A Survey of the Virtual Environments-based Assembly Training Applications

Satyandra K. Gupta[1], Davinder K. Anand[1], John E. Brough[1], Robert A. Kavetsky[2], Maxim Schwartz[2], and Atul Thakur[1]

[1]Center for Energetic Concepts Development
Mechanical Engineering Department
University of Maryland
College Park, MD 20742

[2]Energetics Technology Center
La Plata, MD 20646

Abstract

The advent of virtual environments is presenting new ways of training tomorrow's workforce. Virtual environments offer numerous benefits in training applications. First, virtual environments allow extensive user interactions in a very convenient and natural manner. This interaction is greatly beneficial for increasing the user's retention of spatial information compared to text-based or video-based instructions that are non-interactive in nature. Second, virtual environments provide users with a 3D immersive experience. This feature helps users gain a better understanding of spatial relationships compared to 2D displays. Third, virtual environments support multi-media instructions. One can watch standard videos, view 3D animations, view text instructions, listen to audio instructions, and interact with 3D objects in the scene. This paper describes representative research and associated systems that use of virtual environments in assembly training applications.

Keywords: Virtual environments, training, and assembly design and planning.

1 Introduction

Currently, most people train for performing service, maintenance, and manufacturing operations by first studying the text-based manuals and then practicing the acquired skills under the supervision of an experienced trainer, engineer, or technician. After adequately learning the required skills, the trainees take certification tests. This training model has been used effectively in the past and has produced well-trained professionals. However, the costs associated with this training model are usually very high, due to the amount of resources it requires. As we move towards a society with a richer variety of specialized equipment, a highly mobile workforce, demands for instant service, maintenance, and production, and mounting cost pressures, companies need to explore ways to significantly improve training for performing service, maintenance, and manufacturing operations.

Furthermore, due to the rapid influx of new and changing technologies and their associated complexities, accelerated training is becoming a necessity in order to promote and maintain an advanced and educated workforce.

In this paper, we will focus on those training scenarios where workers need to learn a variety of tasks to execute a procedure and require certification in each task before actually performing the procedure. Examples of such learning scenarios include maintenance of complex equipment (e.g., aircraft, power generation equipment, military equipment, etc.), assembly of devices containing energetic materials, as well as "rendering safe" or disarming explosive devices. In these learning scenarios, a mistake made during the actual task can lead to catastrophic failure, resulting in personal injury and/or property damage. Therefore, one must master the task before actually performing it. Furthermore, a single person typically performs a variety of different and unrelated tasks and often does not get an opportunity to perform the same task on a frequent basis. In these situations, certain details of the process may be forgotten over time, and one must go through periodic re-training to refresh the memory of the already-learned tasks. Additionally, some tasks are not repetitive, and one must be prepared to adjust to slightly different situations. These characteristics make training a challenging problem for this class of tasks and require exploring modern digital technologies for improving the training process.

Virtual environment-based training systems are useful tools that can be used to educate and train individuals in an environment that is non-threatening, relaxed, and allows for users to make and learn from their mistakes without consequence. The following is a partial list of advantages to training in a virtual environment:

- It can occur at any time without the need for the physical components or other workers' assistance.
- It does not involve the real components, so cost savings can be realized if practicing the assembly is destructive or detrimental to the components. The need and the associated costs for physical mock-ups are also eliminated.
- It is safe and isolated from industrial and environmental hazards.
- It can be repeated multiple times.
- Individual steps can be repeated, giving the trainee an opportunity to analyze the process from different perspectives and views.

The rest of the paper is organized in the following manner. Virtual environment infrastructure is described in Section 2. Representative virtual environment-based assembly training systems are described in Section 3. Work on the use of virtual environments to in specialized applications is described in Section 4. Finally, Section 5 presents the concluding remarks.

2 Virtual Environment Infrastructure

A virtual environment typically consists of three important parts – display, user interaction devices, and modelling software [Gupta et al. 2008]. This section describes these components.

Display Systems for Virtual Environments: The display for a virtual environment based training system must be able to render a 3D view of a scene in order to mimic reality and provide immersive experience to the user. Depth perception is central to a 3D display system. Typical examples of spatial tasks that are simulated in training could be found in medicine where the human body and surgical instruments are simulated in a virtual environment or manufacturing where assembly, disassembly and maintenance operations are performed. Two common 3D display technologies are head mounted displays (HMDs) and projection based display systems.

