Industry case studies in the use of immersive virtual assembly

Sankar Jayaram Uma Jayaram Young Jun Kim Charles DeChenne

VRCIM Laboratory, School of Mechanical and Materials Engineering
Washington State University, Pullman, WA

Kevin W. Lyons	Craig Palmer	Tatsuki Mitsui
NIST	PACCAR Technical Center	Komatsu Ltd.
Gaithersburg, MD	Mt. Vernon, WA	Japan

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Abstract

In this paper we report on two engineering case studies that have been conducted as part of a Virtual Assembly Technology Consortium. The objectives of the case studies were to determine if immersive virtual assembly capabilities allow industry assembly situations to be modeled and studied realistically, and to demonstrate the downstream value of the virtual assembly capabilities in areas such as ergonomics, assembly installation, process planning, installation, and serviceability. What is of special significance is that instead of modelling simplified problems or perceived representative situations, the case studies were constructed from actual assembly floor projects and situations encountered at industry member sites and with considerable participation from industry engineers and manufacturing shop floor personnel. Based on the success of the case studies, the consortium members inferred that virtual assembly methods are poised to move out of the realm of special projects and test scenarios to deployment in the actual design and manufacturing cycle. However, in order to be truly accepted in industry, there are still issues to be addressed in terms of ease of use, portability of the applications, and preparation of the models for the evaluations. Thus, the case studies added a new dimension to the exploration and understanding of how this new technology could be of practical value in industry.

Introduction

An engineering case study is defined as an account of an engineering activity that contains some of the background and complexities actually encountered by an engineer and that reflects the engineering activity as it actually happened [1]. The major objective of an engineering case study is to provide a medium through which learning can take place and be applied. A good case study is taken from real life, consists of one or more parts with each part usually ending with problems and/or points for discussion, and includes sufficient data for the reader to treat problems and issues.

The Virtual Assembly Technology Consortium (VATC) was founded in January 2001 with four industry leaders in mid-size/large scale mechanical systems, one government agency, and Washington State University. The consortium is aimed at bringing together industry, government agencies, and universities to address research and deployment related to the use of virtual reality, digital prototyping, modelling and simulation, and visualization techniques to plan, evaluate, and verify assembly processes for mechanical systems. The primary focus is on mid-size/large scale mechanical systems (including automotive, aerospace, earth-moving, and machine tool equipment and their components). One of the goals of this consortium is to perform case studies using virtual assembly and assist consortium members in demonstrating and validating these technologies and tools.

This paper describes in detail two case studies that were performed with VATC industry partners. The first case study was a large press machine assembly scenario to determine if virtual assembly simulations allow realistic modelling of factory floor assembly situations. The second case study was aimed at demonstrating the use of virtual assembly simulations for ergonomic simulations and was focused on the assembly of a fifth wheel assembly onto a truck chassis. These two case studies were part of a larger set of case studies and hence the other case studies are also briefly described.

Background

Initial engineering applications of virtual reality concentrated on providing methods for three-dimensional input and stereoscopic viewing. However, over the past few years, several advanced applications have provided functionality way beyond this and have changed the engineers' perspective of the product development process. These applications span from conceptual design to manufacturing simulation and maintenance assistance. Many of these applications have been fielded with varying degrees of success by industry. This section describes a small sample segment of applications to provide a background to the work presented in this paper.

In vehicle design, operator visibility and operator interaction with devices, switches, and knobs are critical aspects of the final product. Physical prototypes are often built so that users can interact with the vehicle to evaluate placement of these devices. The careful use of immersive environments reduces the number of physical prototypes that are required. An intermediate step, short of developing an immersive virtual environment is the use of computer models of articulated humans, which are programmed to interact with the digital product models. There are several software packages available on the market such as JACK™, DI-Guy™, SAFEWORK®, and RAMSIS™ [2-5]. Using this software, the models are displayed on the computer monitor and moving the viewpoint is accomplished by moving the mouse.

Moving the joints and limbs of the human are accomplished using the mouse and keyboard. JACK™ provides important but limited support for the use of tracking devices in conjunction with the simulated human model. For example, it is difficult to simulate a person leaning out the window of a vehicle cab and flipping a switch at the same time using these computer models. None of these applications satisfactorily allow the user freedom to move in the digital environment using natural human motions. Immersive virtual environments provide this interface. Instead of programming a virtual human, applications can be written where a human interacts with the digital models in a fully immersive application [6].

Virtual assembly applications have been widely used for verifying and planning in mechanical assembly. Ritchie et. al. have developed a virtual assembly planning system for assembling and disassembling parts and modules in a virtual surrounding [7]. Sun et al. [8] developed a framework of a two-handed virtual assembly application. They used the system for the interactive task planning of assembly application. Several researchers have attempted to develop virtual assembly applications with force feedback devices [9-11]. Seth et al. [12] developed SHARP (A system for haptic assembly & realistic prototyping). This system uses physical-based modelling and a dual handed force feedback device capability in order to assemble components in the immersive environment. Wan et al. [13] developed grasping patterns for virtual assembly tasks. They experimented on assembly models and showed that their algorithms worked well for the virtual assembly application. Factors that influence the efficiency of assembly, namely, assembly method, assembly sequence, and assembly time have been examined by Choi et al. [14].

Bullinger et al. [15] at Fraunhofer have shown the advantages of concurrent engineering and the development of *right first time methods* such as virtual assembly planning and virtual ergonomic prototyping. Yeh et al. present a virtual environment for the evaluation of results from a finite element analysis application [16]. In addition to investigating stress contours, the application provides the ability to change the shape of the part and examine the resultant changes in the stresses [17, 18]. Oliver et al [19], working with Deere and Company, placed a virtual front-end loader in an immersive virtual environment. Other successful virtual ergonomic applications include interior design evaluation [20, 21].

A scalable virtual reality application (VR Juggler) has been developed at the virtual reality application center at Iowa State University [22, 23]. Another scalable virtual reality application is Device Independent Virtual Environments- Reconfigurable, Scalable, Extensible (DIVERSE) [24]. This application has been developed at Virginia Polytechnic Institute and State University. Both VR Juggler and DIVERSE provide their own Application Programming Interface (API), which makes it easier for developers to create new virtual reality applications.

Advanced visualization, virtual prototyping, and human CAD systems can provide the engineer with unique perspectives on design and manufacturing problems. These perspectives, when used together, can provide better insight into product design.

