User Activity in an Immersive Cable Harness Design System

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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.

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 given 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.

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 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.

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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.

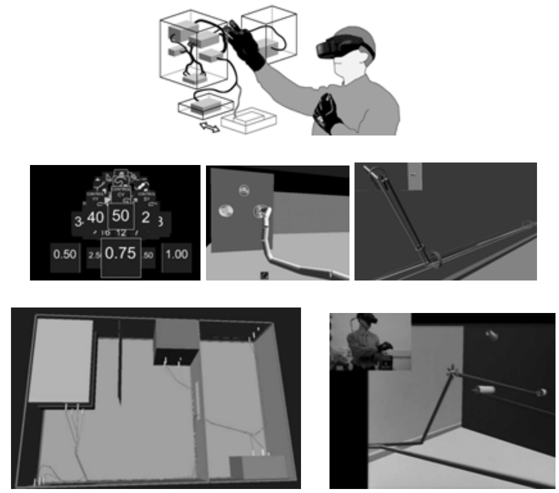

Figure 2: The COSTAR cable harness design system

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: $\rho=-0.89$, $p<.05$) which reflects ***actual*** system usage. Designers also tend to access menus and help/task information in design support (Pair 2: $\rho=0.69$, $p<.05$; Pair 3 ($\rho=0.85$), $p<.05$) 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: $\rho=-0.89$, $p<.05$) where less time in help means more time doing productive design (Pair 5: $\rho=-0.90$, $p<.05$); 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: $\rho=0.69$, $p<.05$). 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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