An HMD is worn on the user's head and has an LCD display for each eye giving different views to each of the eyes. It provides depth perception using binocular parallax visual cue. The HMD is known for its highly immersive and realistic display. However, often being front-heavy, HMDs may cause neck fatigue. Additionally, HMDs tend to have a greater tendency than projection based displays to cause motion sickness in a certain users.

Among the projection based displays, the 3D wall display utilizes stereo images created by one high frame rate projector or two projectors with polarized filters. Stereo effect is created using passive stereo projection or active stereo projection. In the case of passive stereo projection, the video streams coming from each projector are passed through a polarization filter and viewer sees them through polarized glasses in order to view different image streams for each eye. In case of active stereo projection, the images from a single projector are projected in frame sequential mode. The user wears IR controlled shutter glasses which are synchronized with the projector. One of the advantages of the projection based system over HMDs is that it is less likely to cause motion sickness. Another advantage is that polarized glasses or shutter glasses are light and generally these do not cause weight induced strain on the wearer. Finally, with projection based displays multiple users can view the same scene, though only one person generally controls the perspective.

A CAVE is a special kind of projection based display system that combines images projected on several walls to create a highly immersive view for the user. A typical CAVE system utilizes four projectors and projection screens and can accommodate more than ten users at a time. CAVE is the most effective visualization technique today but its use is limited by its high cost that can run to hundreds of thousand of dollars.

User Interaction Devices: The users usually interact with objects in the virtual environment using some sort of an interfacing device which updates the virtual world. Two common interface devices are gloves and wands. The glove type devices have a glove shaped structure consisting of sensors measuring finger flexure. Such glove based technologies can also often provide haptic feedback in the form of small forces or vibrations. One advantage of a glove based system is that it is a very natural interface which simulates the user's hands in the virtual environment. Glove based interfaces can be very useful in scenarios where users need to be trained in specific motor skills as gloves come close to accurately simulating hand manipulations inside the virtual world. However, these systems can significantly increase the cost and complexity of the system. Glove based technologies are less useful in applications where fine motor skill training is not required.

A wand is usually a remote control-like device with several buttons. Depending on the type of tracking system, sensors or transmitters can be attached to the wand to measure its position or orientation. Inside the virtual world, the wand may control a virtual laser pointer, such that the wand's position and orientation are reflected by the virtual laser pointer. Wand interfaces can be used for spatial manipulation operations of virtual objects. They are generally significantly cheaper than glove based systems. Motor skills, however can not be taught as effectively using these types of interfaces.

Modelling Software: There are two levels of modelling for the virtual environments: geometric modelling and physics based modelling. Geometric modelling involves creating visual representations of real objects in the virtual world and performing geometric simulations (e.g., collision detection). Geometric modelling usually entails creating 3D polygon meshes and then performing shading, texturing, and clipping based on camera view and light sources. This modelling is useful for quick real time visual simulations which do not involve physics-based modelling. Often this level of modelling is sufficient for cognitive training. Motor skill training requires use of accurate physics based modelling. Physics based modelling may range from rigid body dynamics to detailed finite element based modelling.

3 Assembly Training in Virtual Environments

A significant amount of recent research on virtual environments has been dedicated to simulation of spatial manipulation tasks in the context of mechanical design, assembly planning and assembly evaluation. Such applications are often very similar to the virtual reality-based applications designed specifically for assembly training. The primary focus on this work is development of new algorithms and software to support real-time and accurate collision detection, physics-based modelling, and assembly path planning. Recent representative works in this area include Detailed Virtual Design System [Arangarasan and Gadh, 2000], Design Synthesis Virtual Environment [Maxwell et al., 2001], Virtual Assembly Design Environment [Taylor et al., 2000], Multi-Modal Immersive Virtual Assembly System [Wan et al., 2004; Jayaram et al., 2004], Prototyping and Design for Assembly Analysis Using Multi-modal Virtual Environments [Gupta et al., 1997], Modelling of Flexible Components for Assembly Path Planning [Mikchevitch et al., 2003], and Virtual Reality Based Decision Support Framework for Manufacturing Simulation [Banerjee and Cecil, 2003]. The secondary focus in this area is the development of new user interfaces for humans to interact with the virtual environments. Representative work in this area includes [Kim and Vance, 2003; Jayaram et al., 2000]. Other references of interest to spatial manipulation tasks include the following work [Chun and Jiang, 2003; Endo and Takeda, 2004; Mania et al., 2003; Wilson and Peruch, 2002; Holl et al., 2003; Wann and MonWilliams, 1996; Bischof, 2004; Klatzky et al., 2002].