VADE - Virtual Assembly Design Environment

In this section we describe the immersive virtual assembly tool used for the case studies presented in this paper. The tool is called VADE (Virtual Assembly Design Environment) and has been developed at Washington State University. It was one of the first of its kind, with the first functional prototype being available in 1995 [25], and is now a fairly mature and well-known tool. There are several papers with details of VADE [26, 27]. However, a brief overview will be provided here to support the case study descriptions.

VADE includes several key capabilities of an immersive virtual reality system. It supports stereoscopic viewing, tracking, and user interaction. VADE supports two-handed assembly. When the user selects a part, the constraints belonging to that part are loaded. These are visually represented by planes and axes on the component that was picked and the corresponding component to which it needs to be assembled. When the user matches a plane or axis on each of the components, the part becomes constrained, and will no longer move in the direction associated with that plane or axis. When a part is partially assembled on the base part and then released, a combination of collision detection, gravity-based motion, and constraint-based motion is used to simulate realistic motion of the part [27]. This allows the simulation of sliding, swinging, and also sliding and swinging simultaneously. Parts follow free projectile motion when dropped by hand, thrown by hand, or when they are free to fall without other parts or environment objects obstructing their path. If the user should let go of the part, gravity will take over and move the part along any unconstrained planes or axes in accordance with the laws of physics. Although the software does not use collision detection in performing assemblies, collision detection is available to aid in identifying interference problems or incorrect assembly paths.

The VADE software has the ability of extracting the assembly information from the CAD model. This information is then used to build a constraint database, which is then utilized in real-time while running the VADE program. The surrounding environment can be created using any user-preferred method. For example, any CAD system can be used to model the geometry of the environment and export the triangulated model. Texture maps can be defined for these environment objects. VADE allows limited parametric modification of parts while in the virtual environment. These parametric changes are communicated back to the CAD model, updated in the CAD model and the geometry sent back to VADE in near real time. For larger parts that cannot be assembled with just two hands, a crane allows users to simulate the manipulation [28]. Parts can be attached to the crane by specifying one or more attachment points interactively. Pendulum equations simulate the motions of parts being manipulated by a crane. Algorithms have been implemented to allow a person to push a part to turn it while it is attached to the crane.

Thus, important functionality has been developed over the last 13 years, some in consultation with the VATC industry and government partners. It was important to put the virtual assembly environment to the test and see how it performed in real-world industry strength case studies [29].

Methodology for case studies

The overarching goals of performing the case studies were two-fold: determine if the immersive virtual assembly capabilities allow realistic modelling of industry assembly situations; and demonstrate the downstream value of the virtual assembly capabilities in the product realization process. Some potential areas for this are ergonomics, assembly installation, process planning, installation, and serviceability studies.

The methodology followed for each case study was as follows:

- *Information gathering and analysis of the real assembly process* - Study the provided video of the real life assembly, visit the sites to observe the real-life assembly situation, and analyze assembly process documentation.
- *Scoping and identification of the specific assemblies to simulate and the process of assembly* - Discuss the desired simulation with the engineers and managers. Select the components to be simulated from the overall scenario. Identify the process for the assembly.
- *Model and environment preparation* - Obtain CAD models of components to be simulated, if needed re-organize the as-designed CAD assembly tree to reflect the as-manufactured assembly on the factory floor, and then export the data from the CAD system to the simulation application. Prepare the environment.
- *Replication of assembly process in the simulation environment* - Set up the initial location of the components in the environment. Perform the assembly using the immersive virtual assembly environment and go through the scenario.
- *Analysis of case study evidence* - Analyze the results of the simulation and identify the differences between simulation and the real-life assembly. Gather problems and issues and discuss lessons learnt. Analyze the capabilities of the immersive virtual assembly technology in simulating real assembly processes at sufficient detail for supporting engineering decisions and in providing support for the ergonomic and assembly analysis of the processes.

Case Study 1: Assembly of a large press machine – Evaluating Modelling and interaction realism

This case study involved assembling the components of a large press machine for a company that manufactures construction, mining, and heavy industrial machinery. In many cases, because of size and transportation issues, several stages of final assembly are performed at the customer site. Thus, in addition to fundamental assembly planning issues, in order to be adequately prepared, the unique environments and constraints of each customer site also need to be considered on a case by case basis. It is not enough to have a generic environment in which the assembly planning is performed and checked.

In the traditional method of evaluating the assembly process, design section personnel, manufacturing section personnel, and customer-site personnel would meet together to discuss the assembly process. Attempts to solve assembly problems would be done using two-dimensional (2D) drawings of the assembly and site sketches. In some cases, this method does not effectively address the concerns. The design meeting attendees do not have enough information or access to relevant applications to readily perform tasks such as calculating the total weight of a sub-assembly, checking whether there is enough space to locate the parts at the customer site, and determining whether collisions will occur between parts and equipment. Because of this lack of information and resources, it is possible that manufacturing engineers cannot effectively address identified problems or anticipate potential problems. Even if they do find a problem, they may not be able to suggest an effective change to the design or be able to communicate it immediately. After several iterations, once all parties agree on the changes and a proposed change is accepted, hand drawings and sketches are made of the suggestions. It usually takes two to three days to incorporate these formally in the 2D drawings. Another meeting is usually held to check whether this is acceptable and if there are any other problems.

The usage of an immersive assembly environment in this scenario is expected as follows. Manufacturing engineers would create a tentative assembly sequence and the customer site environment in VADE. They would do a preliminary evaluation and identify potential problem areas. During the meeting with the various personnel, VADE would be used to perform the assembly simulation with special emphasis on the specific junctures in the sequence that seem to cause problems. VADE allows all meeting attendees to easily visualize the situation and propose solutions. Parametric changes to the models used in VADE can be made from within the virtual environment through a feedback loop with the CAD system, and the assembly sequence can be easily changed by the sequence organizer. This provides a tool for identifying problems, proposing solutions, and evaluating the solutions in a single meeting.

For the case study, the overall methodology described in the previous section was used. The key steps are described in detail here.

