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Organized by
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Introduction to VIRMAN'06

There has now been well over a decade of applied experience of and research into virtual reality (VR) technologies within the manufacturing domain covering many wide-ranging aspects of product engineering from conceptual design, detail design, training, process simulation and assembly through to product support and recycling. This work has been characterised by a diverse range of interested academic and industrial parties involved in many engineering environments. It has been hypothesised that virtual environments will eventually become the natural interface for engineers to use to interact with real time data whilst carrying out multi-task, concurrent engineering activities. If so, when will this be the case? We have also observed the rise and fall of a number of vendors over the last 20 or so years, yet the nature and extent of sustained uptake by industry is still unclear.

The goal of this workshop is to provide an opportunity for academic and industrial researchers and practitioners to share their experiences and explore state-of-the art and state-of-the-practice virtual reality design and manufacturing systems; the aim being to highlight where the main areas of industrial and academic interest are and how it is anticipated that this VR in its various forms will evolve into use as a part of everyday standard engineering tools.

Topics of interest in the presentations include:

- standards for interoperation;
- applications;
- integration;
- benchmarks and comparisons;
- historical reflections;
- return on investment;
- simulation and training;
- design support;
- process planning;
- machining;
- assembly.

We hope that this workshop will act as a catalyst in bringing together a formal, regular dialogue and forum for virtual manufacturing practitioners all over the world so that ideas, concepts and mutual areas of interest can be researched and publicised.

James Ritchie and Rick Dewar
(VIRMAN'06 Workshop Organizers)

1st International Virtual Manufacturing Workshop (VirMan'06)

LIST OF PRESENTATIONS	Authors

<u>KEYNOTE</u>

1. Virtual Manufacturing – Are we there yet?

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Abstract

The phrase "Virtual Manufacturing" caught the attention of design and manufacturing industry and academia in the early and mid 1990s. A dozen years later, and many derivative phrases later (e.g. virtual assembly, virtual maintenance, etc.) has virtual manufacturing delivered on its promises? It is now time to look back at the path we have taken and identify successes and failures. As we move forward, are we addressing the pressing issues which are still a barrier in the adoption of "virtual manufacturing" as a widely used technology? Usability of the associated technologies, integration with other engineering software, cost, role in the engineering process, robustness and availability of software products still pose challenges. This presentation will use examples from research institutions, national laboratories, and industry with the intent of initiating lively discussions and setting the tone for this workshop.

2. User Activity in an Immersive Cable Harness Design System

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http://costar.hw.ac.uk/cgi-bin/WebObjects/costar and http://www.smi.hw.ac.uk/

Abstract

This presentation describes the analysis of user design activity during the evaluation of a demonstration immersive stereoscopic design system for cable harness design called COSTAR (Cable Organization System Through Alternative Reality). During the study ten participants independently completed a sequence of three harness design tasks using the test system. All user interaction with was recorded during each of the design sessions. This data was subsequently analyzed to profile the distribution of user activity according to the purpose of the activity.

Four major activity classes were used: Design, System Operation, Navigation and Information. The Design class was further sub-divided into Goal, Support, and Edit activities to produce a more detailed breakdown of the cable harness design process. In addition measures of 'unproductive activity' and 'idle time' were used to identify relative performance within the different activity classes. The results presented here are from one of the three design tasks. Activity profiles have been constructed from the mean user data and provide, for example, the relative amount of time spent generating core design output compared to other non-core activities such as navigating the model and operating the system. The results suggest that this categorization provides a benchmark taxonomy that can be used to compare user design activity across a wider variety of design systems, technologies and tasks.

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ABSTRACT

This paper describes the analysis of user design activity during the evaluation of a demonstration immersive stereoscopic design system for cable harness design called COSTAR (Cable Organization System Through Alternative Reality). During the study ten participants independently completed a sequence of three harness design tasks using the test system. All user interaction with was recorded during each of the design sessions. This data was subsequently analyzed to profile the distribution of user activity according to the purpose of the activity.

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CR Categories:
Keywords: immersive VR, product engineering, design task analysis

1 INTRODUCTION

The use of interactive immersive virtual reality (VR) will become prevalent in a number of forms over the next few years within the product design environment. The application of this technology will no doubt mirror how expensive turn-key computer aided design (CAD) systems began to impact on industry in the late 1970s and became generally available on low-cost PC-based platforms with extensive real-time solid modelling capabilities. In the recent past the focus of immersive VR applications has been mainly in the research laboratory and in larger companies; however, as this technology becomes cost effective and more widely used in the design and manufacturing engineering sector, it is important to understand how to analyse its utilisation, and evaluate its benefits and limitations, as it begins to impact on *creative* engineering processes such as conceptual and detail design and manufacturing process planning.

In this paper the main focus is on using head-mounted display (HMD) immersive VR as a tool for the analysis of a creative design task, i.e. the 3D generation of cable harness routes, to

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analyse how the engineering designer approaches a problem and what the key issues are with regard to future virtual design systems of this kind. In particular, a task categorisation of system usage is outlined and tested for analysing user activity in a computer-based cable harness design application.

1.1 Research Work Domain

There are now many applications where VR is being applied in the domain of mechanically engineered products and a wide variety of different types of technology that can be used in engineering domains [1]. This paper focuses on HMD systems where the user is surrounded by a virtual world generated by computer graphics; the models within this can be interacted with in real time (Figure 1) depending on the input devices and tracking devices attached to the system.

Figure 1: Head-Mounted Display (HMD)

In the area of product design, VR systems are beginning to change the way in which engineers develop products and work together to generate ideas, embody concepts and produce the information necessary for cost-effective manufacture. So there is a need to understand how creative product engineering processes can be analysed and comprehended in detail when applying immersive VR technology to such a task, how these activities are broken down and where the emphasis on interface and technology development should take place to enhance improvement. One key ring-fenced area with potential for analysis is that of cable harness design and manufacture.

Cable harness design has been engineering problem for many years since many companies still employ physical prototypes for the generation and checking of actual cable routes; even with the application of extensive CAD-based packages available for this task [2]. Early cable harness design work was carried out in the USA in the 1990s in an attempt to automate the choice of a cable harness route [3], with subsequent work using genetic algorithms to tackle the same problem [4]. Wolter and Krol routed 'strings' around 'solid' parts [5] and in some projects robot path planning has been applied to piping systems as a routing solution [6]. Early work at Heriot-Watt University [2, 7] showed that immersive VR has a role to play in this design process. Recent research at Iowa State University [8] employs a VR system for routing flexible hoses that validated VR as a practical tool. Early work at Boeing [9] in the area of augmented reality indicated the early advantages of virtual technologies in assembling cable harnesses.

A survey of the industrial companies in this study showed that there was a need for human expert intervention to make fine adjustments and verify solutions [2]; therefore it is timely to investigate the nature of new human-driven tools to support interaction with data in this domain. The key issue is the integration of the human expert into the 'system' by treating the operator as an integral part of that system [10]. This emphasises the need to examine creative engineering activities in more detail to see how better tools and methods can be introduced to support the cable design task. The efficient and reliable manufacture of cabling systems for many products in such sectors provides designers with a range of challenges. Cable layouts are often so complex that design tends to be carried out as an end activity, which may lead to higher costs or even a product redesign. The problems encountered during the cable harness design stage have a marked impact on the time needed for new product introductions with multiple revisions of physical prototypes being commonplace [2]. VR's unique capability to immerse the user in a design experience makes it an ideal domain in which to carry out detailed design studies and represents a convenient ring-fenced design task which can be measured and analysed in isolation; yet is flexible enough to allow some form of task variety to be built into system experiments in a constrained design environment. An advanced immersive VR-based cable harness design system based on the table-top metaphor [7] and using comprehensive user logging was developed to non-intrusively collect detailed information relating to the design solutions and approaches used by a number of engineers; the designer's workbench metaphor for cable harness design was developed to form the basis of the experimental platform developed for this research [11]. It was decided that the majority of the design tasks undertaken for the initial experiments would focus on the 3D volumetric design since this was considered by the companies to be a priority.

2 APPARATUS AND METHODOLOGY

2.1 Apparatus: COSTAR Experimental Platform

The system developed as an experimental platform for this research was called COSTAR (Cable Organization System Through Alternative Reality). This was implemented on an SGI® Octane2™ (2*600 MHz IP30 processors, 768 MB RAM, 9GB HDD) with V12 dual head graphics (2*VPro V12 graphics boards each with 128MB graphics RAM) driving two SGI® F180 flat panel displays or each eye of a stereo head-mounted display (HMD). Peripherals attached to the system include a V8 stereo headset (Virtual Research Systems, Inc.), Flock of Birds® magnetic tracking system (Ascension Technology Corporation) and Pinch® Gloves (Fakespace Systems, Inc.). The Flock of Birds® system measures both positional and rotational information thus reporting six degrees-of freedom (6DOF). The Pinch® Gloves are cloth with conductive material at the tips of each finger. Signals are generated when two or more fingers come into contact with each other. The software was developed using SENSE8® WorldToolKit® (WTK) release 9 (multiprocessor/multipipe version), running on IRIX (version 6.5.21) using an object-oriented approach, with the implementation being written in C++.

The COSTAR system enables the engineer to design cable harness assemblies within the immersive VR environment, with all design functions including the creation of new objects being performed while they are immersed (Figure 2). Interactions with the system are achieved by means of a custom-built menu system

and pinch gestures, with combinations of two to ten touching fingers, in addition to the spatial input afforded by the Flock of Birds.
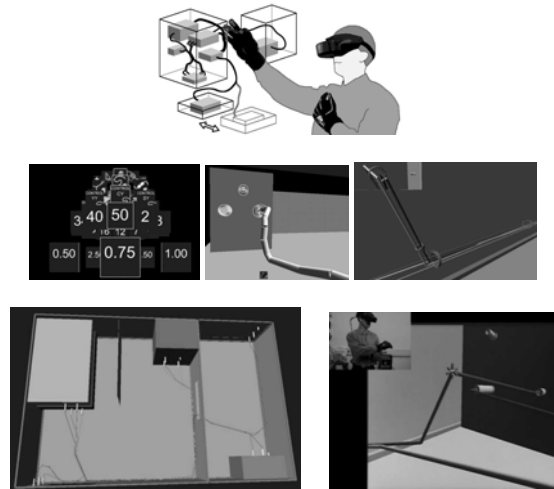

Figure 2: The COSTAR cable harness design system

As the prototype system is fully immersive using two gloves and a HMD, menus had to be designed for ease of use. The current system uses a hierarchical 3D ring. The engineer can simply input the cable harness routes by selecting the appropriate option and plotting points in 3D space, these being subsequently joined together to produce the cable path itself. Subsequent editing of the cables is possible by bending them around obstructions, bunching or pulling them together to form cable harness bundles, inserting additional points and adding connectors and fasteners; again depending on the menu options chosen.

COSTAR logs all of the subject's design activity-related actions, with the position of the hands and head being logged in the order of 50 times per second; the frequency varies with the complexity of model, number of design tools currently being used and the level of collision detection. A suite of Perl scripts are used to automatically post-process the resultant large data files and extract a variety of performance measures including navigation statistics, menu usage, help usage, number of times and duration for which a certain design tool was employed and the number of times functions were cancelled by the user.

2.2 Experimental Methodology

Experiments were designed such that a participant would not use COSTAR for longer than twenty minutes in each session. Three loosely constrained creative design tasks were organised to evaluate the utilisation of each designer's time. These covered the major common design activities for cable harness processes, such as routing, bundling, cable modification, choosing connectors, etc. The log files from these activities were subsequently decomposed and analysed in order to ascertain the areas of the virtual cable harness design system that were used, the kinds of activity the designers performed and their distribution throughout the total design time taken. The users were given sufficient information about the goals of the task along with its main boundary conditions but were then free to determine what form the final design solution should take. This uncertainty of task outcome prevented the evaluation process becoming a prescriptive button pushing exercise as well as giving the participants a sense of

doing a real design activity with the system. The overall design task involved a group of participants undertaking a sequence of three virtual cable harness design tasks. All of the tasks were associated with typical cable harness design practices within the industrial partners, were carried out within the same 'product' model and involved consecutive stages of the overall cable harness design process; namely (1) outline design; (2) detailed design; and (3) redesign. Tasks 1 and 2 were used mainly for training and familiarisation and task 3 for design task analysis.

(1) *Outline Design*: The first task was to generate two new electrical interconnections within the product model. Each of these interconnections had to join two specific connectors within the model and have a specified cable type. The goal of this task was to define the electrical interconnections that would be provided by the harness rather than to produce a representation of the physical harness design, and hence, the routes followed by the cables were not important.

(2) *Detailed Design*: The second task contained pre-defined cable interconnections on a model, a number of which had already been routed through a sequence of cable clips to produce a harness design. It also had three other cables that defined electrical interconnectivity but had not yet been routed to produce a physical path for these cables to follow within the harness assembly.

(3) *Redesign*: The third and final main task started with a product model that contained the design of a completed harness assembly. The participant was then given some 'engineering change requests' requiring redesign of the harness in some manner. The specific changes required were the addition of a new cable to the harness and the removal of one of the cables and its associated connectors. Finally, there was another 'undefined' error within the model that the participants were required to locate and fix. This undefined error was a cable being routed through a solid wall, with the cable therefore requiring re-routing.

Ten participants completed the experiments, nine of whom were drawn from the engineering staff and student populations of the university and the tenth being an engineer drawn from industry. All of the participants were male, eight were 20 – 29 years of age and two were 30 – 39 years of age, all with normal or corrected-to-normal vision. Everyone was right-hand dominant with eight being right eye and two being left-eye dominant. Seven of the participants estimated that they had between 10 – 100 hours of previous CAD experience with three estimating 100–1,000 hours experience. Seven also had no prior VR experience, two had less than 10 hours and one had 100-1,000 hours of VR exposure. The immersive design activity was followed by an informal discussion session during which feedback about the system and the participant's experience with it was collected.

3 ANALYSIS OF RESULTS

The results collected via the log files included performance and usage data, system usability data and system functionality data along with informal subjective discussions regarding system performance and future changes. From the results for task 3, the usage of the system was analysed by means of various novel categories of functionality and system state that were developed specifically for this purpose. In relation to the working environment, it was decided to analyse the time spent in the model, in help and in the menus so that their influence on any design task could be compared against any proposed design task categorisation. This resulted in the distribution shown in Table 1

which demonstrates the average percentage of time spent in each of the environmental category subdivisions as the designers completed design task 3. These show that a very high percentage of the time (69%) involved the users carrying out activities within the model and being creative, demonstrating the intuitive and easy-to-operate nature of the virtual design tool. Only a small proportion of the time (8%) was spent in 'help' supporting informal feedback from the users that the system was easy to use and intuitive.

Table 1: Average environmental category results for design task 3

	Environmental Categories				
	Model	Help	Menu (No model visible)	Menu (model visible)	Total
Mean Time (s)	867	101	289	0	1257
%	69%	8%	23%	0%	100%

After examining the data and the associated experimental activities, the various action sequences within the log files were grouped together to enable a numerical and statistical analysis of the cable harness design approach used by the participants. From these data, a set of design activity categories were defined so that participant activities could be compared and correlated between each other and the environmental categories in Table 1. The final four action sequence categories chosen were:

Design: All activity that the user carries out to directly amend the design solution or associated documentation.

