as a filter [63], so as to generate a feasible assembly plan from the set of CD sequences. [64] and [65] propose manual disassembling/assemblying of components in a virtual environment with trivial collision checks, performed by a computer. [66] proposes a new convex hull based representation of assemblies for geometric reasoning to disassemble the entire component from an assembly.

[67] presents a general framework for virtual disassembly analysis. The A3D system [68] proposes a geometric algorithm to automatically disassemble a selected component from an assembly (defined as selective disassembly) via an approach called Wave Propagation. An example is shown in Figure 9. The user selects a component from the automotive dashboard assembly, and the disassembly sequences are analyzed and then animated in the virtual environment for assembly and disassembly.

6.5 Maintenance Planning

Product maintenance requires the removal of certain components in the assembly for in-place or replacement maintenance/repair. Hence, evaluating those components for disassembly can greatly facilitate efficient product maintenance. Assembly evaluation provides the user with information regarding the feasibility of disassembling the components for maintenance, and in turn the designer may perform design changes to facilitate the ease-of-disassembly for maintenance. As the overall product life cycle costs play an increasingly important role in product realization, engineers have become more aware of the need for incorporating an effective maintenance plan while designing the product.

Maintenance difficulties are often associated with the location of the part that needs to be removed or repaired. There can be poor accessibility for a technician to reach a component to disassemble it, or poor accessibility for required tools to remove the fasteners that attach the component to other components. Another consideration for maintenance planning is the overall cost and time of disassembly and assembly. A virtual model of the product and an operator in the virtual environment can be used to perform, visualize and evaluate feasible maintenance plans in order to determine the cost/time and discover possible difficulties and problems.

The growing importance of maintenance plans in product realization has resulted in a significant amount of research in disassembly evaluation tool development [69] [70] [71] [72]. A disassembly sequence is evaluated either for cost or time, in turn, to assess the product design for assembly and disassembly [73] [74]. Some of the evaluation schemes are listed below. [75] proposes a rating scheme for disassembly based on the difficulty scores of each task in order to determine the overall design effectiveness of a product.

One of the important objectives in achieving VPR is selection of an acceptable design from a large number of choices of Virtual Models of a product. Cost analyses such as the above allow the most cost-effective solution to be selected by a designer during the stages that the product is yet in a virtual form, thereby resulting in rapid convergence to an acceptable yet economical design. [76] estimates the cost incurred by different designs based on Activity-Based-Costing (ABC). The suitability of ABC is explored in the context of design for product retirement. Specific schemes in disassembly evaluation, for maintenance [77] and recycling [78] [79] is also proposed.

A methodology to evaluate a minimum cost sequence to disassemble a selected set of components from an assembly and the applicability of the methodology to applications, such as assembling and maintenance, is described in [80]. Figure 12 shows a virtual human (Transom Jack™ [81]) performing the maintenance work for the car door. Some other researches on maintenance planning can be found at [82] [83].
6.6 Networked Virtual Collaborative Design

With the growing availability and widespread use of high bandwidth networking, there has been increasing interest in network-based collaboration in product realization activities. One such example is the development of tools that permit designers, planners and manufacturers to collectively participate in the design of products and artifacts. Given the increasing trend in which designers, planners and manufacturers are often at different physical locations, it is important to develop tools that facilitate collaboration during all stages of design. A networked virtual environment provides such a tool for all users at many distributed sites to interact with each other and with the shared data, geometric models, and design activities in a many-to-many session from within a common virtual design space.

In collaborative Internet-based CAD [84], a group of people who are involved in the design process, such as designers, manufacturers, and environmentalists, must be able to share data and knowledge in a minimal amount of time. In this scenario the designers need to integrate different components of the product model using a variety of design and analysis programs that can be accessed through the Internet. Minimizing the product design and manufacture lead-time is necessary so that collaborators can rapidly prototype, manufacture and sell the product at a competitive cost. Such collaboration between both the firms designing and manufacturing products is becoming increasingly important because firms must perform specialized activities to remain competitive. This collaboration involves activities such as creation, analysis and assembly of components.