Information Gathering and Analysis of the Real Assembly Process

The video provided by the company and the assembly process documents were analyzed to obtain a reasonable assessment of the assembly scenario. The consultations with the engineers provided additional assistance. The immense size and complexity of the large press machine (Fig 1) made it a challenge to map the components in the video to the components in the Pro/E models provided. It was also difficult to assess the human interaction with the objects. Numerous personnel were working in conjunction to assemble the components together. Their individual interactions with the objects were sometimes hard to identify, due to the fact that some of the workers were hidden behind the very large components. A summary of the actions that were observed are listed (Table 1).

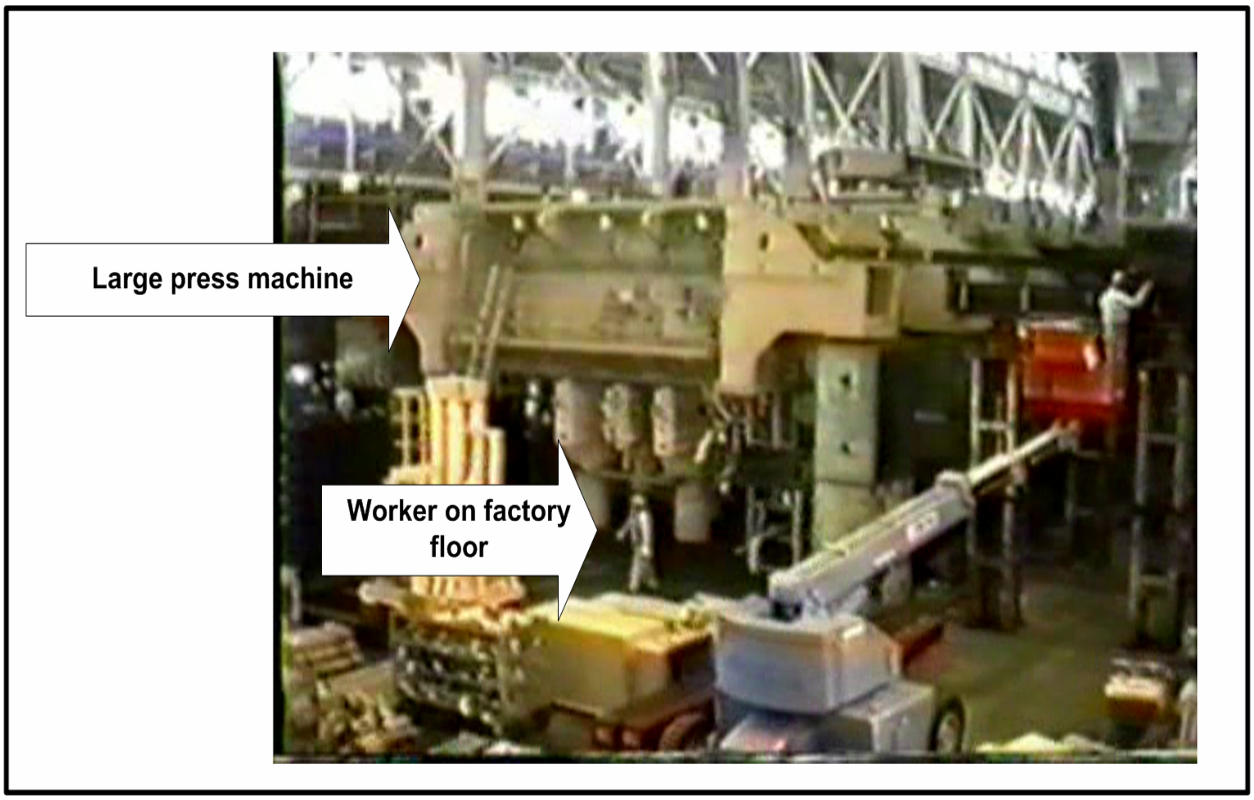

Fig 1. Relative Size of Operator and Large Press Machine

Sample of scenarios and actions that need to be supported	**Level of support by VADE**				
	Fully supported	**Can be implemented with minor changes**	**Can be implemented with major changes**	**Difficult to implement**	**COMMENTS**
Parts to be assembled are located on top of blocks	X				
Part is attached to a lifting beam		X			Part is only attached to a large hook in VADE
Attach the base part to crane using eight attachment points and a cable		X			VADE supported only four hanging points
Assemble nuts and bolts with hand (loosely)	X		X		VADE supported the insertion of a bolt and then the attaching of a nut. Major changes will be required for using two hands simultaneously for two components being attached to the base part and to each other–.
Place a part on the base part and assemble bolts	X	X			Minor changes will be required to allow a person to use both hands to pick up parts simultaneously– one to hold the part in place while the bolt is put in place
Personnel standing on parts and reaching		X			VADE supports a full human model. Collision detection can be used to implement this capability
Medium size parts attached to the crane hooks swing in front of the worker	X				
Lower these parts and place them in the appropriate place	X				
Perform “high wire” act in tight areas	X				
Move the part to a desired position	X				
Use a hammer to drive a part in place	X			X	A visual simulation of swinging of hammer is fully supported. True simulation would be difficult without force feedback and tolerance issues.
Lower big heavy parts and place them appropriately on the base part	X				
Worker waves off the crane operator	X				

Table 1. Sequence of Tasks in Assembly Process

Scoping and identification of the specific assemblies to simulate

The assembly provided was composed of a large number of sub-assemblies in Pro/Engineer (Fig 2). Specific sub-assemblies and components were selected for testing, with eight identified as the key components in the assembly simulation.