Information: All user activity which involves them acquiring information from a text screen.

System Operation: All activities which are required by the user to operate the system but does not affect the design solution.

Navigation: All activity which modifies the participant's viewpoint of the model but do not normally alter the design solution itself.

Since *Design* was at the core of CO-STAR system this was further subdivided into three subcategories to allow more detail to be obtained regarding an analysis of activities whilst the user was being creative. These subcategories were:

Design – Goal: User actions which alter the design solution/model and advance the design towards its final state.

Design – Support: Activities which do not produce a change to the design solution but enable the user to subsequently alter the design.

Drag & Drop (Position Edit): The movement of an object by the user interactively within the model environment.

Two supplementary categories which needed to be separated out from the rest of the category activities were identified, namely:

Unproductive Activity: All category activity that can be removed from the process without affecting the final outcome of a task.

Sequence Breaks: Abeyance in activity between the end of one action sequence and another with no input from the user, e.g. user thinking time.

These were not a direct part of the other category activities and therefore had to b measured separately.

The results of these further subdivisions in relation to the design tasks carried out during the experimentation are shown below in Table 2.

Table 2: Average results for task 3 activity categories

Activity	Mean Time/ participant (s)	St. Dev. (s)	%
Design Goal	86	41	7%
Design Support	28	13	2%
Drag & Drop	147	125	12%
Information	99	34	8%
System Operation	191	65	15%
Navigation	280	85	22%
Unproductive Activity	70	51	6%
Sequence Breaks	356	110	28%
Totals	1257	326	100%

From this table it can be seen that a large proportion of the time was spent navigating around the model (22%) and is probably due to the model being presented in super-scale; i.e. the model surrounded the engineer. Flying was employed because it was the traditional mode of navigation using a HMD with the speed kept constant in the prototype system in order to reduce confounding variables in experimentation. However, with almost a quarter of the time was spent in moving around the model and the categorisation scheme shows that, during the creative design process, it would be advantageous to reduce this time considerably. This backed up an important finding from Ng et al [12] which found that user scaling of the virtual model while immersed considerably enhanced the designer's perception of the product model and the associated design task. Also, a large number of sequence breaks or pauses were apparent which implies that a great deal of potential time exists in the process which can be freed up to support other tasks. Many of these existed within the navigation of the model which points to the need for more effective navigation tools. Also, this time could point to areas in the process where the designer is thinking about the design and will require further analysis. Indeed, around 21% of the time within the system was spent on design-related tasks.

In order to investigate the cause and effect relationships between the various categories and subcategories, statistical tests were carried out to see if any could be identified. This comparative analysis compared all of the *environmental* categories and *activity* categories together. Using the Shapiro-Wilks normality check test of Goodness-of-Fit (W) the data were found *not* to be normally distributed ($p>.1$). This would be expected in an open-ended creative design task of this kind where considerable freedom of expression was given to the engineers to generate a final solution to the associated cable harness design problem. As a consequence of this, nonparametric correlations were evaluated by means of a Spearman's Rho test. The following significant and tending-towards-significant correlations were found as summarised in Table 3, where significant was

defined as $p<.05$ and tending-towards-significant was defined as $p<.1$.

Table 3: Nonparametric correlations for all categories

Pair	Variable (%)	by Variable (%)	Spearman ρ	Prob> |Rho|
1	Model	Design Support	-0.8909	0.0005
2	Menu	Design Support	0.6848	0.0289
3	Help/Information	Design Support	0.8545	0.0016
4	Menu	Model	-0.8788	0.0008
5	Help/Information	Model	-0.9030	0.0003
6	Unproductive Activity	Menu	0.6848	0.0289
7	Unproductive Activity	Drag & Drop (Cable point edit)	-0.6121	0.0600
8	Unproductive Activity	Sequence Breaks	0.5879	0.0739
9	Information	Menu	0.6970	0.0251
10	Drag & Drop (Cable point edit)	Model	0.6364	0.0479
11	Drag & Drop (Cable point edit)	Menu	-0.8303	0.0029
12	Information	Model	-0.9273	0.0001
13	System Operation	Design - Goal	-0.7939	0.0061
14	Sequence Breaks	Drag & Drop (Cable point edit)	-0.6727	0.0330

The results illustrate some obvious and not-so-obvious cause-and-effect relationships between the various activity and environment categories and give an interesting and novel insight into the cable harness design process. If engineers spend less time in the model being creative then they usually spent potentially useful time in design support (Pair 1: ρ=-0.89, $p<.05$) which reflects ***actual*** system usage. Designers also tend to access menus and help/task information in design support (Pair 2: ρ=0.69, $p<.05$; Pair 3 (ρ=0.85), $p<.05$) demonstrating the usefulness of the categorisations used for analysing a cable harness design task. Less time in the menus means more time in the model, i.e. carrying out productive design (Pair 4: ρ=-0.89, $p<.05$) where less time in help means more time doing productive design (Pair 5: ρ=-0.90, $p<.05$); two strong negative correlations. Also, when the designers spend more time carrying out non-productive activities, they were most likely to be in the menu environment than doing other activity (Pair 6: ρ=0.69, $p<.05$). This implies that they are at

their most productive in the modelling (design) environment. Tending towards significance, drag-and-drop is also shown to be an important productive design activity (Pair 7: $\rho=-0.61$, $p<.1$) because the designer is 'improving' the design and justifies the categorisation because it identifies the drag-and-drop task as being central to the design activity itself and its inclusion in the interface; a functionality that is missing in CAD systems of a similar kind and an important, intuitive editing capability within immersive VR. Also, the more breaks designers take either voluntarily or involuntarily within the design activity, the less productive they are, e.g. getting lost in menus, choosing wrong parts (Pair 8: $\rho=0.59$, $p<.1$). This is explained in terms of designers getting "lost" in non-productive activity and then having to revaluate what they are doing before continuing with the design process. Pair 9 (Pair 9: $\rho=0.70$, $p<.05$) supports interview feedback from the designers in which they said that the VR system was intuitive and easy to learn. This is further supported by the fact that when the engineers were in the model they were not looking at the task instructions and vice versa (Pair 12: $\rho=-0.93$, $p<.05$). Pairs 10 ($\rho=0.64$, $p<.05$) and 11 ($\rho=-0.83$, $p<.05$) appear at first glance to state the obvious, i.e. that more time in the model means more time in drag and drop (amending the design) and more time in the menus means less time in drag and drop. However, this again points to a fundamental advantage of immersive VR systems in the design domain in that the availability of an intuitive and natural 3D interaction tool for modifying geometry means that engineers will use this as a flexible tool with which to modify design information. Pair 13 (Pair 13: $\rho=-0.79$, $p<.05$) suggests the need for well designed and specialised task-specific interfaces for all system operations within immersive VR HMD design applications and requires further study. This is also the case when more time spent in inter-sequence breaks meant less creative design time in particular drag-and-drop (Pair 14 $\rho=-0.67$, $p<.05$).

4   CONCLUSIONS

The results of this research have shown that it is possible in HMD immersive VR to successfully design cable harness assemblies and associated fastenings and connectors. As well as this it has been demonstrated that it is possible to examine, categorise and measure in detail the wide range of design activities carried out by cable harness design engineers. The novel cable harness design activity categorisations, along with their subsequent analyses, have provided a much more detailed understanding of design methods in this domain. A numerical and statistical breakdown of activities has been possible the subsequent statistical analyses of which have given an insight into the cause and affect relationships taking place within the cable harness design process itself; a major output of this research. These comparisons prove that it is possible to quantify the extent of the relationship between two or more subtasks within a design process. In the context of cable harness design, this proves that the categories chosen are valid and relevant to the general design function and could lead to a formalised standard and methodology for the analysis of creative computer-based design processes in the future. As a consequence of this, this research is being extended to apply this categorisation scheme within cable harness CAD design environments for direct comparison with VR functionality as well as being used for the acquisition and formalisation of design ontologies related to cable harness design strategies and solutions. One area where this could prove to be useful is that 'thinking time', i.e. when the user is idle, can be extracted from the data and an examination of where this is

occurring could, potentially, provide a capability to imply design intent from actions leading up to and after a decision making event.

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3. Virtual Training Studio: A Step towards Virtual Environment Assisted Training

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Abstract

Manufacturing organizations constantly need to train operators to perform manufacturing and assembly operations. In many organizations, operation instructions are communicated to trainees via paper-based documents, followed by hands-on training under the supervision of an experienced person. Virtual environments present an opportunity to significantly improve the training process by shortening the training time and reducing the overall training cost. In this paper, we discuss the development of Virtual Training Studio (VTS), a virtual environment-based training system that allows training supervisors to create training instructions, utilizing CAD models, and allow trainees to learn the operations in a virtual environment. A unique feature of our approach is development of virtual mentor module that automatically monitors the trainee's progress and provides the hints and warning messages when the trainee makes mistakes during the training session.

Our system is mainly geared towards training operators to recognize parts, memorize assembly sequences, and correctly orient the parts in space.

We foresee a number benefits from the use of the VTS system. First, we believe that the number of personnel required to be trainers will be reduced. Second, the system will provide a convenient mechanism for depositing assembly process knowledge into a central repository for later retrieval by trainees. Third, the VTS will assist instructors in creation of VE tutorials and paper based documentation by generating some of the instructions from the animation sequence and by providing a convenient way of generating 2D illustrations.

Virtual Training Studio: A Step Towards Virtual Environment Assisted Training

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ABSTRACT

In this paper, we discuss the development of Virtual Training Studio (VTS), a virtual environment-based training system that allows training supervisors to create training instructions, utilizing CAD models, and allows trainees to learn assembly operations in a virtual environment. Our system is mainly geared towards the cognitive side of training workers so that they recognize parts, memorize assembly sequences, and can correctly orient the parts in space. We foresee a number of benefits from the use of the VTS. First, we believe that the VTS will accelerate the learning process by providing focused, multi-modal training scenarios that will better prepare the trainee. Second, the VTS will assist instructors in the creation of virtual environment tutorials and paper based documentation by generating some of the instructions automatically and by providing a convenient way of generating 2D illustrations. This capability will offer the users a mechanism for archiving assembly process knowledge into a central repository for later retrieval by trainees. Finally, we believe that the number of personnel required to be trainers will be reduced.

Additional Keywords: virtual environment, training, accelerated learning

1 INTRODUCTION

The labor forces in most industries require continual training and update. Current training methods, for the most part, involve a combination of paper-based manuals, DVD/video-based

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instructions, and/or hands on master-apprentice training. Due to the rapid influx of new and changing technologies and their associated complexities, accelerated learning is a necessity in order to maintain an advanced and educated workforce. We believe that existing training methods can be further improved in terms of cost, effectiveness, time expenditure and quality through the use of digital technologies such as virtual environments (VE). The advent of personal virtual environments (PVE) offers many new possibilities for creating accelerated learning technologies. A significant amount of progress has already been made in the development and deployment of virtual environment assisted training technologies.

However, there are two major challenges that need to be overcome in order to achieve accelerated learning with virtual environments. First, currently creating interactive training instructions for virtual environments requires a significant time commitment, even for moderately complex tasks. Therefore, the goal of accelerated learning is still not attainable once the cost and time of creating the instructions is included in the overall picture. Second, the traditional approach utilized in virtual environment assisted training is based on allowing the trainee to learn on their own. This unsupervised learning model works well only for a limited class of training exercises. One of the best learning models involves the master-apprentice approach. In this model, the master constantly monitors the progress of the apprentice and intervenes at appropriate times to aid learning. Incorporating the master-apprentice model in the virtual environments will significantly help in accelerating the learning process.

We are developing a virtual environment based training system called Virtual Training Studio (VTS) to address these challenges. The VTS is composed of the following three modules: Virtual Workspace, Virtual Author and Virtual Mentor. Virtual Workspace is the fabric that holds the system together. It provides the platform for the other two modules to function and integrates the hardware and software into a cohesive package. Virtual Author is a component of the VTS that allows non-programmers to quickly create new tutorials, generate text based instructions and 2-dimensional images. Virtual Mentor is an intelligent agent running inside the Virtual Workspace that intervenes in the training process when it senses the user having

trouble and provides additional details to further clarify the action required. These modules are a work in progress and have reached various levels of completion.

In this paragraph, we briefly review the related works. A number of researchers use interactive demonstrations as a means for conveniently creating tutorials. An example of this type of authoring tool is the Cognitive Tutor Authoring Tool (CTAT) [1]. Another area of interest is real-time error detection and feedback generation in training sessions. Some researchers have developed techniques to detect errors made by trainees during training sessions and generate hints to provide them meaningful feedback [2]. Yet another area of interest for our research is intelligent adaptive tutorials. A number of researchers have worked on next generation tutorials that can adapt their instructions based on a user's capability and progress [3], [4]. Certain researchers have also explored the use of virtual environments in training applications. Representative areas where VE-based training research has received recent attention is in the medical field where VE-based surgery training is growing and in areas where mistakes in the assembly process are dangerous or expensive [5], [6], [7]. A significant amount of research in this field is devoted to the teaching of motor skills, with the use of haptic devices for example. The principal area of interest to us, however, is the cognitive aspects of spatial learning. Research has confirmed that animations showing the step-by-step procedures have facilitated the learning of procedural knowledge [8] and the use of virtual environments for training has been shown to increase cognitive stimulation over traditional training methods [9], [10].

2 TECHNICAL APPROACH

2.1 Overview of Virtual Training Studio

wide variety of multi-media options such as 3D animations, videos, text, audio, and interactive simulations to create training instructions. The virtual environment enables workers to practice instructions using interactive simulation and hence reduces the need for practicing with physical components. Our system is mainly geared toward cognitive skills; training workers to recognize parts, memorize assembly sequences, and correctly orient the parts in space for assembly. The VTS was designed to be an affordable Personal Virtual Environment (PVE) for training. We developed a low cost wand design and use an off the shelf head mounted display (HMD). The level of physics based modelling that has been placed into the design as well as the hardware selected reflects this design decision. The VTS system architecture is shown in Figure 1.

