Cable Harness Design, Assembly and Installation Planning using Immersive Virtual Reality.

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Abstract

Earlier research work using immersive virtual reality (VR) in the domain of cable harness design has shown conclusively that this technology had provided substantial productivity gains over traditional computer aided design (CAD) systems. The follow-on work in this paper was aimed at understanding the degree to which various aspects of the immersive VR system were contributing to these benefits and how engineering design and planning processes could be analysed in detail as they are being carried out; the nature of this technology being such that the user's activities can be non-intrusively monitored and logged without interrupting a creative design process or manufacturing planning task. This current research involved the creation of a more robust and CAD-equivalent VR system for cable harness routing design, harness assembly and installation planning which could be functionally evaluated using a set of creative design-task experiments to provide detail about the system and users' performance. A design task categorisation scheme was developed which allowed both a general and detailed breakdown of the design engineer's cable harness design process and associated activities. This showed that substantial amounts of time were spend by the designer in navigation (41%), sequence breaks (28%) and carrying out design-related activities (27%). The subsequent statistical analysis of the data also allowed cause and effect relationships between categories to be examined and showed statistically significant results in harness design, harness design modification and menu/model interaction. This insight demonstrated that poorly designed interfaces can have adverse effects on the productivity of the designer and that 3D direct manipulation interfaces have advantages. Indeed, the categorisation scheme provided a valuable tool for understanding design behaviour and could be used for comparing different design platforms as well as examining other aspects of the design function, such as the acquisition of design decision intent. The system also demonstrated the successful automatic generation of cable harness assembly and cable harness installation plans from non-intrusive user-system interaction logging, which further demonstrates the potential for concurrent design and manufacturing planning to be carried out.

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 probably mirror how expensive turn-key computer aided design (CAD) systems began to impact on industry in the late 1970s and eventually 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 use and evaluate its benefits and limitations as it begins to impact on *creative* engineering processes such as conceptual and detail design and manufacturing/assembly 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. We also investigate how the engineering designer approaches a problem and what the key issues are with regard to future virtual design systems of this kind. Specifically, a task categorisation of system usage is outlined and tested for analysing user activity in a computer-based cable harness design application.

This paper initially focuses on immersive VR as an enabling technology in engineering design and then emphasises the specific problems and solutions associated within the domain of cable harness routing. It then describes the immersive VR apparatus and experimental methodology used to investigate how virtual engineering design tasks are carried out for cable harnesses followed by a detailed analysis and discussion of results. This is followed by a section demonstrating the potential for the automatic generation of downstream manufacturing planning data from user activity logging before drawing some conclusions.

1.1 Immersive Virtual Reality

VR itself takes many forms with a wide array of technologies classified as being virtual environments (VEs) of one form or another. There are now many applications where VR is being used for mechanically engineered products and a wide variety of different types of technology that can be applied in engineering domains [1]. This paper focuses on the HMD, 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. The helmet incorporates sensors to track the user's physical movements as well as allowing for relative sound input.

Figure 1: Head-Mounted Display (HMD)

Therefore, if HMDs are to be used within the design platforms of the future it is necessary to carry out research to determine how system interfaces need to be designed to enable this technology to be used to its full effect. Currently, HMD research has shown that there are health and safety issues to address, such as heterophoria change, virtual simulation sickness and oculomotor problems. These effects must be understood to support the future development of product engineering design systems using this kind of design platform leading to, for instance, the recommendation for maximum length exposure durations of approximately 20 minutes [2-6]; therefore, the cable harness design work tasked in this research was set at this time limit.

1.2 Typical Virtual Engineering Applications

In the area of product design, VR systems can 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 [1]. Gomes de Sa and Zachmann [7] see a role for immersive VR throughout the whole product development cycle, outlining the extensive application of this technology for digital mock-ups. They feel that immersive VR, "…must be at least as easy as designing with a CAD system." Ng *et al.* discovered that this was the case since the training times for using an immersive VR design system were much shorter than that associated with traditional CAD systems [8]. Cruz-Niera *et al.* [9] used a C2 CAVE™ environment for architectural design so that students could appreciate a model at full scale. They mention the importance of recording and storing some form of design intent as activities are carried out. Weyrich and Drews [10] used a virtual workbench to design and found that the method appears to effectively support how engineers think during the design process, which points to the importance of collecting subjective information relating to how designers feel whilst participating in a creative activity supported by virtual technologies. These findings also highlight the need to be able to breakdown design processes to determine how systems development can take place to support product engineering activities. Chi-Cheng *et al.* [11] developed a series of interface tests and a classification of interaction activities to investigate how designers interact with an immersive virtual product design studio during a tightly constrained set of design tasks. Their paper does not elaborate as to what form these take but does show that VR gives advantages over the traditional interaction approach. However, these tasks required little original user input and deliberately neglected the "thinking time".