Virtual Environment for General ASsembly, (VEGAS) uses a six-sided CAVE as its platform that is 10 ft. X 10 ft. X 10 ft [Kim and Vance, 2003]. VEGAS uses six rear projected surfaces that make up the walls, ceiling and floor. It uses stereo shutter glasses that are synchronized with the graphics computer to alternately display images for the left eye and the right eye. The graphics computer is a 24 processor Onyx2 Reality Monster, which provides six InfiniteReality2 graphics pipes. A magnetic tracking system is used to track the user’s head and hands. The initial version of VEGAS used a wand; however, the later version used two wireless 5DT Data Gloves.

VEGAS relies on fast collision detection and physics-based modelling. For this purpose, it uses software called Voxmap PointShell (VPS) developed at Boeing. The VPS package converts the input polyhedron model into a voxmap that is made up of small voxels or cubes. The voxmaps are used to perform collision detection and physics-based modelling. Use of voxmaps allows the collision detection software to be very fast, but reduces the accuracy of collision detection. Users pick up virtual parts by using certain gestures and by causing collisions between hand and part models. When a part is picked up, its new location is calculated based on the external force or torque. The external force is a combination of the spring force, the collision force, and the viscous force. The new position is used to update a new spring force and torque. VEGAS allows engineers to analyze assembly paths for part interference and accessibility.

Another virtual reality system called VADE has been developed at Washington State University [Jayaram et al., 1999]. Unlike VEGAS, which uses the CAVE method of stereo display, VADE uses a head mounted display (HMD). VADE uses a magnetic tracking system called Flock of Birds to keep track of the user’s head and hands. It also uses the CyberGrasp glove to track finger positions and provide haptic feedback. A six processor SGI Onyx2 machine uses two Infinite Reality pipes to send stereo image output to the HMD.

VADE assists engineers in assembly design evaluation, assembly plan analysis, maintenance verification, and on-the-fly part modification inside the virtual environment. Physics-based modelling algorithms were developed using friction, number of contacts, and direction of force to allow users to perform fine motor manipulations of virtual parts using one or two hands. VADE's real-time hand-to-object interaction involves checking for intersections between the polygons of a part and the "hair sensors" of the virtual hands. The hair sensors are lines projecting from the triangles of a hand along the triangle normals. The number of hair sensors used can be adjusted based on the computer's processing power. For attachment of parts, VADE uses constraints extracted from the CAD system – ProEngineer. During insertion, a part is allowed to move only along certain axes and planes in order to avoid computationally expensive numerical methods. VADE provides tight integration with the CAD system by allowing certain parameters like hole radius and chamfer angle tagged in the CAD system to be dynamically adjusted inside the virtual environment using menus. In addition to the capabilities mentioned so far, VADE offers real-time collision detection, simulation of dynamic behaviors of objects held in the user's hand, simulation of ballistic motion, and simulation of behaviors of a part that is constrained by a base or container part. Test cases performed with VADE showed that the overall assembly process can be simulated realistically using the virtual environment.

Ritchie et al. developed an immersive virtual assembly system called UVAVU on top of a dVS/dVISE virtual reality system [Ritchie et al., 1999]. The system runs on HP workstation with operating system as UX 10-01. UVAVU could be used in both immersive mode using a Head Mounted Display (HMD) and desktop mode. The default running mode is HMD based immersive mode. The HMD is powered by a graphics accelerator. User moves around in the virtual world using a 3D mouse and manipulates objects and floating toolboxes.

UVAVU provides a virtual platform for users to try assembling the parts and then generates a log of user activity consisting of information about user actions, elapsed time and connections made. This information is used by the system to generate automatic assembly plan. The final pose of all the components are known from the assembly model which is used for snapping the components to final pose even if they are approximately placed by the user. The pilot tests conducted by authors for UVAVU involved three assemblies namely ring assembly, peg assembly and swing assembly chosen from a set of children's toys. The industrial test was performed on a part called printer transport unit for ATM machines. The procedure followed for tests was as follows. First, the assembly was performed in virtual world (UVAVU) that resulted into an assembly plan. This plan was then used to perform assembly in real world. The sequence of operations and time required in each case was logged and compared. Statistical tests suggested that the assembly strategies of user are similar in UVAVU's virtual assembly environment and a real assembly environment.