The Internet offers great potential to VAR-based collaboration between a large manufacturer and its various suppliers (Tier-1, Tier-2, etc.). The applications of collaboration can, for example, be in a situation where a large aerospace company such as Boeing subcontracts to its Tier-1 supplier such as Pratt and Whitney, which in turn subcontracts to Tier-2 and Tier-3 suppliers. Connecting an organization with its supplier through the Internet within a VAR can result in significant gains for large manufacturing organizations.

In [85], an architecture for Internet-based CAD is proposed. The client interface (which is implemented utilizing Java and Java3D) to be utilized by the designer can be downloaded. Utilizing this interface, the designer sends a request to a CORBA-based server which forwards the request to the appropriate CAD server; when the server has completed the operation, the results are returned to the client though the CORBA server, as shown in Figure 11.

An important issue of Networked Virtual Collaborative Design is data transfer. Although the Internet now provides the infrastructure necessary for such collaboration by providing means to share CAD data, due to the limited bandwidth available on the Internet, data transfer must be minimized. This is because a typical virtual model of a product can be very large – an engine block 3D solid model can be as large as 100 megabytes. Practical data transfer rates of today over the Internet will allow a file of such size to be transferred in roughly one hour, resulting in non-real time collaboration. One of principal desirable traits of VAR systems is their inherent immersivity that allows designers to feel that they are working closely with the system and with other designers, and real-time interaction becomes essential. Transmitting the raw data is therefore not an acceptable solution in the near future, and therefore other solutions are necessary. Some of these solutions and their research issues are discussed in [86] [87].

7 EXAMPLE INDUSTRIAL APPLICATIONS OF AUGMENTED REALITY IN PRODUCT REALIZATION

As explained before, AR shares similar principles with VR but has a less stringent requirement on computing
hardware and software. As a result, AR systems present many more immediate applications in product realization in industries to date. Some of these applications are briefly summarized below.

7.1 Augmented Design
A standard CAD application consists of a solid and surface geometry generator and editor. Traditionally, such an application requires a desktop computer, a monitor and standard input devices such as mouse and keyboard. In an AR environment, the monitor, mouse and keyboard are eliminated, leaving the user with an empty real desktop. Using AR technology to create new geometry produces the illusion of the geometry on the desktop. Creating a solid block causes the image of a solid block to appear on the desktop; the user can walk around the desktop and see the block from all sides. Alternatively, the user can grab the block at its corner using the 3D locator and turn it around on the desktop. The user can create a hole in the block using an appropriate command and then see through the hole to the other side of the room. Any editing, stretching, dragging and deleting operations work just as in a standard CAD system.

Most importantly, with AR, 3-D indication and visualization become trivially natural. At the same time, other real items on the desktop are visible and readily available, for example, to check how they fit with the virtual object. Other people in the room using the system will also be able to see the virtual object from their own point of view, so that they can naturally discuss and collaborate on the design. Since the user can look in any direction, there is a virtually infinite workspace. For example, a true library of parts can be placed behind the user; when the user looks in that direction, the library is visible and the selection from it becomes simple. Similarly, objects can be stored in a virtual drawer. Another important possibility is to see large parts in scale. For example, a user can design a new chair and see how it fits in a room or design a new building and actually see how it is going to look in the context of the building site. Seeing parts in context is also important for matching purposes. A designed part can be viewed in its final location within an existing assembly, as shown in Figure 12.

Another possible AR application for design deals with variations of existing products. The system can be used to overlay modifications on an existing product on the desktop without needing to model the entire existing part. This approach retains as much of the real and familiar original part as possible; only the modifications are virtual. This option will work best using additive modification. Subtractive modifications can be made as if residing within the part. Modifications can be varied, switched and manipulated just as in any traditional CAD system and can be viewed simultaneously by several collaborating participants. As in the design application, modifications can be seen in the context of their final use and in true scale. Variations to internal decorations can be explored using this option.