With regard to designer's thinking, this highlights the importance of cognitive issues in design. Design is a creative act, described by McPhee as a mysterious mix of science and art that can only be understood by first understanding how humans think and behave [13]. He also suggests design is instinctive; a notion echoed by Schöns's "knowing-in-action" [14]. Theory also proposes that where instinctive activity does not lead to a satisfactory outcome, the designer suffers a "breakdown"; a difficulty that makes tacit reasoning more explicit [15].

Furthermore, studies repeatedly show design to be unsystematic and ad hoc at the level of an individual's actions; despite the influence of an explicit rationalistic guiding procedure [16]. Even when using the same methods, it has been noted for some time that designers produce appreciably different designs [17]. It is further suggested that a designer's behaviour may be a function of the designer's cognitive load [18] and, as a consequence of this, the related notion of "modal shifts" also emerges [19]. Here, the designer is in a particularly creative state (as indicated by important, novel decisions being made) and rapidly alternates between tasks in recognisable patterns. The nature of the immersive VR platform of the kind used in this research provides the potential for the non-intrusive analysis of design tasks and the recognition of these associated patterns in a manner which would be very difficult with traditional CAD systems. This is potentially further amplified in downstream manufacturing planning task extraction in the process design phase of product development.

The capability of VR during creative design tasks was demonstrated by COVIRDS (COnceptual VIRtual Design System) which showed the interactive capabilities of immersive virtual design [20] using hand tracking and voice input for a VR-based CAD environment; allowing rapid concepts to be modelled through free-form shape creation. Varga *et al.* [21] have also investigated the use of hand motion as a means of creating conceptualised geometry for design purposes and suggest a novel classification scheme for categorising these motions, i.e. contact, speed, adaptability and fidelity; focussing more on free-form geometry than more precise point-to-point sketching scenarios. Work at Heriot-Watt University [8, 22] showed that immersive VR has a role to play in the design process.

As can be seen from this review, there is still a need to understand how the creative design process can be analysed in detail when applying HMD VR technology to the design task, how these activities are broken down and where the emphasis on interface and technology development should take place to further advance the technology.

1.3 Research Work Domain

Cable harness design has been a classic design problem for many years since even with the application of extensive CAD-based packages available for this task many companies still employ physical prototypes for the generation and checking of cable routes [8]. 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 [23], with subsequent work using genetic algorithms to tackle the same problem [24]. Wolter and Krol routed ‘strings’ around ‘solid’ parts [25] and in some projects, robot path planning was applied to piping systems as a routing solution [26]. Work at Heriot-Watt University [8, 27] showed that immersive VR has a role to play in this design process and research at Iowa State University [28] employed a VR system for routing flexible hoses that validated VR as a practical tool but did not analyse its effectiveness as an interactive design tool. Early work at Boeing [29] in the area of augmented reality indicated the advantages of virtual technologies in assembling cable harnesses.

A survey of the industrial companies showed that there was a need for human expert intervention to make fine adjustments and verify solutions [8]; 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 [30]. This approach emphasises the need to examine creative design activities in more detail to see how 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 [8].

VR’s unique capability to immerse the user in a design experience makes it a useful 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 it is flexible enough to allow some form of task variety to be built into system experiments in a constrained design environment.