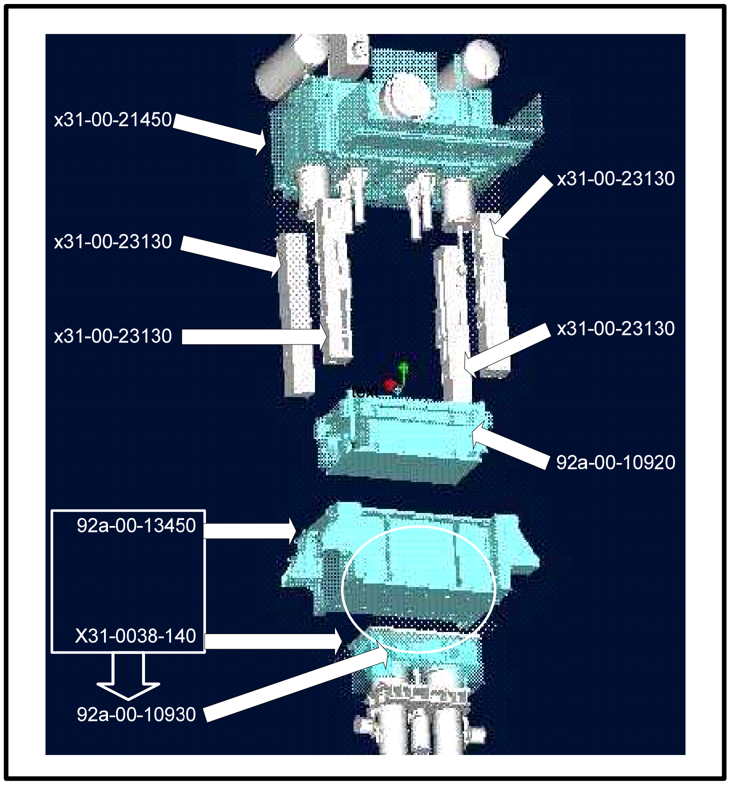

Fig 2. Exploded Pro/E Assembly Model X31-00-21440 of Large Press Machine

Model and Environment Preparation

The CAD to VADE extraction module (Pro/VADE) was used to extract the assembly hierarchy, assembly constraints, and polygonal models of all components from Pro/E.

The assembly hierarchy from Pro/E had one main assembly (x31-00-21440), which contained several sub-assemblies and individual parts at the top level of the assembly. The left half of Figure 3 shows the assembly tree reported by Pro/E. The assembly process provided by the engineer indicated that the sequence needed to be re-organized before being used in VADE. *This was a classic case of the as-designed assembly hierarchy being different from the as-manufactured hierarchy.* The sequence was re-ordered using the tree re-organizer [30]. The resulting sequence is shown in the right half of Figure 3. Note that some sub-assemblies and parts have been removed from the list shown because of the large tree size. In the VADE Assembly Hierarchy, any assembly past level 2 is pre-assembled for use in VADE.

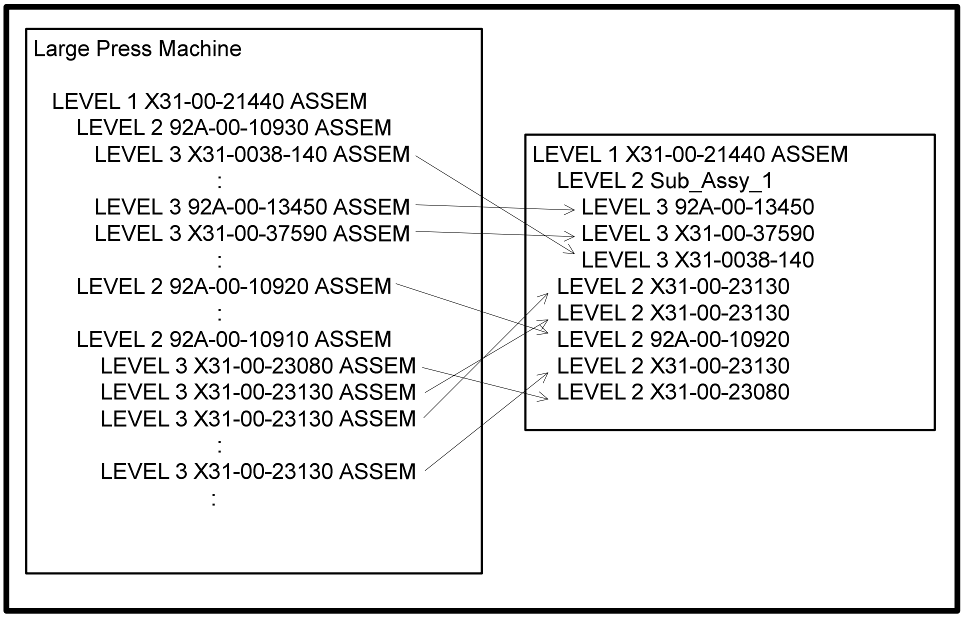

Fig 3. Comparison Between Pro/E Assembly Hierarchy and VADE Assembly Hierarchy

A factory environment that replicated the physical factory was created. Architectural drawings and pictures of the actual factory were used to quickly create the relevant geometry such as walls, floor, pit, and ceiling of the factory using Pro/Engineer. The model was then exported to VADE as triangulated data. The environment was texture mapped with images from the actual factory. A crane was also a part of the environment since the human/crane interaction is vital in predicting problem areas and object movement (Fig 4). The components were located correctly to show the initial position at the start of the simulation.

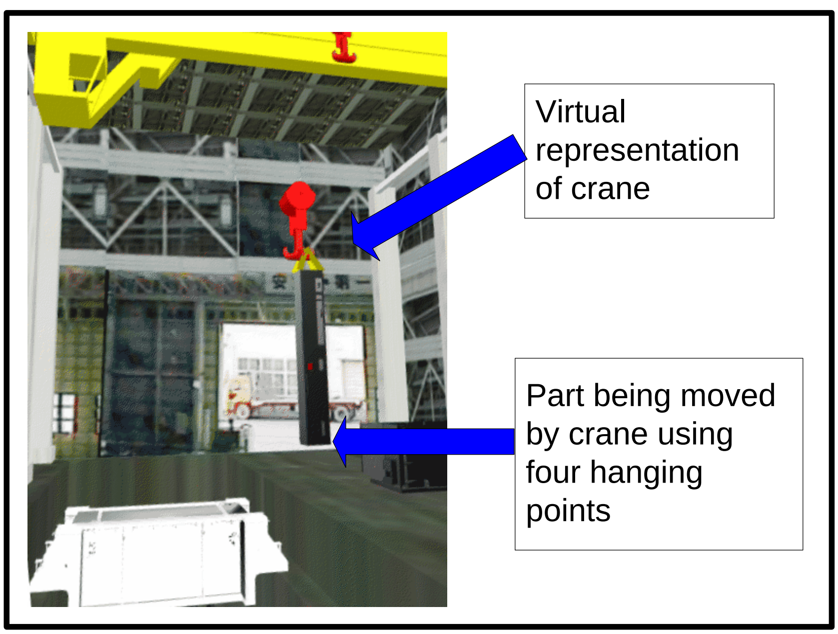

Fig 4. Environment Modelling

Replication of assembly process in the simulation environment

After all the components were located properly and the environment was finalized, the assembly process in the video was simulated in VADE. The assembly process followed by the operators in the factory was as follows (Table 2):