2.2 Virtual Workspace

One of the modules currently under development is the virtual environment infrastructure called Virtual Workspace. The goal of this component of the VTS is to provide the basic infrastructure for multi-modal learning and to incorporate the appropriate level of physics-based modelling consistent with the operation of a low cost PVE. Virtual Workspace houses the necessary framework to allow manipulation of objects, collision detection, execution of animations, and it integrates the hardware with the software to give the user an intuitive, easy to use interface to the virtual environment. Virtual Workspace also acts as the platform for the Virtual Author and the Virtual Mentor. Logic related to dynamically generating animations based on user's placement of parts and the allowed attachment orientations and locations in a particular phase of the assembly resides in the Virtual Workspace. The current version of the Virtual Workspace places the user in a
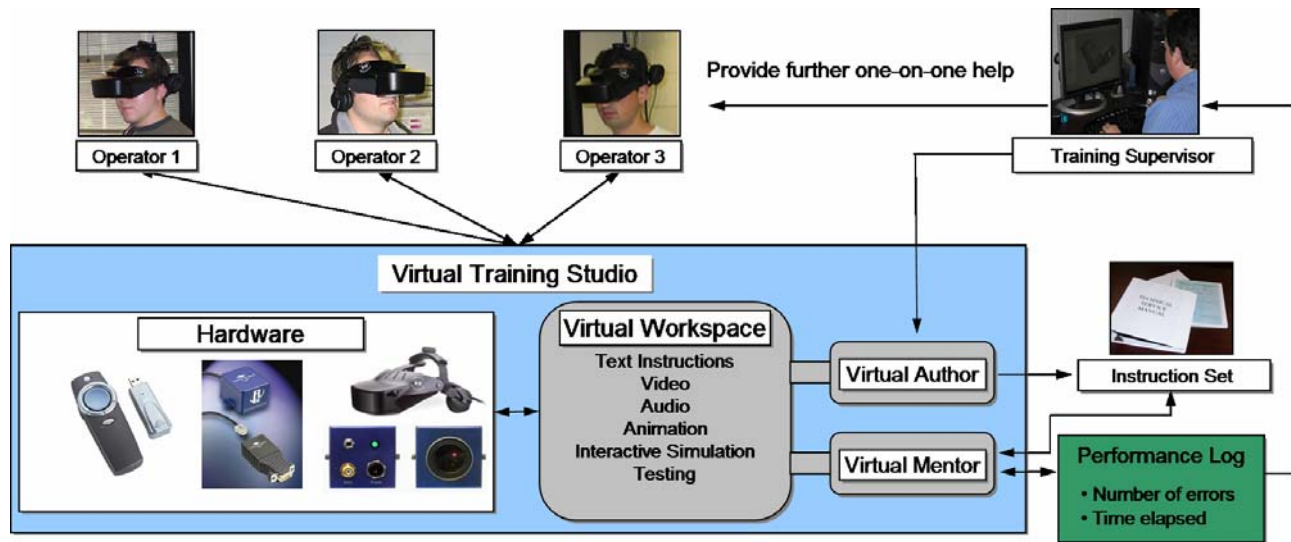

Figure 1. Design of the Virtual Training Studio

One of the goals of the VTS is to ensure that virtual environment based instructions for training personnel in the manufacturing industry can be created quickly so that an overall training cost reduction could potentially be realized through implementation of our system. Another goal is to accelerate the learning process for the trainees through the use of adaptive, multi-modal instructions. With this system, training supervisors have the option of using a

furnished room with a table at the center and a projector screen on one of the walls. Parts used in the tutorial are placed on the table, while video as well as text instructions are displayed on the projector screen. The user interacts with the VE using a single wand, represented in the VE as a virtual laser pointer, to pick up and move objects and to click buttons located on the control panel at the front of the room. The design of the Virtual Workspace also includes the option to interact with the VE through a PC interface. Please see Figure 2 for a screenshot of the Virtual Workspace as

the user would see it through the HMD and see Figure 3 for a picture of a user immersed in the virtual environment.
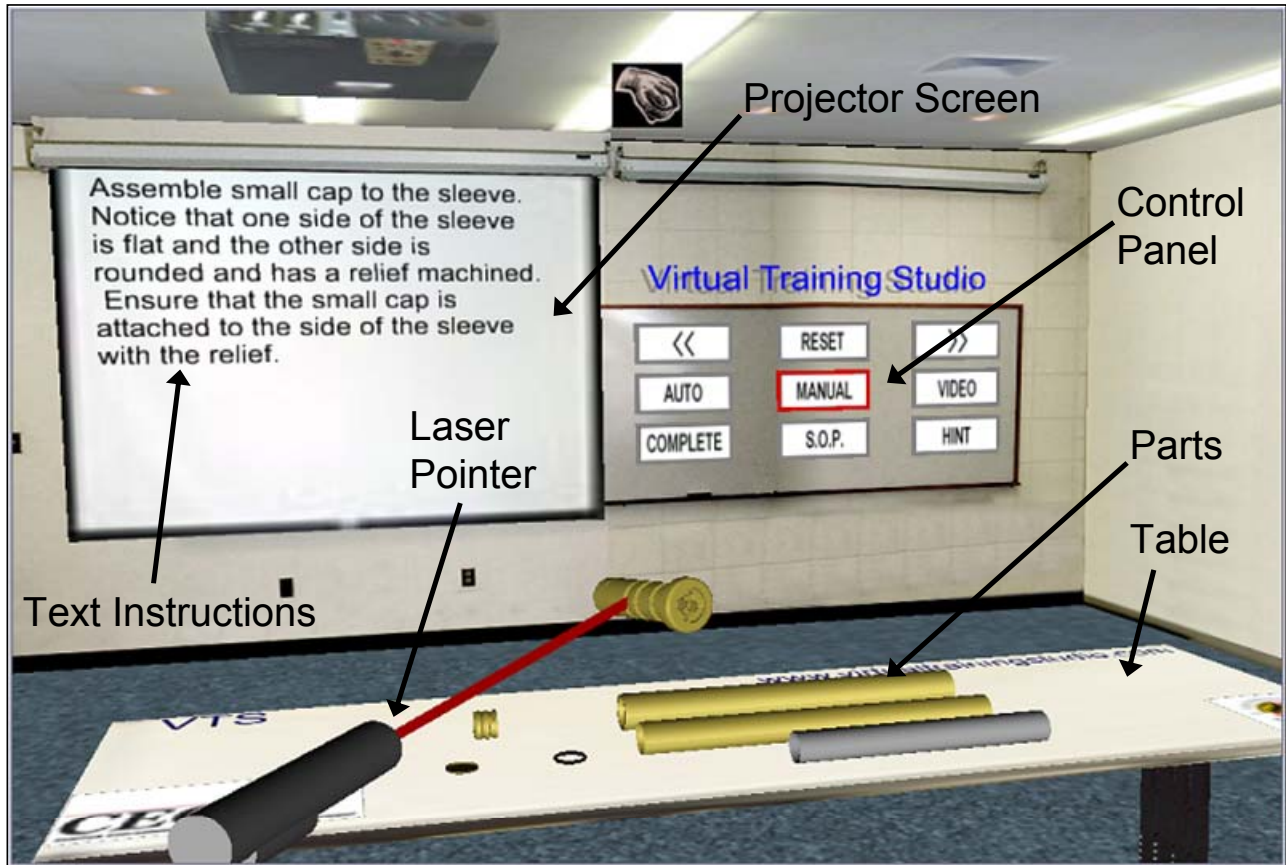

Figure 2. Screenshot of the Virtual Workspace

Figure 3. A user immersed in the virtual environment

2.3 Virtual Author

We are also developing the necessary algorithms as part of a software module called Virtual Author. The goal of the Virtual Author is to enable the user to quickly create a VE-based tutorial and a paper-based manual without performing any programming. Our design allows a human trainer using the VE system to perform a demonstration of the assembly process for the Virtual Author module. The software module then analyzes the demonstration and generates a partial set of text and VE based instructions. The person creating the tutorial (i.e. the author) demonstrates the spatial manipulation (e.g., assembly/disassembly) operations in the virtual environment. The partial set of text instructions is generated automatically by combining data about collision detection and part motion. The module also has the ability to generate 2-D images, for use as visual aids in the text instruction set, from screenshots of the assembly process captured during the tutorial creation. Instructions in the form of animations can also be dynamically generated by recording the assembly paths specified by the instructor and later dynamically creating insertion markers and path markers, which the Virtual Workspace uses for animation. Since the instructor's placement of parts may not be very precise, our plan calls for the system to use segmentation and alignment algorithms in conjunction with collision detection to precisely align and position parts within the overall assembly. In effect, the system, playing the role of a second author, creates most of the

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instructions by observing and analyzing how a human operator carries out the tasks. We believe this module will significantly reduce the time needed to create assembly instructions, in part because it eliminates the need for programming on the part of the trainer. Virtual Author is shown in Figure 4.

them and inserting targeted training sessions. The added details are in the form of additional text/audio instructions as well as visual aids such as arrows and animations. Figure 5 shows some of the tasks of the Virtual Mentor. The main functionalities of this module are described below.
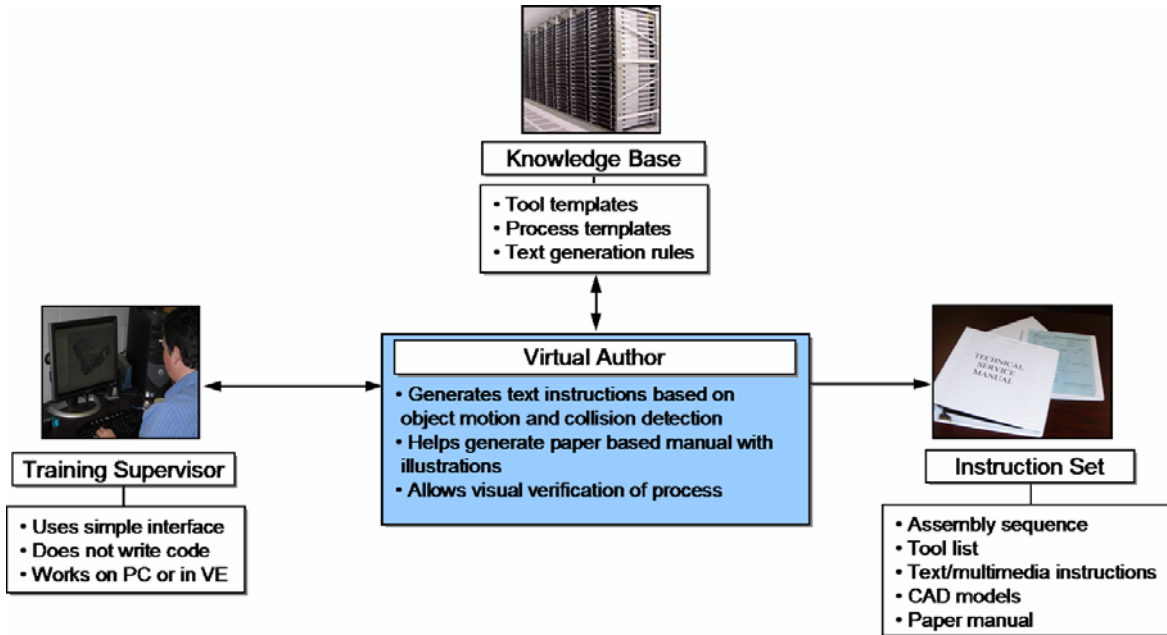

Figure 4. Design of the Virtual Author

2.4 Virtual Mentor

We are also currently developing the necessary algorithms as part of a module called Virtual Mentor. The goal of the Virtual Mentor is to simulate the classical master-apprentice training model by monitoring the actions of the user in the Virtual Workspace and assisting the user at appropriate times to enhance the trainee's understanding of the assembly/disassembly process. If the user makes a mistake during the simulation session, a warning and/or a hint is given to the user. If the user makes repeated errors, then the system attempts to clarify instructions by adding more details in

Error Detection, Error Presentation and Hint Generation: In order to provide detailed error messages and helpful hints in the event of a mistake, the system must first determine exactly what type of error was made. Such a task must be carried out very quickly in order to avoid slowing down the system and interfering with the user's training session. Our design includes the use of a deterministic finite state machine, as well as a multithreading-based algorithm to traverse it, in order to detect error states almost in real time. The system can then generate a descriptive and helpful message based on the attained error state. It is important that trainees receive a very specific and appropriately detailed error message to ensure a complete understanding of the process and to avoid further confusion.

Automatically Adjusting Level of Details in Tutorials: As a result of informal testing of our current system, we discovered the need to provide multiple levels of detail for each step of a tutorial.
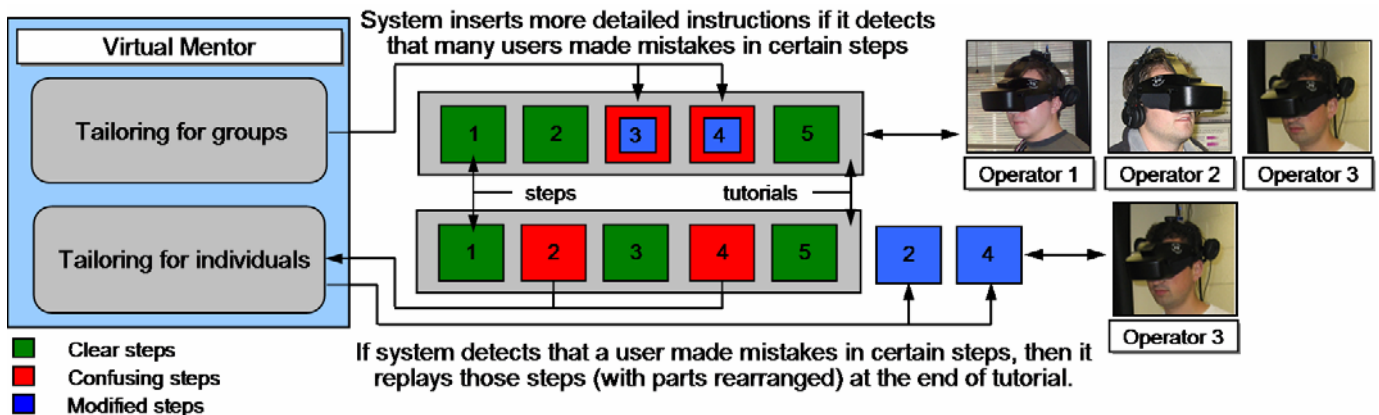

Figure 5. Design of the Virtual Mentor

Through discussions and literature searches, we realized having highly detailed instructions for every single step may slow down the training progress and obscure other details that are important.

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We realized that the system must be able to automatically decide the level of detail that is necessary based on user errors. This function serves a dual purpose. First, it tailors tutorials for each trainee based on their individual performance. Second, it automatically detects and clarifies the potentially confusing areas of the tutorial based on performance of many trainees, therefore allowing the system to make changes to the tutorial on a local and global level.

3   CONCLUSIONS AND FUTURE DIRECTION

Currently we have three separate tutorials for assembly training in the virtual environment. The first tutorial teaches the assembly of a Cartridge Actuated Device (CAD) - a small rocket used in military aircraft ejection seats. The second tutorial teaches the assembly of a single cylinder model airplane engine. Figure 6 shows a screenshot of this tutorial. Figure 7 shows the control panel in the VE and the use of video clips in the airplane engine tutorial. The most recent tutorial teaches the assembly of the front suspension of the University of Maryland Formula Car. Preliminary testing has shown that there appears to be a benefit to training in the virtual environment and that principles being used in the Virtual Mentor module are successful at providing additional details to clarify the training, when necessary. Additionally, the results of a survey conducted with undergraduate engineering students, graduate engineering students and practicing engineers showed that there is interest in virtual environment based training in these demographics when tasked with learning assembly operations.
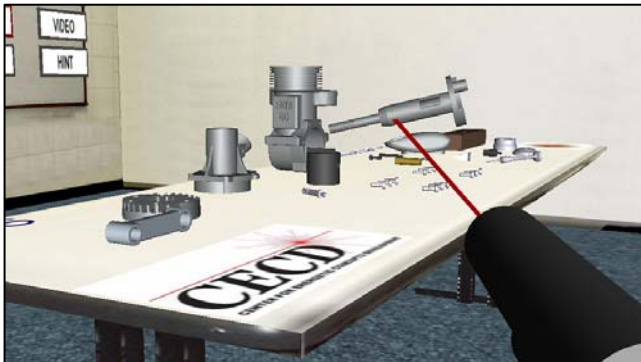

Figure 6. Screenshot of the airplane engine tutorial

We foresee a number benefits from the use of the Virtual Training Studio. First, we believe that the number of personnel required to become trainers will be reduced, since the system will perform the bulk of the training. Second, the system will provide a convenient mechanism for depositing assembly process knowledge into a central repository for later retrieval by trainees, trainers and managers. Third, the VTS will assist instructors in the creation of VE based tutorials and paper based documentation by generating an instruction set from the animation sequence and by providing a convenient way of generating 2D illustrations. Fourth, the system will provide an affordable PVE. Finally, we believe that the most important benefits will be an accelerated learning process as well as a reduced probability of worker error as a result of our novel adaptive training approach.