A system called VEDA developed by Gupta et al. explored the viability of using VR applications to estimate ease of part handling and insertion [Gupta et al., 1997]. VEDA offered a multi-modal virtual environment with visual, auditory, and haptic senses given to the user. VEDA employed two PHANTOM 3D probes (6DOF mechanical trackers) for interaction with the virtual environment and StereoGraphics CrystalEyes shutter glasses for stereo viewing. A Silicon Graphics Indigo Extreme computer with a 100MHz processor was used to run the application. The PHANTOM devices were used to track two points representing the user's index finger and thumb and for the force feedback. VEDA analyzed how users carried out a simple "peg-in-hole" task in both the virtual environment and the real environment. This work was limited to investigating interactions between two-dimensional polyhedral objects. Users were asked to insert pegs into holes inside the virtual environment and in a real environment. Using time of assembly as the main performance measure, this research found that trends in the variation of assembly time with parameters such as friction, chamfer, clearance, and handling distance were the same in the real world and VE. Specifically, assembly completion times in the virtual environment conveyed subtle differences in clearance, handling distance, and other parameters.

Yuan et al. describe an augmented reality (AR)-based system [Yuan et al., 2005]. Many augmented reality systems in use today require sensor systems or markers in order to keep track of the components being used and ultimately track the progress of the user within the assembly sequence. They propose an AR system with a predefined, easily accessed assembly sequence that uses a unique technique to track an interactive pen used to access the assembly data, all without the assistance of markers or sensor systems. The proposed system features a virtual interactive tool, which hosts virtual buttons that provide meaningful assembly information in addition to a visual assembly tree structure (VATS) to manage information and access assembly instructions.

The input device of the proposed system consists of an interactive pen featuring a segmented image map and an interactive point extracted as the input device. Using a neural network, the Virtual Interactive Panel is able to visually track the position of this interactive pen, which allows the user to select virtual buttons (by holding the interactive point on the pen over the desired button) that assist in the assembly process without the need of any sensing devices. These virtual buttons are capable of accessing different directories within the VATS so that users can obtain additional information concerning a specific assembly step. The VATS is composed of organized, predefined instructions that allow the user to start the assembly process from the beginning or access data referring to specific parts and subassemblies. Authors have used the assembly of a 'fun train' in order to demonstrate the AR system using both HMD and desktop configurations. Yuan et al. have demonstrated that it is possible to create a functioning AR system that does not need object markers to guide the user through an assembly task. With further development of the Virtual Interactive Panel software, the possibilities for AR training without the need for sensor systems make it a prime candidate for complex assembly procedures where numerous markers make the standard AR approach too difficult to monitor.

Gupta et al. have developed a personal virtual environment (PVE) based virtual assembly system called Virtual Training Studio (VTS) [Gupta et al., 2008; Brough et al., 2006; Schwartz et al., 2007a-b; Brough et al., 2007]. This system mainly focuses on the cognitive aspects (e.g., ability to recognize the correct part, correctly orienting the part in space, remembering the right assembly sequence). The PVE consists of a head mounted stereo display with head tracking and wand for user interaction. This PVE gives the user a complete 3D immersive experience during virtual assembly. The VTS aims to improve existing training methods through the use of a Virtual Environment based multi-media training infrastructure that allows users to learn using different modes of instruction presentation while focusing mainly on cognitive aspects of training. They have conducted a detailed user study involving 30 subjects and two tutorials to assess the performance of the system. During the first study involving a rocket motor, overall 94.4% steps were performed correctly by the users during the physical demonstration after completing the training. During the second study involving a model airplane engine, overall 97.3% steps were performed correctly by the users during the physical demonstration after completing the training.