	In Real Factory	**In VADE**
Step I	Part 92a-00-10930 was moved from the cinder blocks to the pit.	Part 92a-00-10930's initial position was located in the pit (since this was the base part in VADE)
Step II	Crane and human manipulation were used to attach parts x31-00-23130 (4x) and 92a-00-10920 to part 92a-00-10930	Each of the four x31-00-23130 parts were attached to the crane using four hanging points inserted at the end of the column (Fig 3)
Step III	Part x31-00-21450 was picked up with the crane with eight hanging points and moved in an L-shaped path to its final position. The part was then lowered and attached to part x31-00-23130.	Part x31-00-21450 was picked up with the crane with four hanging points and moved in an L-shaped path to its final position. The part was then lowered and attached to part x31-00-23130

Table 2: Assembly Steps in Real and Virtual Environments

Analysis of case study

The case study was performed entirely by a manufacturing engineer from the consortium member company. This engineer has the responsibility for planning, evaluating, and implementing the assembly processes for press machines and for creating information used to train the workers who will be performing the actual installation. The results and conclusions are based on the feedback, comments, and internal reports of the engineer.

VADE successfully completed the segment of the assembly of the large press machine that we set out to model and simulate in the immersive virtual assembly environment. A separate study was conducted to verify the accuracy of the crane model and the physics behind the crane simulation [28]. The manufacturing engineer who performed the evaluation used the videos of the real scenario and his experience with the actual process he faced on a regular basis at work. He concluded that the environment, components to be assembled, and the movement of the crane were sufficiently realistic to model the assembly process. Since the crane functionality provides realistic motion as to how a specific part is going to behave, it would be advantageous for an operator to run through the assembly sequence in the virtual environment. There were several challenges such as the identification of the components in the CAD system that corresponded to the components seen in the video. Being able to select a subset of components from the full assembly which had over 250 components, and have that subset behave in a functionally equivalent and sound manner was a challenge because of issues such as references, hierarchy, parent-child relations etc. It was also observed that the usability of the simulation tool would have been greatly improved with enhanced hardware, e.g. wireless birds, better user interface in the environment, and force feedback. Overall it was concluded that the virtual assembly environment had sufficient modelling and interaction realism to be of considerable value for evaluation and training.

Case Study 2: Assembly of the Fifth Wheel to a Truck Chassis – Evaluating Downstream Value to Ergonomics

This case study involved the assembly of a forward cab support of a truck chassis for a multinational technology company that manufactures premium commercial vehicles. The focus was on assembling the fifth wheel to a truck chassis.

Information Gathering and Analysis of the Real Assembly Process

The first step was to understand the existing assembly process thoroughly from the information collected (video, snapshots, site visits, and discussions with engineers) and the informational documents provided by the consortium member. The parts for simulation were identified. The Pro/E models were studied and compared with the models observed on the assembly line and in the video and snapshots.

Model and Environment Preparation

The assembly was modified to include only the relevant models. The original model provided had over 350 parts. As it was not possible (and not required) to simulate all these parts, the number of parts were pared down using the reorganization tool described earlier. All relevant information was exported from the CAD model.

A roadblock initially arose when it was determined that the models for the fifth wheel assembly provided by the consortium member were in IGES (Initial Graphics Exchange Specification) format. Pro/E was unable to convert this imported IGES part to the inventor file format to be used in VADE because of gaps and holes in the model due to the IGES translation. This required that the IGES file be imported and the gaps and holes fixed before the model could be added to the Pro/E assembly.

In addition, an environment had to be created in order to accommodate this assembly scenario. The snapshots taken at the consortium member’s site were used to create texture maps. The walls, floor and ceiling were created as thin protrusions in Pro/E, exported to VADE, and then texture mapped to convey the look of a real factory environment (Figure 5). Bins, trolleys, and other components of the environment were also created. The time to create this custom environment was about 20 hours, yet we believe that an expert user could create the environment in about 5 –7 hours. This environment can also be reused for multiple assembly scenarios.

Before simulating the assembly process, all components had to be placed in the appropriate bins or the locations where they were kept in the factory. Originally, the initial position of the parts had to be determined through trial and error, and entered manually into the initial location file. This process was very laborious and time consuming. However, an "immersive positioning" module of VADE was used to manipulate the initial position coordinates by moving the parts around in the environment. The time to place the components in the starting location obviously depends to a large extent on the number of components. Each part takes a few minutes for a first time user using the "immersive positioning" module.

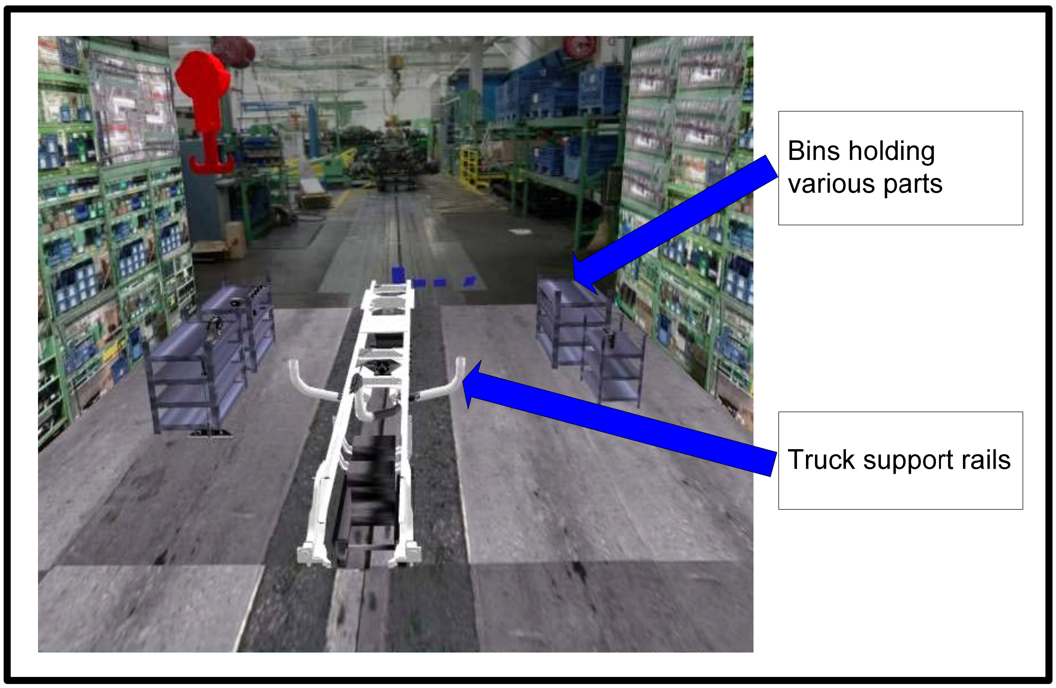

Fig 5. Custom Environment for the Fifth Wheel Assembly

Replication of assembly process in the simulation environment

As observed from the video, the 5th wheel was put into place using the following sequence:

1. Pick up the 5^{th} wheel out of the shipping crate using the crane.
2. Place the 5^{th} wheel on top of the crate and reattach using different attachment points.
3. Move and lower the 5^{th} wheel over the assembly position
4. Fasten the bolts at the various locations

This sequence was followed to the best of the user's abilities. There was one specific instance where VADE was not able to mimic the real-world process. When the 5th wheel was lowered onto the top of the crate, the crate supports the 5th wheel as it pivots and comes to rest on top of the crate. In VADE, the collision detection between the crate and the 5th wheel is possible, but the “cause and effect” of that collision had not yet been implemented (it has subsequently been implemented). Figures 6a and 6b show the 5th wheel attached to the crane right before the part is to be placed on the frame assembly in both the real environment and the virtual environment.

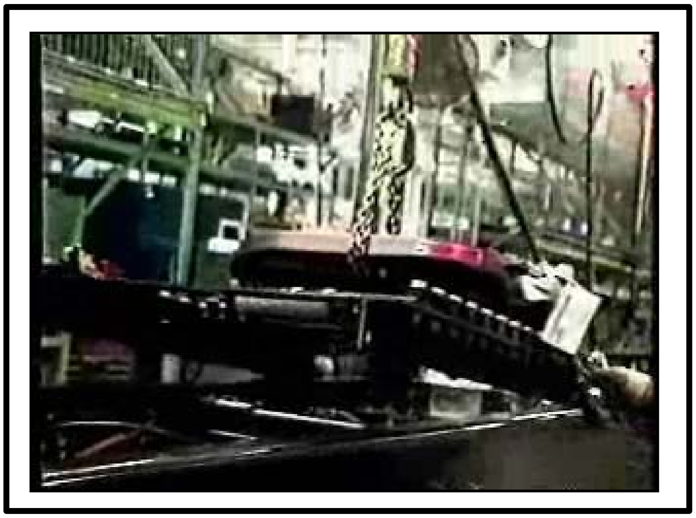

Fig 6a: Lowering the Fifth Wheel with a Crane in the Real Factory

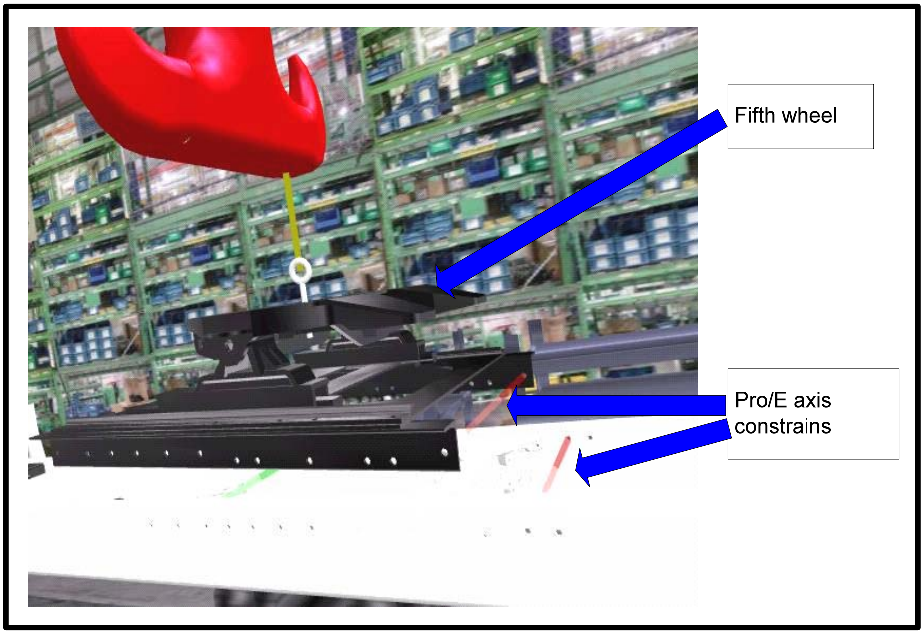

Fig 6b: Lowering the Fifth Wheel with a Crane in VADE

After the fifth wheel is placed on the chassis, various bolts are used to fasten the 5th wheel to the chassis (Fig 7).

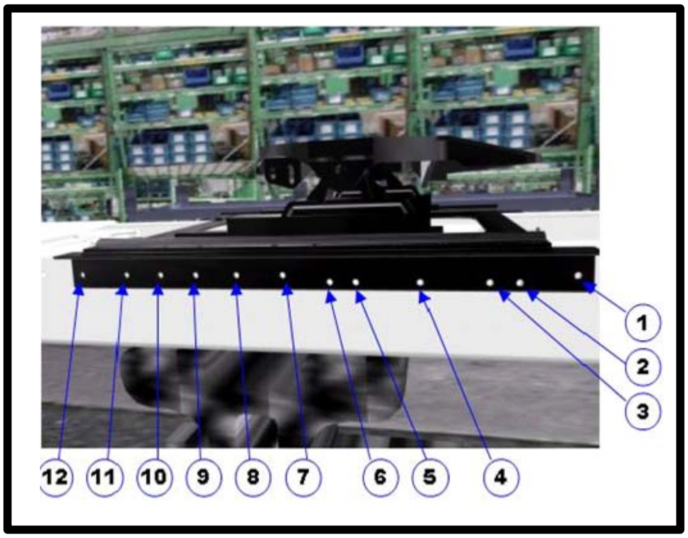

Fig 7: Labeled Bolt Positions

During the visit to the consortium member site, it was discussed that the worker's posture needed ergonomic improvement for easier access and efficient assembly. In the factory, bolts 1 through 4 are assembled from the rear of the truck. Figure 8 shows the 1st person and 3rd person view of assembling Bolt1 in VADE. Figures 9a and 9b show the assembly of Bolt 2 in real life and in the virtual environment.