The ability to bring the (see-through) display to the working field has tremendous potential. The effect of modifications on an existing design with a computerized representation can now be superimposed onto the real artifact. The medical application of State et al. [88] [89] is yet another example. Other potential users include an architect trying to fit a new building into a city skyline, an artist trying to place a new statue in a museum, or a car designer interested in knowing how a redesigned rearview mirror would adapt to the frontal view of a current car model.

7.2 Augmented Manufacturing
Manufacturing engineers can benefit from AR technology in various ways. As the manufacturing process proceeds and a part is fixed to a machine, the AR application can constantly show the operator the current state of cutting edges and workable surfaces or other critical dimensions as they vary (e.g., the inner surface of a hole as it is being drilled). The AR application could also show the operator the next production step (for example, which segment should be cut out next), with appropriate text and voice annotation (guided manufacturing) projected on the real parts. An AR application could also aid in interpreting a drawing by virtually placing the digital drawing on top of the real part so that the section of the drawing in question appears to coincide with the real part. This enables the operator to focus his/her attention at one location, rather than switching between the drawings and working parts.

7.3 Guided Maintenance
The primary benefit of AR-based engineering maintenance procedures is the option to guide a maintenance person through the precise maintenance procedure sequence in operation and/or training. After the maintained device has been identified and positioned with respect to the technician, the AR computer guides the person by providing text and voice instructions while highlighting relevant internal parts and sometimes animating the required operation. It is clear that this type of augmented on-the-job training (OJT) will significantly reduce training time as well as simplify maintenance-related updates and warnings in dangerous and varying working conditions. An additional important capability relevant to AR-based maintenance is the ability to see hidden parts, such as electric wires or water pipes, as shown in Figure 13.

Figure 12. Augmentation of the final location of a designed part with an existing assembly.
7.5 Augmented Assembly/Disassembly

During assembly and disassembly, the AR computer can instruct the worker regarding which parts to be placed or removed next by highlighting relevant parts, animating operations and providing text and voice instructions. Figure 14 illustrates such an example application. This is especially useful in disassembly since a worker typically must deal with a large variety of models. In-context instruction could significantly improve productivity and simplify update for new models. Furthermore, hidden internal elements that the disassembler cannot see but should be aware of can be highlighted as necessary.

7.6 Augmented Training/Simulation

Engineering training and simulation can greatly benefit from the ability to merge a virtual object with real surroundings. For example, in a simulated manufacturing process, it is possible to place virtual raw material in a milling machine and run the milling sequence. As the simulation progresses, virtual raw material will be removed from the raw object until the final part is obtained. Thus, the correctness of the NC program can be verified on the real machine without the danger and cost of using real material. For training purposes, an operator can use a real milling machine to cut virtual material.

The ability to augment a viewed scene also has potential in educational applications. AR technologies can be used to annotate real scenes, such as naming cities and places in a bird’s eye view of some area or naming mechanical parts in an inspected engine. In addition, important parts of an image can be emphasized, or a student can be guided through a sequence of operations.

7.4 Reverse Engineering

In geometrical reverse engineering, the geometry of a three-dimensional object is modeled by sampling the existing geometry and fitting curves and surfaces to the raw data. It is often difficult to estimate the quality of the current model with respect to the source and to determine whether and where additional samples are required. Using AR engineering techniques, it is possible to reconstruct the object incrementally and point at regions of the artifact that require further reconstruction refinement. Furthermore, the overall quality of the reconstruction could be inspected by overlaying the reconstructed computer model onto the original part so that it appears to reside on top of the existing source geometry. Any mismatch, error or severe deviation will immediately be apparent.

7.7 Augmented Quality Assurance

Quality assurance (QA) is becoming increasingly important in product realization in today’s competitive market. During typical QA procedures, an engineer places a product onto a test bench and executes a series of measurements. The results are compared with product specifications and the part is either accepted or rejected. AR can assist these QA procedures in several ways. The required QA form can be overlaid onto the real product, making any inconsistencies immediately apparent. Critical dimensions can be overlaid on the product, thus facilitating the measurement process. As dimensions are measured, the resulting data can be checked and the result displayed on the product itself, thus eliminating the need to refer to

Figure 13. Maintenance in an augmented engineering environment.