Earlier work at Heriot-Watt University in the area of cable harness design compared an immersive VR design environment called CHIVE (Cable Harnessing in Virtual Environments) with a number of CAD systems and demonstrated that HMD virtual technology gives productivity benefits during creative cable routing design activities. This showed conclusively that VR provided substantial productivity gains over traditional computer aided design (CAD) systems [31]. The follow-on work discussed in this paper was aimed at understanding the degree to which various aspects of the immersive VR system were contributing to these benefits and how engineering design and planning processes could be analysed in detail as they are being carried out. The nature of this technology is such that the user's activities can be non-intrusively monitored and logged without interrupting a creative design process or manufacturing planning task providing considerable potential for understanding creative design activities with no interruptions to cognitive thought processes. Central to this research was the use of a more robust and CAD-equivalent VR system for cable harness routing design, harness assembly and installation planning which could be functionally evaluated using a set of creative design-task experiments to provide detail about the system and users' performance. This was based on the table-top metaphor (see Figure 2) and using comprehensive user logging was therefore developed to non-intrusively collect detailed information relating to the design solutions and approaches used by a number of engineers, as well as automatically generating assembly plans from user interactions. It was decided that the majority of the design tasks undertaken for the initial experiments would focus on the 3D volumetric design process since this was considered by the companies to be a priority with regard to cable route planning since 2D schematic design could be easily handled using proprietary packages.

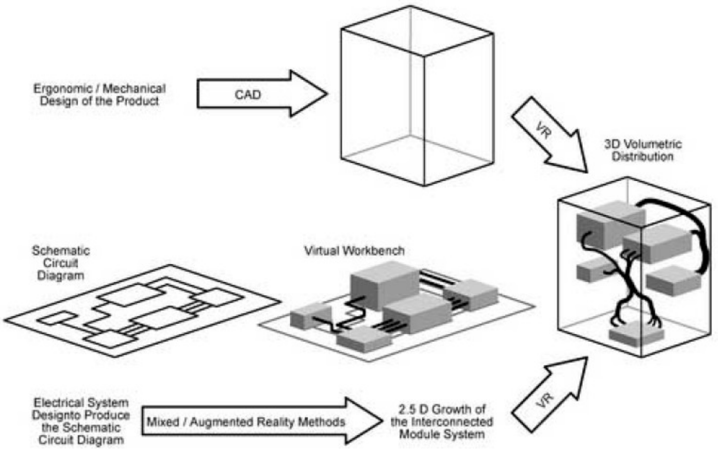


Figure 2: Workbench metaphor, from [23]

2. Apparatus and Methodology

2.1 Apparatus: COSTAR Experimental Platform

The system developed as an experimental platform for this research was called COSTAR (Cable Organisation System Through Alternative Reality). This was implemented on an SGI® Octane2™ with V12 dual head graphics driving each eye on a V8 stereo HMD. Peripherals attached to the system include a Flock of Birds® magnetic tracking system and Pinch® Gloves. The software platform used for developing the COSTAR system was the SENSE8® WorldToolKit® release 9.

The COSTAR system enables the engineer to design and assembly-plan cable harness assemblies within the immersive VR environment, with all design functions, including the creation of new objects, being performed while they are immersed in the system (Figure 3). 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 system.

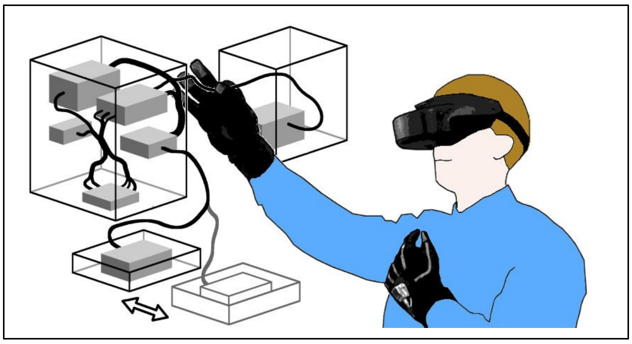


Figure 3: The COSTAR cable harness design system

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), as applied by Liang and Green [32], and more recently by Gerber [33] (Figure 4). The engineer can input the cable harness routes by plotting points in 3D space, these being joined together to produce the cable path itself. Subsequent editing of the cables is possible by selecting the plotted points and bending them around obstructions, bunching or pulling them together to form cable bundles, inserting additional points and adding connectors and fasteners; depending on the menu options chosen. Figures 5-8 show the system with various operations being performed.