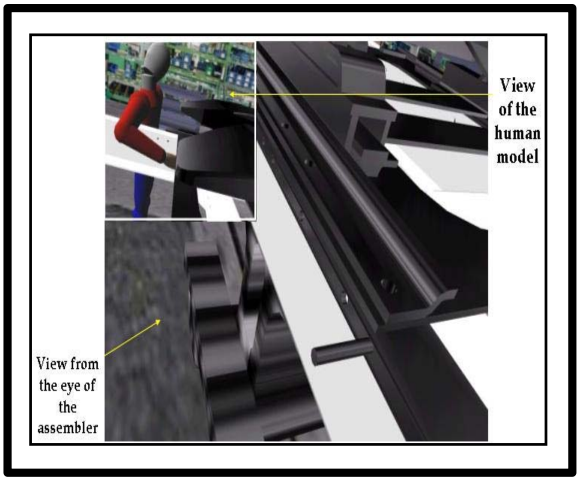

Fig 8: Worker Inserting Bolt 1 in VADE

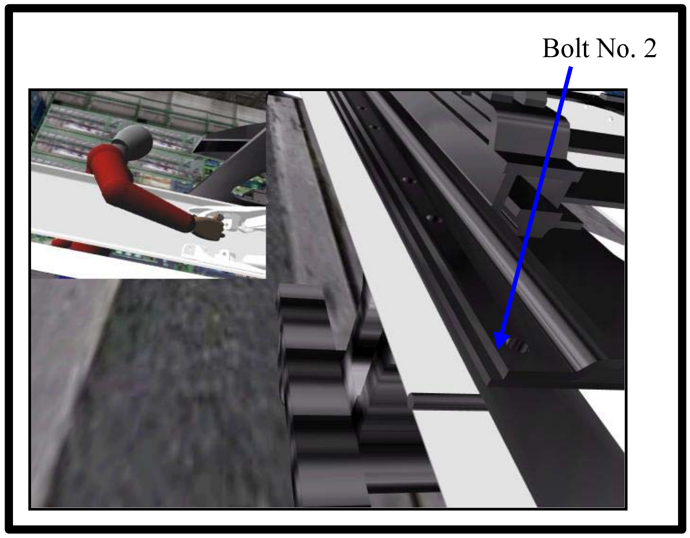

Fig 9a: Worker Inserting Bolt 2 in Real Life

Fig 9b: 1st Person and 3rd Person Views in VADE

Bolts 5 and 6 are assembled by the worker squatting down and reaching out (Fig 10).

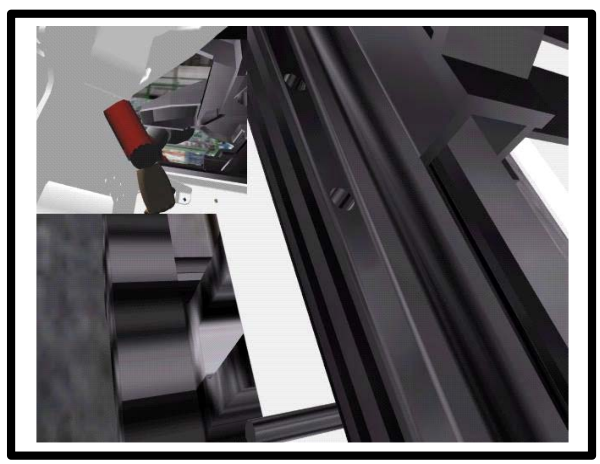

Fig 10a: Positioning Bolt 5 in a Real factory

Fig 10b: Positioning Bolt 5 in VADE

Analysis of case study evidence

The case study and the associated problems were presented to the VATC by manufacturing engineers and workers in the assembly line. The replication and studies in the immersive environment were completed by an ergonomist/engineer from the industry partner. The results and suggestions for assembly process improvements were presented to the manufacturing engineers for further considerations. Analysis of case study evidence and conclusions were based on the comments and internal reports of the industry partner engineers and ergonomists.

The immersive virtual assembly environment was successful in replicating the assembly scenario and providing an insight into ergonomic issues during assembly. As before, a less cumbersome virtual reality setup, better user interfaces in the environment, and force feedback would have improved the simulation. Setting up the models and the environment for the simulation are involved tasks that need considerable attention.

In an attempt to remedy the situation of limited accessibility in Figure 10, several scenarios were simulated. It was originally thought that the workers would have easier access to bolts 4-6 if the top plate of the 5th wheel could be moved forward; however, during simulation it was found that a cross-member between the rails exists at bolt 4. The cross member inhibits access from above the assembly. For bolts 5-6, sliding the 5th wheel forward was definitely advantageous. The conclusion was thus made that bolts 1, 2, 3 and 4 should be assembled from the rear of the truck (as is currently done in the factory). Bolts No. 5 and 6 should be assembled by sliding the top plate forward, rather than from going under the rails. Thus, the case study provided specific downstream value to ergonomic considerations.

Other Case Studies

In addition to the two case studies that have been described in detail in this paper, three other case studies were performed as part of the consortium activities. We will provide a brief description here for completeness. Details can be obtained from the references if there is further interest. One case study was to reproduce the assembly of truck support rails and suspension in the virtual assembly environment [31]. Another case study involved the assembling of a piston in an engine. VADE was used in identifying some aspects of repetitive motion injury that occurred in the assembly sequence and to provide suggestions in reducing/eliminating this problem. A complete parametrically scalable human model was used for the piston assembly test case, driven by inverse kinematics through the use of six tracking sensors. It was used to analyze the ability of people of different sizes to be able to perform a given task, and also to do a preliminary study of warnings for injuries [32-34]. The third case study was related to assembly sequence exploration. This involved the assembly of various brackets and miscellaneous components to the chassis of a truck. This study involved the creation of assembly sequences and identification of sequence problems. VADE was used to assemble the brackets in a spatial sequence and several conflicts which arose due to space and reach restrictions were documented and the assembly sequence was modified to avoid those conflicts [31].