In this scenario, a technician uses an AR environment to visualize internal pipes in the wall and obtain guided drilling instructions. Such guided maintenance also raises the important notion of on-line update. Consider a maintenance person servicing photocopy machines. Years ago, when there were only a few types of photocopy machines, learning to service them was relatively simple. Today, however, the numerous manufacturers and various models make it extremely difficult to keep up-to-date on all possible maintenance procedures. This is a good example of information overload resulted from technological advancements. Through AR, guided maintenance can significantly simplify these servicing tasks by providing continuous updates on-line. The information used by the computer to guide maintenance personnel is prepared by the machine manufacturer and can be continuously updated and distributed via the Internet. The machine also provides an Internet link to be accessed for AR maintenance guidance, thus alleviating the need for various digital instruction panels on the machine because the machine itself directly guides the maintenance. On-line update is also important because it enables the supplier to continuously update maintenance procedures as new problems are reported or new procedures devised. The concept of on-line update from different suppliers calls for further research in the standardization of AR engineering information protocols.

Figure 14. Augmentations of highlighting relevant parts with arrowed instructions.

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external instructions. Figure 15 is an example of such an AR application in QA procedures.

![Figure 15](image1)

**Figure 15. Quality assurance data is overlaid onto a real product**

7.8 Other Related Applications

Many interesting applications of AR technologies can be found in areas beyond product realization. For example, AR technologies are a growing field of interest in medical applications. Medical imaging tools such as CT and MRI can create large 3-D data sets of a patient's internal organs in real time. These data sets can then be used to create a graphic model, which in turn can be displayed in a surgeon’s HMD, allowing him/her an inside view of the patient. Furthermore, image processing techniques can be used to distinguish between different types of tissue in the MRI or CT data, and color these objects in a way that allows the surgeon to recognize different organs more easily than he would with natural vision. This ability is most useful in minimally invasive surgery [11], minimizing the trauma of an operation. At UNC Chapel Hill, for example, the womb of a pregnant woman was scanned with an ultrasound sensor, and a 3-D representation of the fetus was displayed in a see-through HMD [90]. In another project, an ultrasound-guided needle biopsy of a mockup breast used an AR system to guide the needle to the location of a tumor [91].

Military jet fighters are equipped with Head Up Displays (HUDs) that supply registered data, such as artificial horizon lines, target designation boxes, and projectile position estimation, as well as all other critical flight data. Combat helicopters use monocular HMDs for both night vision and weapon designation. Most systems use an optical head tracking device to track LED emitters on the pilot's helmet and reconstruct the 6DOF position from a cockpit video camera. In the near future, similar HUD systems can be used in cars for night vision enhancement, map navigation, or highlighting road edges in poor visibility conditions.

Mechanical head trackers have been used by the military in the past as well. At the Honeywell Technology Center in Phoenix, Arizona, a see-through HMD has been designed for tank commanders to display relevant combat data [92]. At the NASA-Langley Research Center, an AR application using a see-through HMD is designed for F-18 fighter jets [93]. Aircraft flight critical information such as horizon line, pitch ladder, and velocity vector symbol are presented corresponding to the outer world. This display can be viewed in a wide field of view, much wider than with conventional HUD systems. Furthermore, this HMD will display the “energy state” of the aircraft as virtual lines in space, recommending a preferred line for the pilot to maneuver with regard to conservation of his potential energy. This is a good example of how AR can provide virtual data that is not visible in the real world.

8 CURRENT STATUS AND FUTURE CHALLENGES

Using the VAR technologies for product realization applications is a rapidly evolving field of study today. Many achievements have been made; but more joint R&D efforts are needed from both the engineering and computer science research communities. As with the case of any CAE subjects, these joint R&D efforts will lead to much significant advancement for both the tools (i.e., VAR technologies) and applications (i.e., product realization), which is not achievable if pursued separately. The following is an incomplete list of some R&D opportunities for engineers and scientists who are interested in making the VAR technologies a true reality in engineering.