In the future, we plan to broaden our current design in the area of adaptation and tailoring of the instructions. We believe that our concept of adaptive, multi-modal instructions has great potential to maximize the training effectiveness of tutorials created and operated using our system. Our next generation design calls for more sophisticated techniques for performing automatic detection and clarification of confusing parts of the generated tutorials and for custom tailoring of the generated tutorials to the skills and abilities of individual trainees. We also plan to perform more extensive testing of our system with various demographics so that we can get a better understanding of the learning mechanisms that are occurring and how we can further improve and accelerate the learning process through the use of VTS.

Figure 7. Use of video instructions in the airplane engine tutorial

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4. Concurrent Operations Simulation in Immersive Virtual Reality

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Abstract

Discrete event simulation is often used to identify manufacturing issues early in the design process in order to avoid unnecessary capital investment and significant rework of a manufacturing process. The majority of the simulation software packages currently provide animation capability so designers can visually examine part flow thorough the faculty. These tools, however, confine designers to viewing post-processed simulation results using the traditional two-dimensional computer interfaces, such as the monitor, keyboard and mouse, with limited options for making real-time changes to the simulation scenario.

This paper presents a novel general-purpose simulation analysis application that combines concurrent simulation with the advanced data interrogation and user interaction capabilities of immersive virtual reality systems. The application allows for interactive modification of the simulation parameters, such as assembly tasks' durations, while providing the users with the available simulation information by effectively placing the operator in the midst of the environment being simulated. Implementation and functionality details of the developed application are presented. Feedback from designers who used the application to analyze a proposed manufacturing operation is also discussed.

5. Design Evaluation and Modification of Mechanical Systems in a Virtual Environment

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Abstract

This contribution introduces applications for the visualization of simulations in virtual environments for product evaluation and modification. To investigate design evaluation and modification, two software prototypes have been developed by the authors using VVE technology. First, a software tool for 'Design Evaluation in a Virtual Environment' (DEVE) is presented together with an application in civil engineering to illustrate the mode of operation and added value of the use of VVE. It has been proved that linking the simulation software with the virtual environment for evaluation purposes requires real time bidirectional communication of graphical information which can be successfully achieved with current computer technology. The tool includes a suite of software modules and a user interface to facilitate the link between the simulation results and the virtual environment. The interface allows simulations achieved using conventional Multi-Body Systems (MBS) software such as ADAMS or any other similar computer program implemented by the user.

The second tool aims to facilitate 'Design Modification in a Virtual Environment' (DMVE). For this purpose, a real time dynamic simulation is a further and more demanding requirement. Two dynamic formulations are investigated in order to study the real time simulation issues in the context of design modification: the classic formulation based on rigid interconnected bodies and a new formulation developed by the authors based on particles dynamics. Both implementations have been tested on a mechanism application and in the same computing conditions.

Design Evaluation and Modification of Mechanical Systems

in Virtual Environment

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ABSTRACT

Usually the design process is iterative, involving many evaluations and modifications of the solutions chosen in the earlier stages. For this purpose, the computer simulations became in the last decade common instruments in the industrial environment. This paper introduces applications of the visualization of simulations in virtual environment for product evaluation and modification. The use of visualization in virtual environment (VVE) for simulation offers to the engineer more realistic representations of the design and advanced facilities to interact with the model during the simulation. This facilitates a better understanding and a quicker decision in product development based on more realistic, immersive simulations. From the computational viewpoint, evaluation and modification of the design require different implementations. While design evaluation is based mainly on visualization facilities which could be more sophisticated in case of VVE, design modification requires interactive changes of the model during the simulation. Therefore the real time computation capability is another important issue that has been considered in this paper.

To investigate design evaluation and modification, two software prototypes have been developed by the authors using the VVE technology. First, a software tool for Design Evaluation in Virtual Environment (DEVE) is presented together with an application in civil engineering to illustrate the mode of operation and added value of the use of VVE. It has been proved that linking the simulation software with the virtual environment for evaluation purpose supposes real time bi-directional communication of graphical information which could be successfully achieved with the current computer technology. The tool includes a suite of software modules and a user interface to facilitate the link between the simulation results and the virtual environment. The interface allows simulations achieved using conventional Multi-Body Systems (MBS) software like ADAMS or any other similar computer program implemented by the user.

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The research carried out and the applications presented demonstrate practicality, flexibility and versatility of the VVE technology in design evaluation and modification. However, the computer efficiency in real time dynamic simulation is limiting the range of applications to models of moderated size in the case of design modification.

Keywords: design evaluation, design modification, multi-body system, multi-particle system, virtual environment

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1. INTRODUCTION

Virtual environments (VE) can be used as effective tools for training, education as well as in the product engineering processes. Visualization in VE is the use of computer graphics to create visual images that aid in understanding and interaction during various engineering processes. In case of simulations, this may be the output of real-time numerical simulation or can be based on pre-recorded data or scenario. Non-immersive interactive visualization systems implemented for the conventional desktop and mouse are effective for moderately complex problems, while virtual reality displays provides a richer set of spatial and depth cues with significant added value for complex applications.

For virtual prototyping purposes, conventional MBS software (e.g. ADAMS) offers parameterization possibilities, design evaluation, but they usually compare the results using graphics, tables of data or graphic animations. However, from the user viewpoint the interaction with virtual worlds and realistic behavior of objects is very important. Realistic behavior can help to achieve consistency and predictability, especially when dealing with designing mechanical systems. Therefore, linking simulation and virtual reality is clearly enhancing the design process, offering powerful visual evaluation tools.

Interaction plays a very important role in virtual environments. Virtual reality devices, such as immersive visualization and haptic systems, provide users with powerful new interfaces where they can interact with digital models in 3D. Interactive systems, in software terms, are traditionally associated with the relationship between the user and the software product through the system's interface [5]. In particular, Virtual reality interfaces allow the rapid, interactive and intuitive exploration of the simulations, enabling the phenomena at various places in the volume to be assessed. However, interactivity requires real time processing and this is nowadays one of the main limitations for a breakthrough in this field.

The applications presented in this paper are illustrating the visual evaluation and modification of mechanical systems, integrating the usual interactive facilities offered by a virtual environment (e.g. stereoscopic visualization, walk-through, interactive object handling). The interfaces presented combine various computer programs, for computation of the kinematics and dynamics of the mechanical system, for introducing design modification by changing positions of elements and joints and for exporting simulation data into the virtual environment in which visual evaluation can be easily done.

When Design Modification in Virtual Environment (DMVE) is targeted, ideally a real time computation would enable the user to visualize the modification effect on the design during the simulation and adopt quickly solutions for improvement. However, current computational power is still limiting this possibility in many cases. For the kinematic and dynamic simulation of articulated mechanical systems several formulation are known. A comparative evaluation of efficiency for the various formulations is presented in [7]. However, when the real time simulation is not possible, as far as the type of application allows, DEVE (Design Evaluation in Virtual

Environment) could be achieved using the pre-recorded data alternative.

In this paper approaches for both methods together with an assessment of the potential of the various dynamic formulations for this kind of applications are presented. First the DEVE approach developed by the authors for civil engineering applications is presented, then the real time design modification (DMVE) in each model formulation is described following the classification proposed in [7] and finally a DMVE application for a car suspension mechanism is described.

2. DESIGN EVALUATION IN VIRTUAL ENVIRONMENT

Simulation in a virtual environment provides significant added value in design evaluation especially in the case of civil engineering structures for example at the stage where piping and cabling of the building are designed. At these stages, for which VR assisted design tools already has been fully implemented [8], it is important to know the most stable elements of the building, able to support the cables and pipes, in order to avoid gas losses or electric fires in the event of an earthquake. For this purpose, a simulation software module has been developed by the authors in the larger context of the project IRMA – "A Reconfigurable Multi-purpose Virtual Reality system for Industrial Manufacturing Applications" [10].

The simulation module in virtual environment developed was adapted particularly for applications in civil engineering. The civil engineering metallic structures are usually designed as mechanical systems with zero degree of freedom, although mobile joints like in usual mechanisms are involved (revolute, spherical, etc). The zero degree of freedom allows to precisely designing the force flows in the various branches of the metallic structure. In the first stage of design, the structure is conceived like a mechanism able to transmit the vertical and horizontal forces. In the next stage, the structure mobility is cancelled by articulating further bodies (bracings) into the system. In this way, the effort flows are well established from the very beginning and the structural role of each element is carefully decided. For the purpose of this paper, the application chosen is the simulation of industrial building structure behaviour during earthquake. The software developed includes three modules, devoted to the three main stages in model definition and simulation: pre-processing, processing and post-processing (Fig.1).
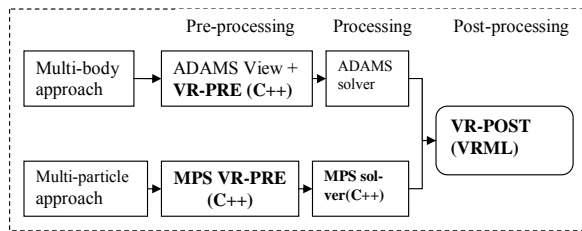

Figure 1. The VR simulation module

For the purpose of visualization in virtual environment, typically the VRML (virtual reality modelling language) file format is employed. In DEVE applications, the limitation originates from the difficulty to convert the graphic scenes in VRML format and communicate them in real time to the virtual environment. Therefore, the research carried out included two cases: (i) the *full scene approach* in which the solid model of the system has been entirely transferred to the virtual world and (ii) the *multi-particle system (MPS) approach* in which the systems has been represented graphically by a collection of spheres, which allow an automatic transfer. For the dynamic simulation module, as fig.1 illustrates, the work included two

parallel approaches (one for each case): (i) the utilization of a commercial solver (the MBS approach) and (ii) the development of a new software, based on MPS formulation approach. The latter allows an easy association of the spheres to the flexible configuration of the various elements of the mechanical system. For both approaches, a pre-processing software module and a common post processing software module have been developed, in order to allow integration and communication with the IRMA VR core software [10].

2.1   The MBS Approach

For the MBS approach the software ADAMS has been used [9], which considers the mechanical system as a collection of interconnected bodies and formulates the motion equations as

$$\begin{cases} [J][\ddot{q}] = [\psi], \\ [m][\ddot{q}] - [J]^T[\lambda] = [Q_{ex}], \end{cases} \quad (1)$$

In (1) the kinematic constraints corresponding to the joints are represented by the algebraic equations of the generalized accelerations $[\ddot{q}]$ and the internal forces are included in the generalized forces vector, $[Q_{ex}]$.
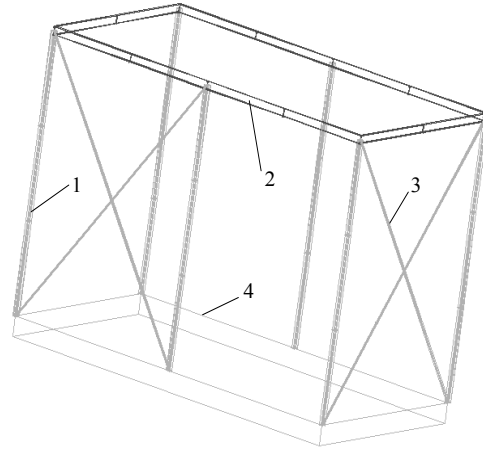

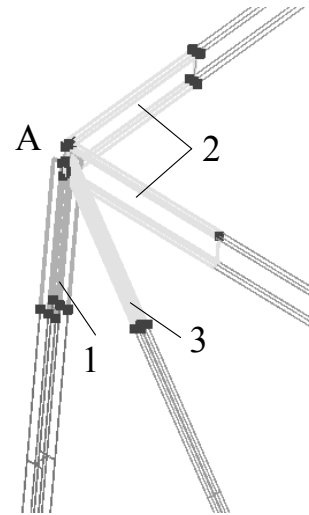Figure 2. The MBS model of the metallic structure

Figure 3. Detail of corner

The internal forces introduced by the flexible beams are modelled as „beam" entities, which introduces spring-damping forces on all six degrees of freedom of the 3D space of the form

$$[F]=[k][\delta]+[c][\dot{\delta}] \qquad (2)$$

in which [k] is the stiffness matrix, [δ] is the deformation vector, [c] is the damping matrix, $[\dot{\delta}]$ is the deformation speed of the beam and $[F]=[F_x \quad F_y \quad F_z \quad M_x \quad M_y \quad M_z]^T$ is the vector of the spring-damping force. The stiffness and damping constants from (2) are determined with relations that depend on shape and dimensions of the real beam (in section and length), as well as materials used. Thus, the geometric input data of the beam model for the MBS software simulation is limited to the description of the profile and the connection points with the adjacent bodies. In principle, modelling a flexible beam in the application handled consisted in its division in a number of rigid segments, linked by elastic beams.
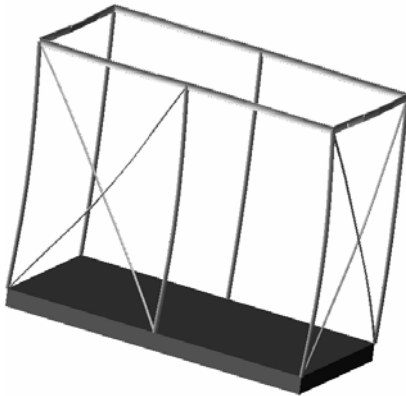

Figure 4. The structure in a deformed stage

In order to illustrate the modelling steps and feasibility of the MBS simulation approach, a simplified metallic structure was selected from a real life project (fig. 2). The metallic structure is part of an industrial plant and includes 6 columns, 6 beams and 4 bracings. These elements are made in steel laminated profiles of I shape of 205x210 mm for the columns (marked with 1), 107x403 mm for beams (2) and 105x107 mm for bracings (3). The dimensions of the metallic structure simulated are: 20 m length, 10 m depth and 14 m high. In the corners of the structure the different kind of elements are linked with revolute joints. In order to avoid the structure to have mobility, bracings are articulated in different perpendicular frames of the structure. The discretisation of the constructive elements into rigid parts is made such as to obtain segments of 2 m length. In this way, the columns have been divided into 7 rigid parts each, the beams in 5 parts and the bracings have been divided in 9 rigid bodies. The building foundation is modelled as a rigid body to which the ground motion is applied (the earthquake ground motion). The columns (i.e. the firsts segments of the columns) are linked by spherical joints to the ground. The first and the last rigid segment of each beam are articulated to the columns by revolute joints. The axes of these joints are perpendicular on the plane of the adjacent bodies, i.e. the beam rigid segment and the column rigid segment. The bracings are linked to the columns through revolute joints in a similar way as the beams. For example, in the corner A from fig. 3 three revolute joints are illustrated: two between the beam segments (2) and column segment (1), respectively the revolute joint between the bracing segment (3) and the column (1). The model obtained has 109 rigid ungrounded bodies, 20 revolute joints, 6 spherical joints and 530 DOF. Out of the foundation body and the end segments of the beams, columns and bracings, all the other segments are not kinematically constrained but only the internal forces (flexible links). The weight of 150N/m², corresponding to the roof has been taken into account by charging each beam with a supplementary mass of 10kg. For the purpose of the simulation the "earthquake" has been introduced as a simple harmonic excitation force on the foundation of the building. This body was linked to the ground by a planar joint in horizontal plane, while the excitation considered was on the direction of the foundation rectangle diagonal, with amplitude of 15kN and frequency of 2Hz. A deformed state of the system is presented in fig.4.