Lim et al. reported the influence of haptic feedback on the user performance in the context of virtual assembly [Lim et al., 2007]. The authors conducted their study on performance of users in case of peg-in-hole kind of assembly insertion operations. The experiment performed in this research studies the effect of rigid body dynamics, stereo display and haptic feedback technologies on time taken to perform six different assembly operations in a virtual environment. The six assembly operations chosen were combinations of technologies used and geometry of hole and peg. The haptics was implemented using Sensable Technologies' OpenHaptics toolkit, stereo visualization using VTK Kitware's visualization toolkit and dynamics using Aegia's PhysX physics engine. The users were asked to perform the same set of tasks in virtual as well as real environment. The statistical significance tests on the results obtained from above experiments suggested that the haptic feedback does affect the user performance when geometries such as chamfer are present. Based on their experiments authors conclude that the haptic and stereo technology can improve the user experience by enhanced tactile and visual feedback. Authors note that computationally expensive collision detection and dynamics computations can slow down scene refresh rate.

4 Specialized Applications

He et al. have developed training system for maintenance of STEs (special type equipment), which may include explosive or hazardous materials [He et al., 2003]. In this work, three goals are established for their system. The first goal is to provide an immersive training environment. The second goal is to act as an operational tutorial and dynamic aid for assembly/disassembly processes. The third goal is to provide force feedback in the virtual environment to allow the user "a kinesthetic sense of when he/she interacts with the virtual object." In order to accomplish these goals, the authors have described the groundwork and features necessary to develop such a system, which include an intelligent kinematics modelling system, a VE manager capable of hosting and categorizing interactions with the user, and an operation monitoring system capable of identifying difficulty with the assembly/disassembly process and providing the appropriate dynamic cues to assist the user.

The proposed kinematics modelling system works by dividing the part motion into two kinds: the motion controlled by the user's hand and the uncontrolled motion such as dropping or sliding an object. The virtual environment manager described by the authors is responsible for defining the assembly relations and the correct order for the assembly/disassembly process in order to assure the validity of the training program. In order to provide the trainee with feedback and assistance during assembly sessions, the VE manager also includes the ability to detect the recurrence of incorrect assembly/disassembly motions by comparing them to a predefined set of ideal movements and to act on them by providing the user with some type of dynamic cue (video, audio) to help the trainee correctly complete the task.

Andre et al. describe a training system for aircraft maintenance training application [Andre et al., 2003]. The initial system is called Virtual Environment Safe-for Maintenance Trainer. This system provides apprentice technicians with an opportunity to practice maintenance procedures associated with F-15E model aircraft. This system decreases the use of actual aircraft in training and hence creates new training opportunities. The system enables interactive experiences with front and rear crew stations, weapons stations, and the ground. The system evaluation results have indicated that improvements should be made in the areas of graphical representation and the joystick pointer. These improvements are planned to be incorporated in the new version of the system called Generalized Operations Simulation Environment.

Badler and Allbeck describe a system called Advanced Visual and Instruction Systems for Maintenance Support [Badler and Allbeck, 2006]. This system explores the use of an HMD, wearable computers, new input devices, and augmented reality software in a training application. As a part of this system, instructions are generated from expert demonstrations. First, expert performance is captured via multi-media during demonstrations. Second, multi-media tracks are interactively cleaned up to generate task segments. Third, individual task segments are linked to entries in a parameterized action representation database. Fourth, parameterized action representations are returned as output for the interactive presentation. Finally, instructions are presented to the user via interactive manuals, augmented reality, or virtual reality.

Ritchie et al. reported application of virtual reality in 3D cable harness design and installation planning [Ritchie et al., 2007]. The authors discuss the application of HMD as an enabling VR tool for creative design of cable harness. The design of cable harness when performed in virtual world is logged for future analysis. The findings of this research shows that it is possible to design and plan the assembly and installation of cable harness in immersive virtual environments using HMDs. Also, a wide range of cable harness designer's activities performed in virtual environment is examined, categorized and measured. This analysis of design activity has provided a more detailed understanding of design methods in this domain and a detailed outline of which aspects of VR are being used and where to focus future system development effort to improve performance.

5 Conclusions

The advent of virtual environments is presenting new ways of training tomorrow's workforce. The studies presented in this paper point out numerous benefits of virtual environments in assembly training applications. First, virtual environments allow extensive user interactions in a very convenient and natural manner. This interaction is greatly beneficial for increasing the user's retention of spatial information compared to text-based or video-based instructions that are non-interactive in nature. Second, virtual environments provide users with a 3D immersive experience. This feature helps users gain a better understanding of spatial relationships compared to 2D displays. Third, virtual environments support multi-media instructions. One can watch standard videos, view 3D animations, view text instructions, listen to audio instructions, and interact with 3D objects in the scene.

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