8.1 Human-Computer Interaction

The core challenge of any VAR system is always in human-computer interaction that requires very advanced user interfaces. Most current VAR systems still use mouse/keyboard user interfaces that should be replaced by more advanced hand/voice-based user interfaces with intelligent recognition systems. Some of the important research issues here are the development of robust and noise-free tracking technologies, post-tracking noise filtering technologies, high speed graphics rendering and representation, high fidelity stereoscopic displays, and more ergonomic user interface, etc.

In current VAR systems, head mount display (HMD) devices are the common medium for projecting stereo images into the human eyes. These heavy devices often cause users to feel nausea and headaches. This problem can be partially overcome by a new type of display devices that use a pair of glasses, which weigh a few ounces, to provide direct stereo vision to the human eyes. New lightweight devices, which provide direct stereo vision and one that allows human to easily interact and immerse into the computer's virtual images, need to be developed. One such device that is currently in development uses a laser-beam that is projected directly into the human eye.

8.2 Haptic and Force Feedback

For design and manufacturing engineers to collaborate more effectively and effortlessly within a mixed virtual and physical reality environment, it is desirable to provide a sense of touch to the designer when the manufacturer machines a particular part. The haptics devices of today are rather primitive for two fundamental reasons. First, the human skin has a very large number of sensors per unit area, which renders most man-made haptics devices inadequate in comparison to the high fidelity of the natural
skin. Second, providing a force feedback to a human hand requires, by definition, an inertial system for the feedback effect to be realistic. An example of an inertial system is a six degree-of-freedom robot, the end effector of which could be attached to a finger (an example of this technology is the Phantom by Sensable Technologies). However, if force feedback is to be provided to two fingers, then two robots will be needed and they might interfere with each other. Extending it to 10 fingers on two hands is far more daunting (i.e., requiring 10 robots all of which trying not to occupy the same physical space). This presents a significant technical challenge and opportunity to the engineering discipline as a whole.

8.3 Data Representation

Over the last 25 years, CAD representation has been mostly based on the technology of old-day drafting. However, designers are not draftspersons, and they think at much higher levels of requirements of the product than do draftspersons. In addition, efficient representations for allowing multiple designers to collaborate simultaneously or asynchronously need significant research efforts. These requirements become more apparent in VAR systems and applications. The product definitions and representations need to be significantly overhauled so that the designers can singly or collaboratively work on virtual products. For example, shape representation with respect to topologies, geometry and assembly will need to evolve significantly. In addition, currently CAD systems are limited in the accuracy of the representation. In the aerospace industry, for example, the range of accuracy of part representation can be several orders of magnitudes, which is not possible in today’s VAR system.

Product data management (PDM) system is yet another area that needs major improvements. While significant studies have been made in PDM and data modeling technologies, this field has a long way to go before it become seamless for VAR applications. The recent advent of the Internet also adds to the need for more rapid progress in this field. Fundamental research issues here involve efficient modeling of features on a component design, components in an assembly design, modeling, storage, and retrieval of data information and knowledge about the product.

8.4 Networked Collaboration

As we move into an era of downsizing and outsourcing, product data will have to be shared over the Internet through VAR interfaces. Slicing a complex product definition into smaller individual units that would allow a team dispersed in several different organizations and perhaps in several different countries to retrieve, evaluate, and modify will become increasingly important. The product design environment of tomorrow will have multimodal interfaces, multiple ways of reviewing the product design, multiple levels of representation for the product geometry, and multi-lingual user interfaces to support group design activities. Since collaboration often involves geographically dispersed users, data itself would have to be dispersed over the network at different sites. High-speed data transfer rates become important. For example, Internet II represents a new protocol of network that would allow two orders of magnitude higher data transfer rates than the current Internet. Distributed-database represents the new paradigm of storage for the model of the virtual products. Little has been done in the development of such distributed databases for VPR systems. All of these topics need extensive research and investigation in the future.