A real life building was fully modelled and simulated also (a full warehouse) in order to demonstrate the method for large systems (fig. 5). This steel-structure building has a larger number of elements and it was modelled as follows: 393 moving parts (not including the grounded body), 133 revolute joints, 22 spherical joints and other 10 fixed joints for the roof elements. The number of the degrees of freedom of the entire model was 1566. The excitation taken into consideration was a real earthquake of magnitude of 6.5 degrees on Richter scale, and the displacement of the base was imposed accordingly. In this case the peak values of the acceleration were: 0.31 m/s² (for up-down direction), 0.77 m/s² and 0.52 m/s² in the horizontal plane and for the displacement 1.6 cm (up-down), 5.4 cm and 2.5 cm (two directions in the horizontal plane). The simulation proved that the structure was supporting easily the earthquake, the most important displacements being recorded at the roof level. The building state in a simulation frame as resulted from ADAMS is shown in fig. 5.
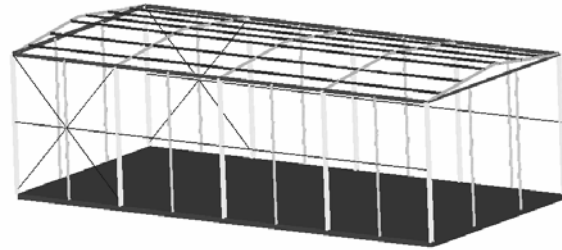

Figure 5. The simulation of the SPES building application

For the virtual reality simulation of this building's behavior the IRMA-VR software has been used [10]. The core integration module is the Delfoi Integrator, a PC based message broker used to link a virtual environment and a production/failure database scenario, to different simulations. In order to use the IRMA VR system, Delfoi software [10] was used to link an Excel database (containing the pre-computed data history of the displacement and rotation of every solid element within the modelled steel structure) with the VRML model of the building in order to obtain the VR simulation. The DEVE module offers facilities to manipulate the simulation in a virtual environment, as freezing the system for measurements of earthquake effects at certain moments of time, zooming, setting up the observer location and attachment (local position, when the observer is located on the building floor and observes the earthquake or global position, when the observer is on a still position), loading the transparent model of the unaffected building and comparing with the current simulation position (fig. 6), taking measurements etc. These facilities are very useful in the evaluation of the design and optimal choice of the piping and cabling paths, to ensure maximum safety.
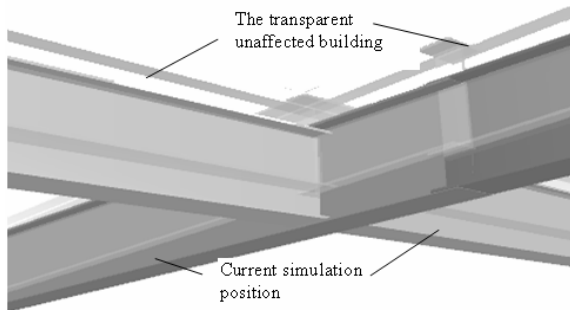
Figure 6. Comparing the simulation with the unaffected position

2.2 The Multi-Particle System (MPS) Approach

For the same purpose (DEVE), a second solver has been developed by the authors based on the MPS formulation. Within this formulation, the rigid bodies are modelled as sub-systems of mass particles that are conserving entirely the original mass properties of the body [7]. This condition requires a minimum number of 4 equivalent mass points in 3D space for each rigid part. The beams, columns and bracings have been divided in the same way as for multi-body approach, and each rigid part was furthermore modelled with a set of 6 mass points in order to facilitate the definition of the mobile and flexible connections between the various bodies. The 6 mass points associated with each rigid part are located at the extremities, in order to facilitate the definition of the spring elements between the two adjacent parts (figure 7). The multi--particle model considers the mechanical system as a *collection of particles* subject to a set of absolute and relative constraints. The main difference with respect to the conventional multi-body models consists in the overall dynamic model which contains no bodies because they are replaced by point masses. From the visualization viewpoint the advantage is that the VRML transfer is done automatically. As the spheres represent particles, no body reference is included and thus the rotational motion which usually characterizes the 3D bodies becomes irrelevant for the case of point masses. The mass matrix and external force vector are computed for particle without relation to any Body Reference Frames. In this way, the body moments of inertia are no more relevant and the mass matrix is very simple. As presented in [7], the mechanism representation includes a *particle based model* for each rigid body and *point contact models* for each type of joint. The *rigid body model* consists in a set of particles separated by constant distances, each particle being associated with a concentrated mass according to the inertial equivalence with the real object.
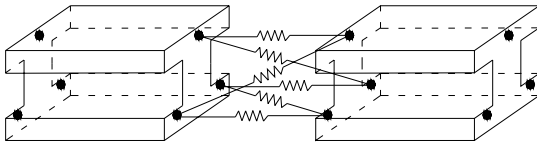

Figure 7. The equivalent spring mass system for a beam modelled by 2 rigid parts

Once the position of the particles is established in the body frame, the point masses can be easily obtained from the inertial equivalence conditions:

$$
\begin{aligned}
&m_1 y_1^2 + m_1 z_1^2 + m_2 y_2^2 + m_2 z_2^2 + m_3 y_3^2 + m_3 z_3^2 + \\
&+ m_4 y_4^2 + m_4 z_4^2 + m_4 y_4^2 + m_6 z_6^2 + m_6 y_6^2 + m_6 z_6^2 = J_{xx} \\
&m_1 x_1^2 + m_1 z_1^2 + m_2 x_2^2 + m_2 z_2^2 + m_3 x_3^2 + m_3 z_3^2 + m_4 x_4^2 + \\
&+ m_4 z_4^2 + m_4 x_4^2 + m_6 z_6^2 + m_6 x_6^2 + m_6 z_6^2 = J_{yy} \\
&m_1 x_1^2 + m_1 y_1^2 + m_2 x_2^2 + m_2 y_2^2 + m_3 x_3^2 + m_3 y_3^2 + m_4 x_4^2 + \\
&+ m_4 y_4^2 + m_4 x_4^2 + m_6 y_6^2 + m_6 x_6^2 + m_6 y_6^2 = J_{zz} \\
&m_1 y_1 z_1 + m_2 y_2 z_2 + m_3 y_3 z_3 + m_4 y_4 z_4 + m_5 y_5 z_5 + \\
&+ m_6 y_6 z_6 = J_{yz} \\
&m_1 x_1 y_1 + m_2 x_2 y_2 + m_3 x_3 y_3 + m_4 x_4 y_4 + m_5 x_5 y_5 + \\
&+ m_6 x_6 y_6 = J_{xy} \\
&m_1 x_1 + m_2 x_2 + m_3 x_3 + m_4 x_4 + m_5 x_5 + m_6 x_6 = 0 \\
&m_1 z_1 x_1 + m_2 z_2 x_2 + m_3 z_3 x_3 + m_4 z_4 x_4 + \\
&+ m_5 z_5 x_5 + m_6 z_6 x_6 = J_{zx} \\
&m_1 y_1 + m_2 y_2 + m_3 y_3 + m_4 y_4 + m_5 y_5 + m_6 y_6 = 0 \\
&m_1 z_1 + m_2 z_2 + m_3 z_3 + m_4 z_4 + m_5 z_5 + m_6 z_6 = 0 \\
&m_1 + m_2 + m_3 + m_4 + m_5 + m_6 = M
\end{aligned}
\tag{3}
$$

The generalized co-ordinate's vector representing the system state space has the form:

$$
[q] = [x_1 \quad y_1 \quad z_1 \quad x_2 \quad y_2 \quad z_2 \quad x_3 \quad y_3 \quad z_3 \quad ... \quad x_p \quad y_p \quad z_p]^T,
\tag{4}
$$

For dynamic simulation, the equations have the same general form as for MBS model

$$
m\ddot{q} - J^T \lambda = Q_{ex},
\tag{5}
$$

in which the mass matrix is a diagonal matrix

$$
m = diag[m_1 \; m_1 \; m_1 \; m_2 \; m_2 \; m_2 \; m_3 \; m_3 \; m_3 \; ... \; m_F \; m_F \; m_F]
\tag{6}
$$

The Lagrange multipliers include the joint reaction forces (including no torques as rotation of point masses is no relevant) and also the constant distance reaction forces between the particles of the rigid bodies.

The application taken into consideration was the same as for multi-body approach (the structural cell of a building, fig. 2). The input data to generate the VRML file includes only the number of mass-points in which the entire metallic structure has been divided. The user tasks in the pre-processing stage, facilitated by the VR-PRE module are:

a. *Geometric modelling* of the mechanical structure - this is performed using the standard capabilities for 3D modelling of AutoCAD geometric modeller,

b. *Discretisation of each element of the structure in smaller rigid parts and association of a set of 6 equivalent mass points to each rigid part - this is performed automatically by a program in AutoLISP able to exploit the AutoCAD geometric model,*

c. *Calculation of equivalent spring-mass system of each element of the structure,*

d. *Generation* of the *input data file* for the MPS based solver module.

The multi-particle model resulted for the structural cell contains the following elements: 745 mass-points corresponding to 113 solid elements, 576 translational springs and dampers, 20 revolute joints, 6 spherical joints, 1 planar joint, 1557 constant distance constraints.

For the virtual reality presentation of the results a graphical user interface has been developed (figure 8) to link the MBS/MPS solver to the IRMA VR software and to enable various tools for comparing different designs and evaluate the simulation results.
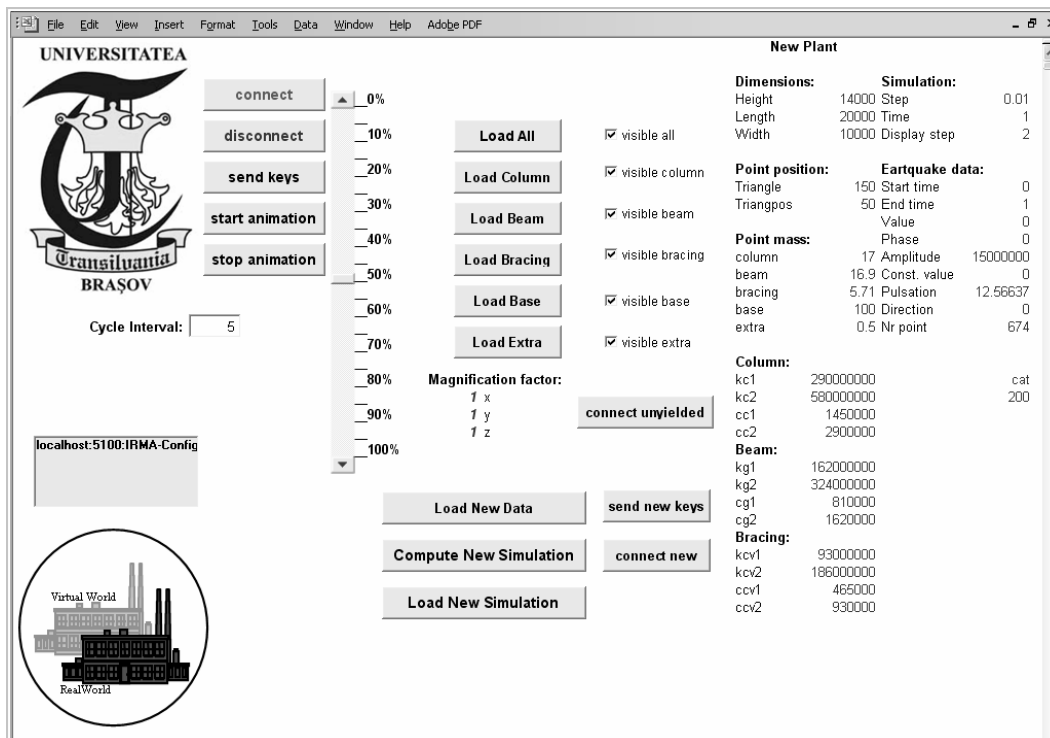
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Figure 8. The GUI for the VR simulation

For comparing different designs, the input data for the solver can be changed with the interface and, after re-computing the structure's behaviour, the new result can be put side by side with the old ones in the virtual reality environment. In addition, magnification factors have been introduced in order to scale building of different dimensions to be able to compare different designs. In figure 9 a VR simulation frame of the structure is shown as displayed by the post-processing module. The spheres corresponding to the point-masses are coloured according to the magnitude of the forces acting on them and provide an indication for the level of local stresses.

2.3   Comparison between MBS and MPS Solvers

Despite of the larger number of equations, the MPS model provides several features with relevance to the non-linear mechanical system simulation:
- The representation of forces and inertial mass properties is significantly simplified.
- The constraints and the corresponding algebraic equations are of small variety. This is simplifying both constraint and Jacobian matrix formulation.

The MPS model allows the extension for the treatment of flexible multi-body systems by replacing the some or all distance equations with the flexibility principles for each body. The computation time for the two approaches for a 1 second simulation in 100 steps and the same external load (amplitude of the 15kN and frequency of 2Hz) are the followings:
- ADAMS, 1.02 min (Adams-Bashforth-Moulton integration method)
- C++ application, 18.7 min (backwards Euler integration method)
- MATLAB-version of the MPS solver, 20.77min (backwards Euler integration method)

The MPS formulation is obviously computationally slower, since the number of equations is much higher than the MBS formulation. However, in case of similar conditions of implementation, for large systems the difference is much smaller as shown in [7]. In the presented case a body is represented by 6 mass points which generate 6x3=18 differential equations plus 12 algebraic constant distance equations to model the rigid body conditions, that is 18+12=30 DAE equations per body, comparatively with 6 differential equations per body in MBS formulation. Although from a general perspective the MPS approach is attractive, for the real time simulation it has disadvantage in the increased number of entities describing the model (for each body at least four points are required, while in MBS approach one body=one entity). This is requiring longer times, in the post-processing stage as well, for communicating the results and up-dating the geometry. However, as only one type of geometric entity is involved, the up-dating process can be made automatically.
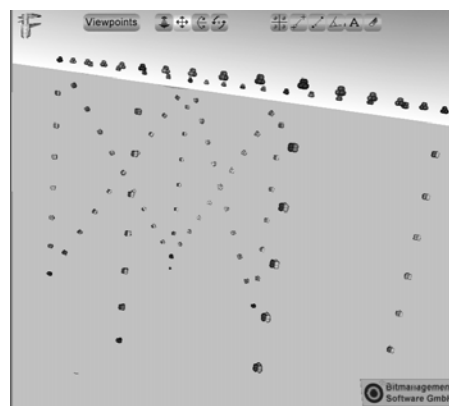

Figure 9. MPS simulation of the structure

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The post-processor achieved, VR-Post allows to present the results in both approaches and allows the user to freeze the system in a desired state, take measurements of the displacements, to display the strength in the beam segments in a similar manner as in conventional FEM packages (colored elements), to walk into the structure and „see" in more detail the behavior of the respective structure part during the earthquake. This set of VR facilities is offering to the user the possibility to evaluate the behavior of the various building elements during earthquake and take appropriate decisions for reinforcement or choice of the path for the infrastructure paths.