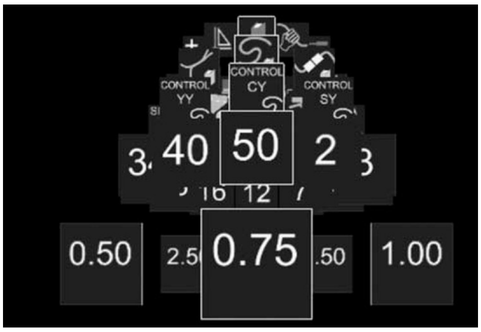


Figure 4: Hierarchical ring menu

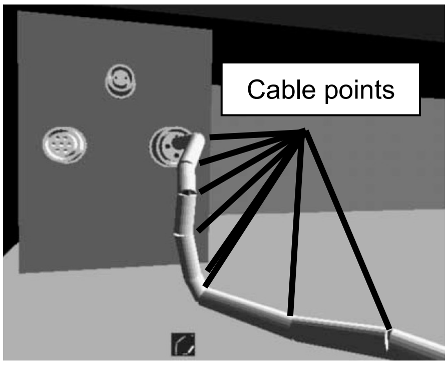


Figure 5: Creating a cable from point to point

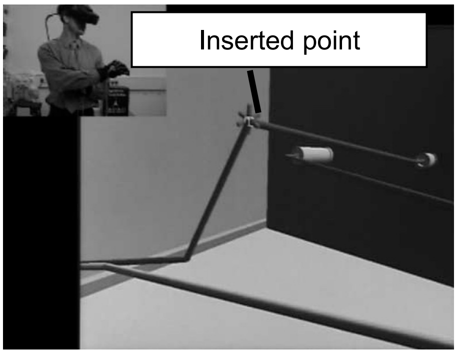


Figure 6: Inserting a cable point

COSTAR logs all of the user’s cable harness design and assembly activity-related actions, with the position of the hands and head being logged approximately 50 times per second.

3. Experimental Procedure

As already mentioned, the experimental cable harness design tasks were to be completed in around 20 minutes for health and safety reasons. Three loosely constrained creative design tasks were organised to evaluate the utilisation of each designer’s time. The tasks covered the common design activities for cable harness processes, such as routing, bundling, cable modification and choosing connectors. 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. Since this was a detailed design study there was a need to provide the participant with a realistic design problem for which they then had to provide a solution; the major goal being to evaluate the ways in which the system and technology supported or hindered the engineer during their work, and how the engineer tackled the design problem itself. Therefore, participants were given sufficient information about what the goals of the task were 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 controlled experiment - the intention being to give participants a sense of doing a real design activity with the system. This reflects our earlier discussion of design itself being a creative act that could not be assessed by a rigid process. All of the tasks were associated with typical cable harness design practices within the industrial partners, were carried out within the same 'product' model (Figure 7) 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 participant training and familiarisation, and task 3 for design task analysis.

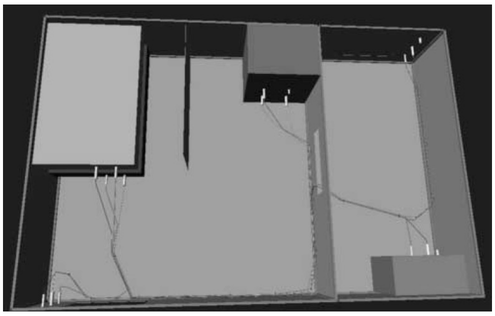


Figure 7: Model on completion of the experimental tasks

(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 in 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. The user was instructed to, "route the outline cables in the model through the cable clips to

complete the cable harness design." However, the individual participants needed to use their 'engineering' judgement as to what the completed harness design should be and how to achieve that goal. Figure 8 shows a partially completed route.

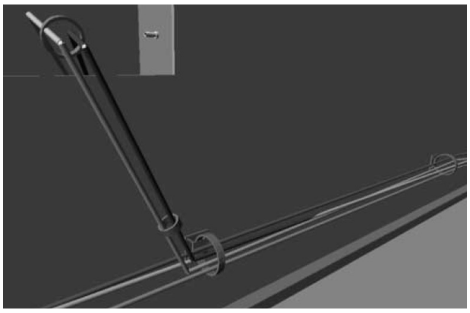


Figure 8: A partially completed route

(3) ***Redesign***: The third and final 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. Identical session structures were used at each of the three evaluation task sessions. The immersive design activity was followed by a semi-structured interview during which feedback about the system, and the participant's experience with it, was collected.

4. Analysis of Results

Data collected via log files included performance and usage data. In addition, post-experiment data was collected in the form of system usability and 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 for these experiments and followed on from the broader categories applied by Chi Chen *et al.* [11]. The new categorisation reflected general system usage and allowed the analysis of key parameters and functions during a user's interaction with a computer-based design tool, such as CAD or VR. In relation to the working environment, it was decided to analyse the time spent in the model, in help screens and in the menus so that their influence on a design task could be compared against a proposed detailed ***activity*** task categorisation.