8.5 Device Calibration

Calibration between the virtual and real worlds is a critical challenge in all VAR systems, especially for AR applications. For example, while virtual manufacturing systems allow rapid analysis between two virtual entities in the virtual space, the interaction between the virtual and the physical entity is not so simple. Corroborating a physical environment, such as a factory, with its virtual equivalent requires significant research progress in device calibration, reverse engineering based measurements, and metrology.

While mixed reality environments will allow fundamentally new methods of product realization to emerge, they are full of challenges. Virtual worlds created within a computer tend to be idealistic. However, the real world is always constrained by finite accuracy of measurements by devices. Due to errors introduced by noises in the real world, such as electromagnet, Infrared and ultra-violet interference, physical devices are always subject to significant errors. The sensor technology also needs to be improved significantly before such interaction between physical and virtual worlds is possible. For example, while most position tracking sensors in VAR environments are based on electromagnetic signals, on the real factory floor, which forms the test bed of a physical/virtual reality system, these sensors will not function appropriately due to electromagnetic interference. Alternative technologies such as mechanically oriented gyroscopic tracking devices are only available in the prototype stage. Clearly, such developments must be further encouraged. Another example is that of calibrating a virtual machine tool with a real machine tool, such that the designer working with the virtual machine tool can get force and haptics feedback when he/she interacts with the virtual models.

8.6 Robust Technologies

VR devices working in a factory environment in the future will have to be very different from those used in the laboratory setting at the present. Just like the first computer, the first VR devices of the 1970s and 80s were developed and tested within research laboratories. In the 90s, a new set of devices that work within the harsher environment of the factory floor has been developed. An example of such a device is the gyroscopic tracker, which is not affected by the electromagnetic interference typically found on the factory floor. In research laboratories today, one finds a new generation of portable/wearable computers, along with wearable augmented reality systems that allow a human user to interact with a mobile computer attached to his/her waist, for example. The next generation of these devices, which will allow engineers to work within a factory setting, is now under development.
A factory environment is also hostile to wires and cables. Therefore, wireless versions of VAR devices such as the keyboard, mouse, tracker, etc., will be increasingly important in the future. Research challenges in this area include developing sufficient wireless bandwidth for rapid transmission of large amounts of data between the various devices. This will have an impact on the electrical engineering and the communications fields as well.

9 SUMMARY AND CONCLUSIONS

When digital computers were first introduced to the engineering profession four decades ago, no one had anticipated the significant role that they could play in real-world practice. They were too slow, complex, expensive, time-consuming and cumbersome to use in any applications. However, driven by the strong belief in this exciting potential, many engineering and computer science researchers worked tirelessly to break major technological barriers that led to the current great successes. Today, it is hard to imagine any real world engineering tasks that can be performed without the help of digital computers.

History is going to repeat itself for the virtual and augmented reality technologies in product realization. As presented in this paper, many VAR systems are in their experimental stages, and their real world applications are still very expensive. However, the exciting potentials that these technologies have already demonstrated to date are so overwhelmingly convincing that we must not be shortsighted or discouraged by their present limitations. Product development engineers should join forces with computer scientists and electrical/electronics engineers to actively pursue R&D efforts in VAR systems, that will lead to a full success of these new technologies in industrial practice.

It is clear that the marriage of VAR and PR will result in many challenging problems for the engineering (design/manufacturing) and the computer and information systems (computer science/electrical engineering) communities. While we have highlighted some research opportunities, new research areas are expected to evolve continuously as the two communities start to work together in a more collaborative fashion. With further developments in VAR for PR, it is expected that the practicing designer and manufacturer will also need to rethink the way product realization is done. The Information Age allows product designs to be represented, manipulated, transmitted and stored more efficiently on computers. VAR technologies provide a natural interface to make this IT revolution happen. The natural merger of the two will evolve the product realization process into new paradigms of people, resources and organizations distributed in time and space. We are just seeing the beginning of a major revolution that will lead to many exciting possibilities in the near future. The CIRP community has an inescapable duty to take on a strong leadership role in the exploration of these great opportunities.

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REFERENCE