3. DESIGN MODIFICATION IN VIRTUAL ENVIRONMENT

Making a design modification on the mechanical system means that the input data file, which contains all the information about the linkage, has to be changed accordingly and normally the simulation should be run again with the new set of data as it were a totally different system. However, using the previous approach, real time simulation is possible only for simple systems.

The alternative proposed in this paper is to reuse the results of the initial system and compute only the modifications with an incremental computation approach. In case of the mechanisms, without altering the number of bodies which defines the mechanical system and the type of connections between them, the design modification can be done by modifying the position of a joint or modifying the position of a body. As it is known the most common joint employed in planar linkages are the revolute and translational joints. In order to enhance the efficiency, for design modification, the incremental computation allows the computation of the modified simulation using the initial structure thread, in which some of the variables are already available from the initial evaluation. Because no change has been considered in the structure of the system, the modifications in the input data file will depend on the method used for describing the system, as the methods presented are using different sets of geometric parameters Therefore, in what follows, the mathematical formulation for design modification is presented for each of the two formulation (MBS and MPS).

3.1 Design Modification Employed in Multi-Body System Formulation

In the multi-body system formulation, the Cartesian coordinates of the elements are used mostly for the description of the system [4]. According to this, the generalized coordinates of the system are the position and orientation of each mobile element (most often the origin coordinates and the orientation angle with respect to the Global Reference Frame – GRF). Not all the coordinates are independent because of the geometrical constraints introduced by the joints. Each constraint is represented by a geometric condition written mathematically as an algebraic equation linking the generalized coordinates of the adjacent bodies. The structure of the entire system can be described by the position of the elements and at the coordinates of point, which defines the joints.

Modifying the position of a revolute joint implies the modification of the local coordinates of the two points which define the revolute joint, other data about the mechanism remains unaffected (in the equations of revolute joints it is usually considered that two point of two bodies are in the same place during the simulation). The new coordinates of the two points (P_i, P_j) in their local frame (fig. 10) can be computed knowing their original coordinates (x_{Pi}^i, y_{Pi}^i, x_{Pj}^j, x_{Pj}^j,), the

orientation angle of the two bodies (φ_i, φ_j) and the revolute joint modification values (Δx_r, Δy_r):

$$\begin{bmatrix} x_{Pi}^i \\ y_{Pi}^i \end{bmatrix}_{new} = \begin{bmatrix} x_{Pi}^i \\ y_{Pi}^i \end{bmatrix} + \begin{bmatrix} \cos\varphi_i & -\sin\varphi_i \\ \sin\varphi_i & \cos\varphi_i \end{bmatrix} \cdot \begin{bmatrix} \Delta x_r \\ \Delta y_r \end{bmatrix} \quad (7)$$

$$\begin{bmatrix} x_{Pj}^j \\ y_{Pj}^j \end{bmatrix}_{new.} = \begin{bmatrix} x_{Pj}^j \\ y_{Pj}^j \end{bmatrix} + \begin{bmatrix} \cos\varphi_j & -\sin\varphi_j \\ \sin\varphi_j & \cos\varphi_j \end{bmatrix} \cdot \begin{bmatrix} \Delta x_r \\ \Delta y_r \end{bmatrix} \quad (8)$$

The translational joint is usually defined by 4 point (P_i, Q_i, P_j, Q_j,), two on each body (fig. 11), which lies on the same line. Modifying the position of the joint in a parallel position has no effect on the kinematics and little on the dynamics. More radical c onsequence on the behaviour can be achieved by rotating the joint's line (fig. 11).

Presuming that the point P_i is not changing its position (is in the centre of the rotation), than, in the input data file, the local coordinates of the other 3 points has to be changed. If the joint's rotation angle is Δa_t (the original angle is α), then new coordinates will be:
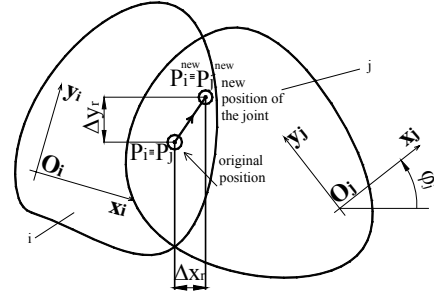

Figure 10.   Modification of a revolute joint translational joint

$$\begin{bmatrix} x_{Qi}^i \\ y_{Qi}^i \end{bmatrix}_{new} = \begin{bmatrix} x_{Pi}^i \\ y_{Pi}^i \end{bmatrix} + \begin{bmatrix} d_{PiQi} \cdot \cos(\alpha + \Delta a_t) \\ d_{PiQi} \cdot \sin(\alpha + \Delta a_t) \end{bmatrix} = $$
$$= \begin{bmatrix} \cos\Delta a_t & -\sin\Delta a_t \\ \sin\Delta a_t & \cos\Delta a_t \end{bmatrix} \cdot \begin{bmatrix} x_{Qi}^i - x_{Pi}^i \\ y_{Qi}^i - y_{Pi}^i \end{bmatrix} \quad (9)$$
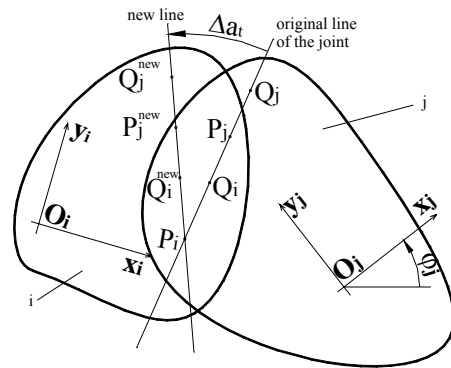

Figure 11.   Modification of a translational joint

$$\begin{bmatrix} x_{Pj}^j \\ y_{Pj}^j \end{bmatrix}_{new} = \begin{bmatrix} \cos\varphi_j & \sin\varphi_j \\ -\sin\varphi_j & \cos\varphi_j \end{bmatrix} \cdot $$
$$\cdot \left(\begin{bmatrix} x_{Pi} \\ y_{Pi} \end{bmatrix} + \begin{bmatrix} \cos\Delta a_t & -\sin\Delta a_t \\ \sin\Delta a_t & \cos\Delta a_t \end{bmatrix} \cdot \begin{bmatrix} x_{Pj} - x_{Pi} \\ y_{Pj} - y_{Pi} \end{bmatrix} - \begin{bmatrix} x_{Oj} \\ y_{Oj} \end{bmatrix} \right) \quad (10)$$

$$\begin{bmatrix} x_{Qj}{}^{j} \\ y_{Qj}{}^{j} \end{bmatrix}_{new} = \begin{bmatrix} \cos\varphi_j & \sin\varphi_j \\ -\sin\varphi_j & \cos\varphi_j \end{bmatrix} \cdot$$

$$\cdot \left(\begin{bmatrix} x_{Oi} - x_{Oj} \\ y_{Oi} - y_{Oj} \end{bmatrix} + \begin{bmatrix} \cos\varphi_i & \sin\varphi_i \\ -\sin\varphi_i & \cos\varphi_i \end{bmatrix} \cdot \begin{bmatrix} x_{Pi}{}^{i} \\ y_{Pi}{}^{i} \end{bmatrix} \cdot \right. \qquad (11)$$

$$\left. \cdot \begin{bmatrix} \cos\Delta a_t & -\sin\Delta a_t \\ \sin\Delta a_t & \cos\Delta a_t \end{bmatrix} \cdot \begin{bmatrix} x_{Qj} - x_{Pi} \\ y_{Qj} - y_{Pi} \end{bmatrix} \right)$$

The consequence of the modification of a body's position or orientation angle will be that other elements, which are linked to it, will have their geometry altered. Because joint are described using points, in the input data file only the coordinates of those points will be modified which describes the modified body's joints. Position of external loads, springs and damper are also described by point. If these elements position is influenced by the position of the body on which they act, than the coordinates of those points will also change accordingly.

If body i position is modified by Δx_e, Δy_e (fig. 12) and it is linked with a revolute joint to body j, than only the P_j's coordinates will change, P_i's coordinates, in the local reference frame, remaining the same. The new coordinate of P_j can be written as:

$$\begin{bmatrix} x_{Pj}{}^{j} \\ y_{Pj}{}^{j} \end{bmatrix}_{new} = \begin{bmatrix} x_{Pj}{}^{j} \\ y_{Pj}{}^{j} \end{bmatrix} - \begin{bmatrix} \Delta x_e{}^{j} \\ \Delta y_e{}^{j} \end{bmatrix} =$$

$$= \begin{bmatrix} x_{Pj}{}^{j} \\ y_{Pj}{}^{j} \end{bmatrix} - \begin{bmatrix} \cos\varphi_j & -\sin\varphi_j \\ \sin\varphi_j & \cos\varphi_j \end{bmatrix} \cdot \begin{bmatrix} \Delta x_e \\ \Delta y_e \end{bmatrix} \qquad (12)$$

In case of the modification of the orientation angle (φ_i) of the body i with Δu_a and this element is linked by a translational joint to body j, than the coordinates of P_j and Q_j will be modified in the input data file. For P_j the coordinates are (for Q_j is similar):

$$\begin{bmatrix} x_{Pj}{}^{j} \\ y_{Pj}{}^{j} \end{bmatrix}_{new} = \begin{bmatrix} x_{Pj}{}^{j} \\ y_{Pj}{}^{j} \end{bmatrix} - \begin{bmatrix} \cos(\varphi_j - \varphi_i) & -\sin(\varphi_j - \varphi_i) \\ \sin(\varphi_j - \varphi_i) & \cos(\varphi_j - \varphi_i) \end{bmatrix} \cdot$$

$$\cdot \left(\begin{bmatrix} \cos\Delta u_a & -\sin\Delta u_a \\ \sin\Delta u_a & \cos\Delta u_a \end{bmatrix} \cdot \begin{bmatrix} x_{Pi}{}^{i} \\ y_{Pi}{}^{i} \end{bmatrix} - \begin{bmatrix} x_{Pi}{}^{i} \\ y_{Pi}{}^{i} \end{bmatrix} \right) \qquad (13)$$

Other modifications in the position of joints can be written in the same manner.
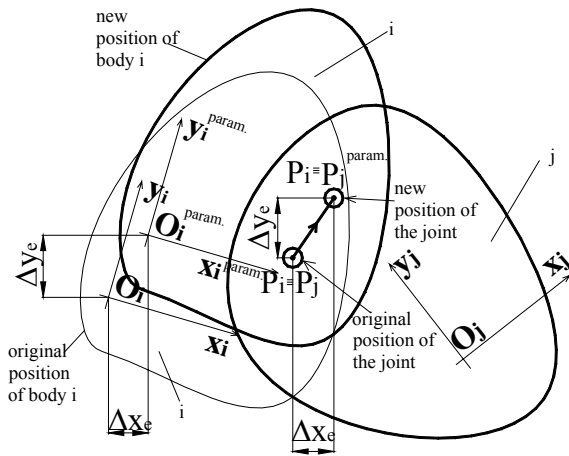

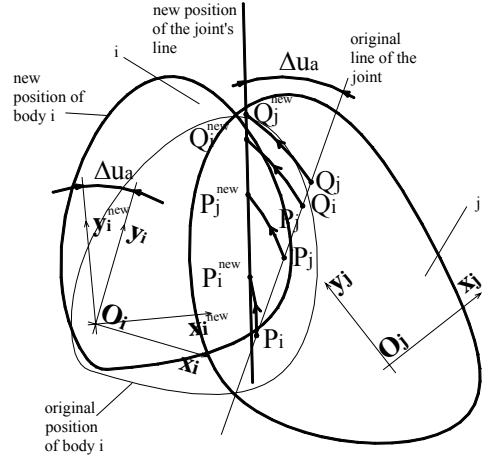Figure 12.   Modification of a body's position

Figure 13.   Modification of a body's orientation

3.2   Design Modification with Multi-Particle System Formulation

The multi-particle system formulation is based on the coordinates of points in the global reference frame [7]. Because in the VE the user is modifying the coordinates of some points, all these modifications will be naturally reflected in the input data file by incrementally modifying the coordinates of the points involved:

$$\begin{bmatrix} x_{Pi} \\ y_{Pi} \end{bmatrix}_{new} = \begin{bmatrix} x_{Pi} \\ y_{Pi} \end{bmatrix} + \begin{bmatrix} \Delta x_{P_i} \\ \Delta y_{P_i} \end{bmatrix}$$

Therefore, the MPS formulation can be straightforward used for DMVE applications.

3.3   Interactive Design Modification with MBS and MPS Solvers

In the interactive design modification process the efficiency of the dynamic solver has crucial role in achieving realism. In the comparison process of the two solvers two applications were developed. In both cases the mechanical system is considered in the same manner a collection of rigid bodies and of mass-points, connected by various constrains. The applications are processing a text file (the input file) which contains all the data needed about the mechanism in the simulation process. This file contains data about the analysis type (kinematic or dynamic), time interval of the simulation (including the computation step), initial position and orientation of each element (in the MBS case), coordinates of point which describes various element (joints, forces, springs, dampers), joints (revolute, translational and composite joints), driving motions, mass properties of the elements, external forces, springs and dampers [2].

The developed programs are using a Cartesian coordinate approach [4]. The constraints on the motions of the bodies due to the joints are formulated in terms of Cartesian generalized coordinates (position and, in the MBS formulation, orientation of a mobile reference frame assigned to each element). In the computational modules (2 and 5) are solved with Adams-Bashforth-Moulton predictor - corrector method, and Baumgarte stabilization for reducing the constraints violation. The design modifications can be made interactive, with the

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mouse, using touch sensors implemented in the VRML file. The user can modify position of bodies and joints with the mouse, during the computational processes. The communication with the VE is made by the Matlab's Virtual Reality Toolbox. This resulted in the integration of a near real-time dynamics and kinematics computational engine with the interactive VRML world.

The computational time needed for the MBS formulation was 12% smaller than for the MPS model, although the dynamic formulation and the implementation of the modifications involved were much easier implemented in the latter.