Once the individual case studies were completed, the information from the various simulations was integrated. The immersive virtual assembly tool was installed at all consortium member sites and the test cases simulations were demonstrated on site. The engineers and consortium members drew conclusions from the collective evidence. They identified the strengths and weaknesses of the technology and suitability for deployment in industry. In addition they also drew conclusions from experiences in installing the solution at the member sites.

Discussion

Formulating and completing these case studies under the umbrella of the VATC consortium provided a valuable opportunity for industry, government, and university to work together and to gain valuable insight into the issues involved from their respective perspectives. The test cases provided the university researchers with complex practices and settings in which the technology had to perform and in turn provided the industry partners with focused deployments of cutting edge technology. It also provided a process and opportunity to reflect on the advantages and disadvantages of the existing immersive virtual assembly methods and challenges in adapting them to real-life situations. Further, this allowed for improvement based on an understanding of the industry-specific problems and the subsequent guided enhancement of the functionality.

We feel strongly that there is a huge leap in going from prototypes and simple demonstration projects to real-life projects. It goes way beyond the issue of just larger models or more steps. One stark example of issues that were not even considered in the original simple prototype - it was initially a surprise that the as-designed assembly hierarchy was different from the as-manufactured assembly hierarchy. Considerable effort was put in parallel to create an application to rearrange the CAD assembly hierarchy accordingly and export this new information for a correct simulation. This showed that very often in overly simplified problems, many assumptions that we tacitly make are really not relevant or correct and there are issues that one did not even think about.

One identified limitation of the case studies is that the feedback from the users is subjective and no quantitative data was obtained in these case studies to measure in some specific way the effectiveness of the virtual assembly environment. We feel that this does not detract from the significance since the aim is to provide industrial exemplars for the work. Real industrial case studies of immersive VR in this domain are few and far between. As future work, experiments could be targeted to find quantitative information on the value of simulated environments to make meaningful engineering decisions and whether they can provide significant benefits over current practices.

As the test cases were being performed, it was apparent that there were key strengths in the virtual assembly environment. These are outlined below along with a number of limitations and potential improvements that were discovered. Some are specific to the overall technology and some are specific to the implementation that was used.

Strengths

- Ease of Assembly Setup - Models were easily extracted from Pro/Engineer and imported into VADE for the test cases. Each scenario was carried out with minimal changes to the Pro/Engineer data files.
- Assembly Customization - The assembly data coming from the CAD system could be easily customized using the reorganization and pre-assembly tools. This was particularly helpful in replicating the truck rail and suspension scenario that had a large number of parts. The bulk of the parts were pre-assembled before the study, leaving only the parts that concerned the study available for assembly.
- Constraint Based Motion - The use of constraint-based motion significantly eased the assembly process and provided realism in the absence of haptic devices.
- Scalable Human Model - A complete parametrically scalable human model was available for use, driven by inverse kinematics through the use of six tracking sensors.
- Ergonomic and Aesthetic Studies - Ergonomic and aesthetic evaluations typically need full-size and complete prototypes. Space requirement, reach, and visibility studies could be carried out in the virtual environment. The application can also be utilized to study a new product, as the user can view and interact with the object in an immersed 3D environment.
- Realism - The environment and the objects in the environment provided a high sense of realism. Because of the combination of realism and environment interaction, this is an excellent tool to train workers.
- Scalability of Hardware and Peripheral Devices - VADE has been implemented on a range of SGI computers. It has also been ported to Linux PCs. The tracking devices (Flock of Birds and Cyberglove) all run as separate processes and provide data to VADE through shared memory. This allows for easy replacement of these hardware devices with others (e.g. ultrasonic tracking, 5DT glove, etc.).

Limitations/Suggested Improvements

- In the truck assembly factory, parts were often slid along the floor or table. The environment was unable to simulate sliding of parts on the floor or table.

- In VADE, the user frequently used uncomfortable postures when manipulating parts that were assembled by hand. This was because it was easier to twist the body with "weightless" parts than to drop the part and re-grip it. This could be resolved by allowing the use of two hands to grip and manipulate the part.
- With the large press machine, when the largest part came into view, it was sometimes difficult to keep up the graphics refresh rate. This can be addressed by not including internal polygons, which do not contribute to the assembly simulation.
- There needs to be the ability to save the intermediate state of an assembly simulation and come back to it later.
- Currently, the left hand has no glove and does not have a tracked hand representation. That hand cannot grab a part in the same way that the other (right) hand does. Even though most assembly situations are simulated adequately, a representation of the second hand which has all the functionalities of the first hand would be an improvement.
- Although VADE is capable of detecting a collision, it does not prevent the user from passing the part through the collided entity or the user's body from going through parts. To accurately reflect real world scenarios, the user would need some sort of force feedback system to restrict the arm from passing the part through the entity. A newer implementation of VADE now supports the bouncing of parts when they collide with other parts, along with more complete impact physics modelling [35].
- The execution of the collision detection is a processor expensive process. For now, the user has an option to turn collision detection on or off.
- VADE is able to communicate with Pro/E only, not with other CAD systems.

The overall challenges of deploying immersive virtual assembly systems are in the areas of a) increasing the ease of use of the hardware and software, b) enhancing portability of the applications, c) simplifying preparation of models for simulations, and d) integration of this technology with other simulation tools currently being used to provide complementary functionality, and e) limitation in standards to support integration.

Conclusions

As virtual environment technology has matured, the importance and feasibility of using this technology in mainstream industry projects has grown. Engineering case studies are gaining wide acceptance in engineering practice and education. In this paper we have presented case studies in using immersive virtual assembly technology for projects in industry. The case studies selected real-life industry situations from industry members of the consortium and used the immersive virtual assembly technology to create a meaningful simulation. The immersive virtual assembly tool used, VADE, was able to perform and successfully complete each test case provided. The realism and technical feedback provided by VADE offers engineers an advanced tool in assembly technology. The application was installed at various industry and government locations.

The willingness of industry to get involved in embracing and deploying this technology appears to be increasing and the technology will play an enhanced role in future manufacturing simulations and planning. It is often not straight forward or easy to take prototypes and simplified problems and extend them to industry-grade situations. In our opinion, at this juncture, research and case studies that define and address approaches to engaging this new technology for real-life challenges are almost as important as enhancing the core and innovative functionality of the technology.

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