In fig. 14 and 15 such an interactive simulation frames are presented. For an automotive suspension mechanism, the revolute joint's position of the lower arm can be interactively changed with the mouse in the touch sensor aria during the computation process.
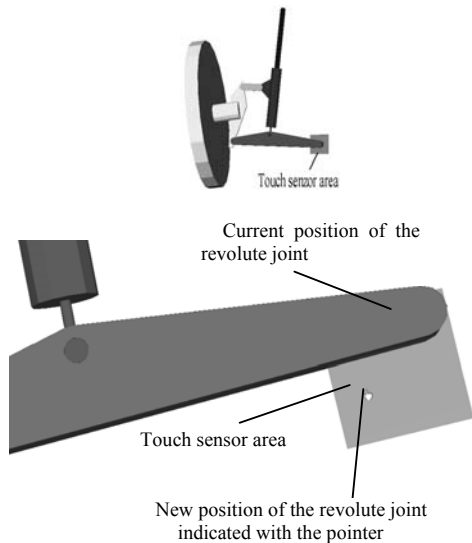

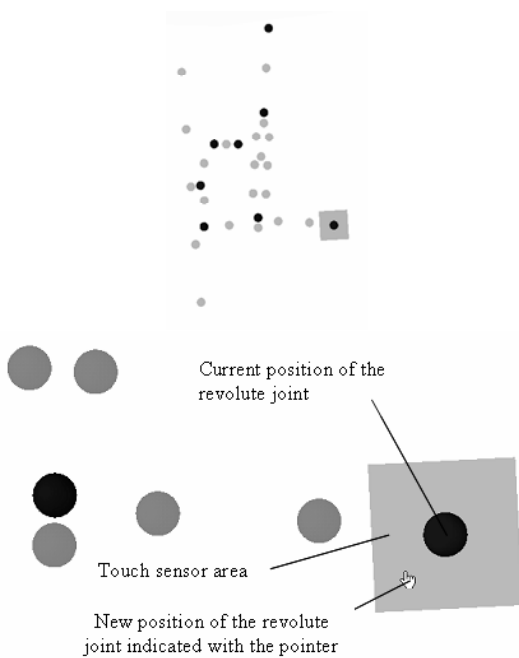Figure 14. Interactive simulation with the MBS formulation

Figure 15. Interactive simulation with the MPS formulation

In fig. 15 the lighter spheres are added with the purpose of reconstructing the original shape of the elements involved and they are not influencing the dynamic behavior of the system. Its number depends on how accurately the user is intending to reconstruct the original shape. If a certain region or point behavior is under investigation, than only in that region are needed the supplemental spheres.

4. CONCLUSIONS

The application of VVE for product evaluation and modification has been presented. It has been shown that the mathematical formulations for evaluation and modification applications are different. While for the evaluation purposes the usual dynamic formulations could be used (MBS, MPS or others), for modification an incremental formulation must be used in order to enhance the simulation efficiency.

Two applications have been presented in order to illustrate the concepts, the interfaces and the interaction metaphors: a complex civil engineering structure for the DEVE module and a car suspension mechanism for the DMVE module. It has been demonstrated that simulation could be linked to VVE and new facilities interesting from the design process viewpoint are added for the user.

For the evaluation process the MBS formulation is much more suitable because of the original shapes of the element's of the mechanical system are maintained. However, when modification is involved, the shape of the elements has to be changed accordingly. A way of achieving this is by employing the MPS formulation. Nevertheless the computation time increases, but the formulation is much easier for both the dynamic formulation and the implementation of the changes. For a certain region of the system more points can be added and their path can be visually followed in the VE.

With some minor modification on the multibody system by moving one or more bodies, or changing the position of one or more joints the entire behaviour (kinematic or dynamic) can be changed. The modification can be easily followed and evaluated in the virtual environment due to the facilities offered by the VR interface: the two animations can be superimposed, various elements can be hidden, the transparency of the models can be modified for better visual evaluation of the consequences of the changes or the changes can be made interactively with the joystick or mouse in case of desktop VR applications. The visualization software also offers measuring tools for distances and angles. As a result, the virtual environments can be developed in a way that all work can be done there without having to leave the environment.

The research carried out and the applications presented demonstrate practicality, flexibility and versatility of the VVE technology in design evaluation and modification. However, the computer efficiency in real time dynamic simulation is limiting the range of applications to models of moderated size in the case of design modification.

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6. A Haptic Assembly, Machining and Manufacturing System (HAMMS) Approach

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Abstract

Virtual design and assembly systems are engineering applications that allow engineers to plan, evaluate, and verify the machining of mechanical components. These environments range from typical projections of 3D objects onto a 2D display (e.g. monitor) to a fully immersive virtual environment often tightly coupled with Computer Aided Design (CAD) systems. Although digital representations provide data for *downstream* manufacturing and assembly processes, the impact of tacit information and interaction has largely been sidestepped. Visual perceptions are important, however, it is tactile feedback that humans rely upon for interaction. Haptic interfaces have the potential to do this for 3D data and still provide realistic interaction with parts in the virtual environment. This paper presents an experimental haptic human-computer interface as a cognitive tool that enhances the product development process. The interface aims to support the user in assessing, for example, component surface quality and tool wear as a function of machining using physical-based modeling. The objective is to study human factors associated in these virtual domains and to quantify the impact of Haptics on productivity.

7. A Dual-Handed Haptic Interface for Virtual Assembly

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Abstract

Virtual Prototyping techniques are increasingly used throughout the design process to simulate components of the product realization process related to design, manufacture and assembly of components. Using virtual reality technology these techniques provide an immersive and intuitive environment which can be used as a digital test-bed for early prototypes. The work presented here describes the development of SHARP (System for Haptic Assembly & Realistic Prototyping), a portable VR interface for virtual assembly.

Physically-based modeling is used for simulating realistic part-to-part and hand-to-part interactions. A dual handed haptic interface using the PHANToM® haptic devices is developed for providing realistic part interactions. The capability of creating subassemblies enhances the application's ability to handle a variety of assembly scenarios. Swept volumes are implemented for addressing assembly and maintainability issues. A network module is added for communicating with VR systems at dispersed geographic locations for promoting collaborative design and development. Support for various types of VR systems allows an easier integration of SHARP into the product design process resulting in faster product development, easy identification of assembly and design issues and a more efficient and less costly product design process.

Industrial CAD models from a John Deere hitch are successfully assembled using SHARP.

8. A Structural Assessment of Haptic-based Assembly Processes

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Abstract

Computer-aided assembly systems provide engineers a useful diagnostic and analytical tool in the design of mechanisms and form-fit-function features. These virtual environments employ a variety of spatial snapping and alignment techniques for part placement and attachment. The advent of haptics and its integration into virtual assembly systems now allows users the added advantage of tactile information. Of interest here, is how the application of a haptic-based system can affect productivity and its qualification of design parameters. In this paper a structural approach is undertaken to establish basic metrics for human-computer interaction procedures in assembly processes in relation to component design. It is envisaged that this study can be used to identify assembly/disassembly motions against part shape to generate effective process plans.

9. Digital Archive of Manufacturing Knowledge based on Virtual Manufacturing

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Abstract

The author has studied virtual manufacturing systems from 1991 and has conducted VirtualWorks project, which was started at Osaka University and moved to Hokkaido University at 2003.

VirtualWorks project includes the system architecture of virtual manufacturing system, the object modeling method, VR interface, and real machine interface.

After 2000, VirtualWorks has been applied for keeping manufacturing knowledge in active form and it can expand the application of virtual manufacturing from the modeling and simulation tools to the knowledge management platform.

In the workshop, the author will explain the historical issues of 15 years VirtualWorks project and the future research plan for practical use of virtual manufacturing technologies.

Digital Archive of Manufacturing Knowledge

based on Virtual Manufacturing

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ABSTRACT

The author has been running a R&D project for virtual manufacturing systems from 1991. The project, named VirtualWorks project, includes research items about a system architecture, an object modeling method, VR interfaces, real world interfaces, digital human models, and others. In the last five years, VirtualWorks has been mainly applied for knowledge management problems in manufacturing knowledge in order to expand the application fields of virtual manufacturing from just modeling and simulation tools to a knowledge management platform.

Keywords : virtual manufacturing, knowledge

1   INTRODUCTION

Digital manufacturing is a key concept of manufacturing in this IT age. Most manufacturing activities such as designing, planning, controlling, operating, and monitoring are performed or supported by computer systems and communication networks with advanced IT. In such digital working environment, production engineers should carry out a considerable part of their works via the computer interface without facing to the real manufacturing systems. The digital world coming out with computers is going to split the conceptual world and the real world. These two worlds are now connected by electronic data via the digital world. A virtual manufacturing, which is constructed and operated in the digital world of computer systems, is a clear image of the goal for IT enhanced manufacturing.

Manufacturing systems are going toward the knowledge-intensive ones under rapid innovation of digital manufacturing. Now, we have a very important problem: how to realize knowledge-intensive manufacturing in the context of digital manufacturing. As one answer to this problem, I have been developing a digital archive of manufacturing knowledge based on virtual manufacturing.

2   VIRTUALWORKS

For the integrated modelling and simulation system, the author's research group has been developing a virtual shopfloor construction environment named VirtualWoks from 1991.[1]-[4] The main features of VirtualWorks are summarized as follows.
- Supporting object oriented modelling with 3D models.
- Executing time-driven simulation of device behavior by using 3D models and physical constrains.
- Providing an open system architecture for distributed and parallel computing.[5]
- Enabling a read-virtual data exchange mechanism by using proxy objects.
- Handling various modelling elements including workpieces, tools, information networks, NC programs, and shopfloor workers (digital human models [8]).
- Providing different types of user interface including stereo graphics, 3D sounds, motion capture, head-mounted display and a haptic display.[6][7]

An example of a virtual shopfloor built with VirtualWorks is shown in Figure 1. VirtualWorks is developed by using
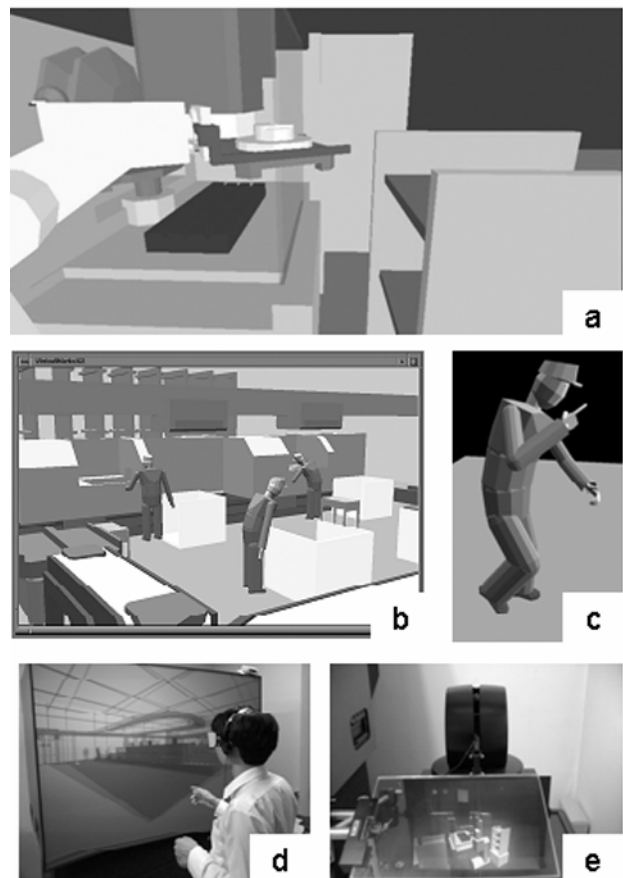

Figure 1: Overviews of VirtualWorks
a: assembly cell, b: shopfloor with workers, c: digital human model, d: stereo view e: stereo view + haptic device interface (XEONA)

EUSLISP, an object oriented robot programming language developed by Dr. T. Matsui at National Institute of Advanced Industrial Science and Technology (AIST)[9]. VirtualWorks has high flexibility and interactivity such as dynamic object modification and incremental program loading.

3 DIGITAL ARCHIVE OF MANUFACTURING KNOWLEDGE

The author has been joining a research group for manufacturing knowledge management. The main interest of the group is summarized as follows.

How can we enhance manufacturing knowledge in industry by using new technologies of information processing and communication?

Several experiences of system development for knowledge processing give us an important observation that symbolic representations conventionally used in artifitial intelligence (AI) and knowledge engineering (KE) have difficulties for describing manufacturing situation and it leads us to the following remarks.

Knowledge as a whole system
It is almost impossible to extract and describe knowledge itself explicitly. What we call knowledge in a usual sense is just an interpretation on brain's performance about a certain task. If you can do task-A well, then I can say that you have knowledge of A. What you have in your brain is a whole 'knowledge system', not just a collection of knowledge segments.

Recording evidence of knowledge utilization
While the direct extraction of knowledge from experts is almost infeasible, we can record the evidential data of knowledge utilization by monitoring expert's actions and speaking voices. Comparing our knowledge as a black box function, we can indirectly presume the function by collecting data about input-output relations. When we want to understand our knowledge, one stable but laborious approach is to collect its 'input-output relations' as many as possible.

Transferring knowledge by exchanging the evidential data of knowledge application
Getting the evidential data of problem solving from an expert, one may be able to extend his own knowledge so as to solve the problem. In this case we can recognize that 'knowledge' is transferred from the expert to somebody other. As argued above, knowledge itself cannot be extracted and represented, but we can transfer knowledge indirectly via data of knowledge application processes. The point is to find the most effective way of presenting evidential data of knowledge application processes.

Based on the remarks above mentioned, the question is now rephrased as follows.

How can we get and utilize the evidential data of expert's knowledge application with which other non-experts can extend their knowledge by using new technologies of information processing and communication?

Traditional ways of knowledge transfer from a master to pupils frequently tell us that a master cannot teach knowledge and skills directly to pupils. Pupils should learn such knowledge and skills by observing the master's doing and by repeating it by themselves. The key concept of this approach is 'context'. A master and pupils in the traditional training share the context of knowledge utilization by working together and
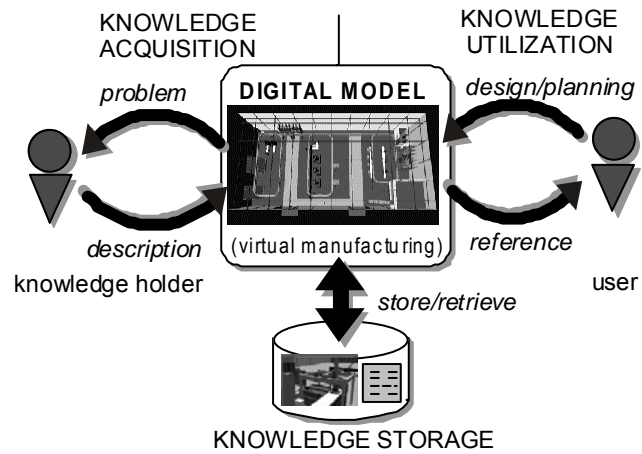

Figure 2: Configuration of Active Knowledge Archive

pupils can understand the means of the master's doing in the context. The subject of this research is to realize the context sharing for manufacturing knowledge transfer by using current advanced technology of information processing and communication.

In order to support the context-oriented description of knowledge application, the author has proposed an approach based on virtual manufacturing. The problem/task situation to be solved is presented as a model of an integrated modeling and simulation system such as virtual manufacturing. An expert understands the situation by observing the model via computer graphics and evaluates it using computer simulation.

The expert operates and improves the initial situation model by using his/her knowledge. The operations to the model are automatically recorded in a virtual manufacturing system. The description items which cannot be reflected on the model operations should be explicitly input to the system by the expert through an automatic dictation or text typing. These additional data associated to virtual models are named eK-record.

An each case of knowledge application is represented as the resulted model in the integrated modeling and simulation system. The solved point or improved performance can be directly examined on the revised model by executing computer simulation in virtual manufacturing environment. Information about alternative actions and evaluation should be entered to the system by the experts or by other reviewers. Once eK-records are stored in the system, the sequence of knowledge utilization processes can be played back and presented to other people. Figure 2 illustrates the basic concept of Active Knowledge Archive.

If designers or engineers want to solve a new problem/task such as facility design, machine layout, production process planning, and robot programming, using the virtual manufacturing system, it is helpful for them to refer to the previous experiences by other experts stored in the system. Since the initial model of the current problem/task is also represented in the system, the model data is used to find previous cases of solving a problem/task. The result of problem solving is also added to the system as executable data of operation history.

This framework of knowledge acquisition, storage, and utilization including methods, systems and eK-records is named Active Knowledge Archive. In this framework the evidential data of applying expert's knowledge are recorded as the 'active' knowledge in the practical situation. The contents of the

knowledge archive are not stable. The knowledge archive is always active because it is dynamically revised by new tasks or new evaluations, and data stored in the archive may be appropriately interpreted and organized for a specific purpose.

4   SYSTEM IMPLEMENTATION

Active Knowledge Archive has been implemented on VirtualWorks.[10[11] A new mechanism which manages the correspondence between model objects and eK-records is introduced to construct Active Knowledge Archive. The author has named it 'Knowledge Tag'. A Knowledge Tag shows the existence of a knowledge application record on an entity in VirtualWorks. In this implementation, each Knowledge Tag has one of six colors on computer display so as to distinguish their categories of the default classification of knowledge application. Each Knowledge Tag has attributes of a spatial region and a time interval which specify the knowledge application region and process time in the 4D space by modeling and simulation shown in Fig. 3. When a Knowledge Tag becomes active, a graphical symbol appears nearby the corresponding entity and a user can select it by pointing with a mouse or other interface devices. The selected Knowledge Tag sends the data of Universal Resource Identifier (URI) to the eK-record browsing system described next.

In order to generate the designated situation in VirtualWorks from eK-record, 'Virtual World Situation Identifier' (VWSI) is newly introduced. VWSI specifies a base definition file of factory models, the revision number for model generation, and the spatial region and the process interval to be focused. VirtualWorks interprets VWSI and loads model data files and differential files, and executes process simulation until the specified time in order to generate the specified situation in VirualWorks.

Each eK-record is described in a XML (eXtensible Markup Language) style including links to other contents. Document Type Definition (DTD) for XML files is prepared based on the description items shown in Table 1. For giving the layout of items, a XSL (eXtensible Stylesheet Language) file is defined and each eK-record described in XML is transformed to HTML content and displayed by using Web browsers. In the window for eK-record browsing, the simulation status reports from VirtualWorks and the history of model revising are also displayed in addition to the content of eK-record.
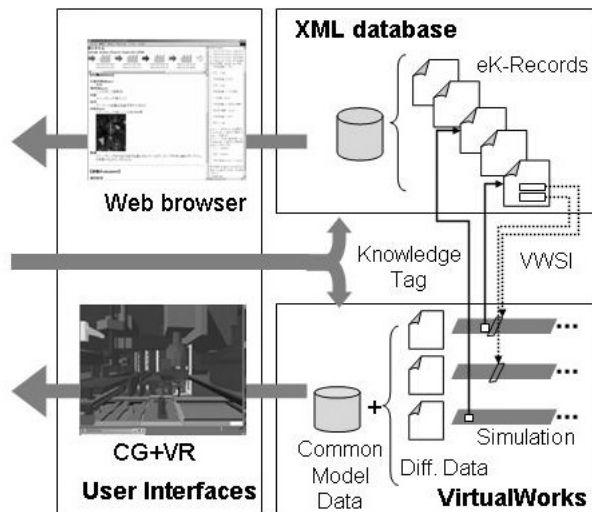
The situations specified in eK-records are displayed as process simulations by VirualWorks. Since VirtualWorks can manage multiplex simulation processes, the user can compare the both situations before and after problem solving in parallel.

5   CASE STUDY

The author had applied the method of Active Knowledge Archive and the implemented system to a practical case of automation system development in industry. The object of the case study was an automatically assembling cell for automobile's fuel pumps developed and operated by DENSO Corporation and Daishin Seiki Corporation. The manufacturing cell, named CAC, consists of many machines and devices such as three robots, an automatic warehouse, a work pallet conveyor system, many sensors and so on. (See Fig. 5.) These components are closely packed in approximately two meters cube so as to shorten the length of object transfer and they are well synchronized for fast and precise assembling operations. The CAC won a R&D award from an academic society and has been continuously improved for realizing higher quality and productivity. Much amount of knowledge has been applied onto the CAC by system designers, production engineers and field engineers individually. Therefore, various intentions are implicitly embedded in the structure and behaviors of the CAC and no body knows all processes of system design and modification.

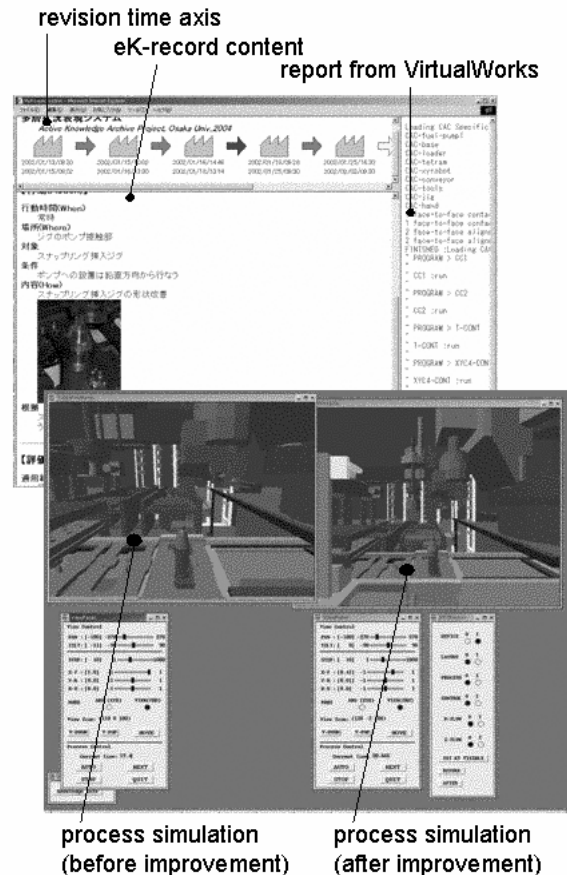The author visited the company and had several interviews

Figure 4: GUI of Active Knowledge Archive

Figure 3: Prototype system configuration for AKA

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with engineers while looking at the CAC in operation. Based on the interview data, eK-records are prepared and attached to digital models of the CAC constructed in VirtualWorks via Knowledge Tags. Figure 6 shows CG presentations of CAC digital models, and Fig. 7 presents the snapshots of the prototype system's user interface. Using the prototype, a user can find Knowledge Tags attached to the digital models of CAC and read XML eK-records in the Web browser. When a VWSI in the eK-record is selected, the request is sent to Vir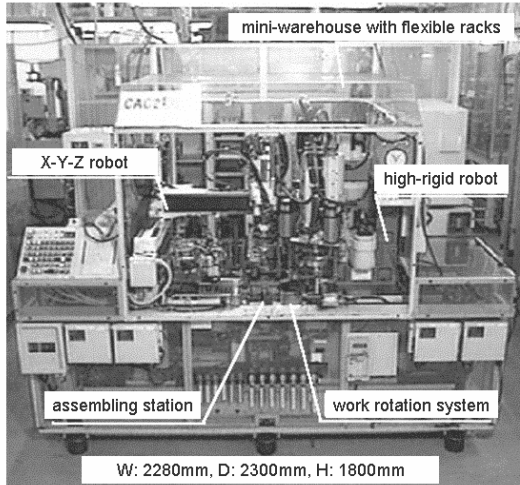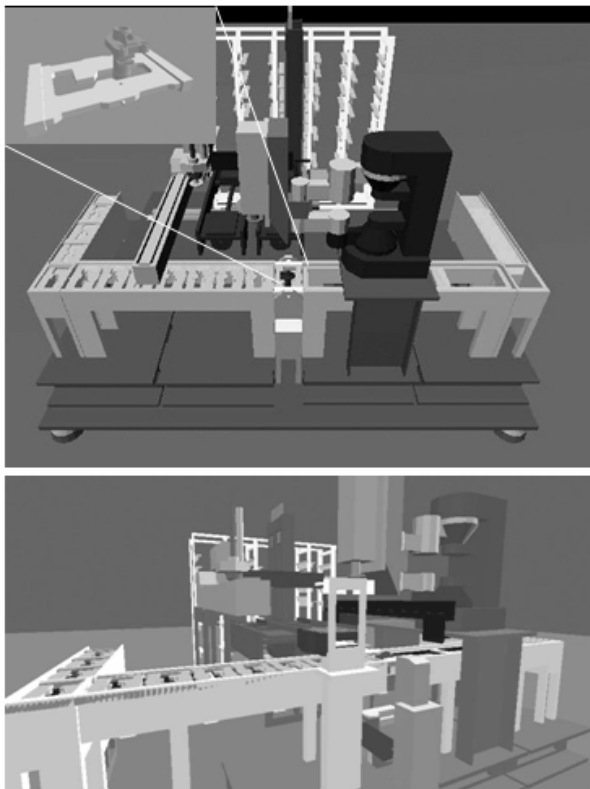tualWorks and the specified situation of CAC is automatically loaded and simulated. Thus, the user can compare the improved CAC's structure and behaviors with its original ones. The prototype system has no GUI for editing a digital model yet and a system user has to use a text editor to revise a digital model. The interactivity in model modification will be improved in the next development.

6 CONCLUSION

The current functional level of the prototype system realizes the core part of the Active Knowledge Archive and needs more implementation. The authors' research group continues to develop more practical system which can be applied for all phases of data acquisition, storage, organization, and utilization.

I also think that there can be many other realization approaches toward the Active Knowledge Archive which doesn't use the virtual manufacturing technology. Combining manufacturing knowledge with digital engineering will develop our understanding of manufacturing systems.

Figure 5: Outlook of DENSO CNC

Figure 6: Digital models of CAC by VirtualWorks

Figure 7: Active Knowledge Archive for CAC

XEONA, multimodal human interface, was designed to utilize the sense of haptics combined with stereo viewing, and to integrate a virtual object with a real object. Figure 5 shows the overview of XEONA and VMS viewing by XEONA. The advantages of XEONA as a user interface device are i) direct object pointing in the 3D space, ii) natural stereo viewing, and iii) force feedback for object handling in the virtual space, and iv) merged view of real objects and virtual objects (AR).
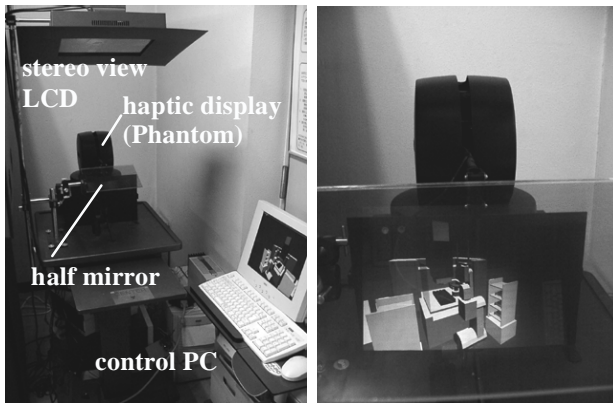
(a) overview of XEONA   (b) VMS in XEONA

Figure 8: Multimodal interface XEONA and its application to virtual observation and handling
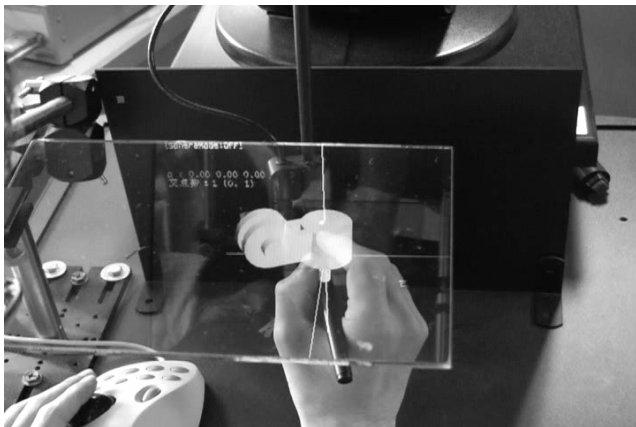

Figure 9: virtual object operation in XEONA

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10. Rapid Development of Immersive Applications

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Abstract

Rapid prototyping in Virtual Reality (VR) is a practice that can reduce time and costs from the product development cycle. Typically, developers create a customized VR application to meet the specific needs of the manufacturing and engineering problem at hand. VR application development utilizes software specific to VR such as VR Juggler[1] in conjunction with visualization libraries such as OpenSG[2], Open Scene Graph[3], OpenGL[4], or Performer[5]. In most situations, development of each application is approached as a new effort, with little attention to reuse existing software with similar features.

We have developed a "template" application that bundles common software components such as navigation, input processing and loading/handling 3D models as modules. Thus, developers can concentrate programming efforts on creating modules for manipulating models, reacting to user input, and coding specific application needs. The template application consists of modular pieces that abstract the lower level APIs. With it, developers pick components of the template they want to use to quickly build an application. Flexibility is provided for writing customized versions of any of the template's modules. In this way, developers can take advantage of the modular approach and encapsulate parts of their code that can be portable and used across their custom applications.

Furthermore, this approach allows upgrading core code of the template application and even adding additional functionality without breaking existing code.

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[3] Open Scene Graph Open Source Tool, http://www.openscenegraph.org

[4] OpenGL, http://www.opengl.org

[5] OpenGL Performer, http://www.sgi.com

11. Using the Semantic Web to Enable Integration with Virtual Engineering Tools

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Abstract

Ideas and tools developed for the semantic web can be applied to the engineering community to enable integration with engineering tools and software. The ideas upon which the semantic web is founded, along with the technology that is used to implement it, provide a platform on which virtual engineering tools and interfaces can be extended to create a web in which contextual information is readily accessible to engineers. When the semantic web and virtual engineering methods are fully realized, computer hardware and networking capabilities will work to provide information and tools to access information meaningfully. The question that must be answered in this age is: How will information be integrated in a manner that will allow commercial and proprietary software tools to remain separate while also being integrated in a manner that will enable the end user to control and query these tools with little to no knowledge of the tools implementation or inner-working details? The answer to this question will depend largely on the ability to implement open interfaces and schemas that can evolve over time as well as open source toolkits that enable development teams to collaborate at a high level. This paper discusses potential applications of the semantic web that explore these questions. In addition, specific capabilities that are being developed in VE-Suite are discussed.