As a result, we developed ***environmental*** categories and, on analysing the log files, produced the distribution shown in Table 1 and Figure 9. These data demonstrate the average percentage of time spent in each of the new ***environmental*** category subdivisions as the designers completed design task 3. We can see that a high percentage of the time (69%) involved users carrying out activities within the model and, to some extent, being creative. Only a small proportion of the time (8%) was spent in 'help/task instruction', supporting the informal feedback from the users that the system was easy and intuitive to use.

Table 1: Environmental category subdivisions for design task 3

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

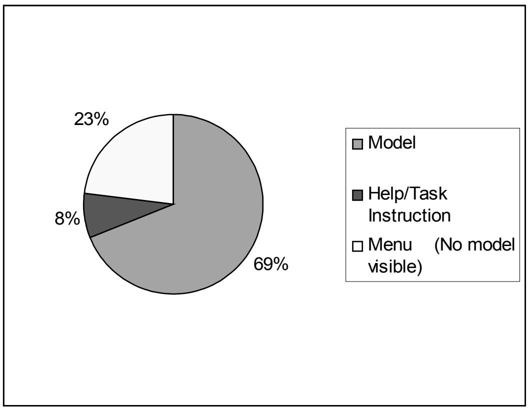


Figure 9: Average time distribution for environmental category subdivisions

After analysing the data and the associated design process 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. In the lexis of cognitive task analysis, these action sequences are often called “task plans” [34]. 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 four action sequences, or ***activity*** categories, chosen were:

(a) ***Design:*** all activity that the user carries out to directly amend the design solution or associated documentation.

(b) ***Information:*** all user activity which involves them acquiring information from a text screen.

(c) ***System Operation:*** all activities which are required by the user to operate the system but does not affect the design solution.

(d) ***Navigation:*** all activity which modifies the participant’s viewpoint of the model but does not normally change the design solution itself.

However, due to the fact that design was at the core of CO-STAR system then this was further subdivided into three subcategories to allow more detail to be obtained regarding an analysis of activities carried out whilst the user was being creative during the design task. These subcategories were:

(a) ***Design – Goal:*** user actions which alter the design solution/model and advance the design towards its final state.

(b) ***Design – Support***: activities which do not produce a change to the design solution but enable the user to subsequently alter the design.

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

The results from this categorisation structure are shown in Table 2 and Figure 10.

Table 2 –Time Distribution for Activity Categorisation

	Activity Category						
	Design Goal	Design Support	Drag& Drop	Information	System Operation	Navigation	Totals
Mean Time (s)	131	57	157	106	296	510	1257
St.Dev.	52	13	130	36	77	160	
Mean Time (%)	10	5	12	8	24	41	100

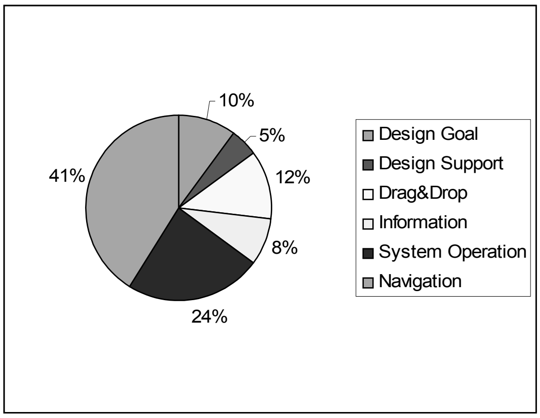


Figure 10 – Average Time in Activity Categorisations

From these results it can be seen that a large proportion of the time was spent navigating around the model (41%). This reflects the experimental model being presented to the designer in super-scale; i.e. the model surrounded the engineer. Flying was employed as the navigation mode because it was the traditional type of navigation used with an HMD. The flying speed was kept constant in order to reduce confounding variables in experimentation. However, with such a large proportion of the time being spent moving around the model, the categorisation scheme shows that, during the creative design process, it would be advantageous to reduce navigation time considerably. This backed up an important finding from Ng *et al.* [31], 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, as well as reducing the amount of navigation necessary.

Also, a large number of sequence breaks or pauses were apparent during the cable routing process, implying that idle time potentially exists in the process. Many of these breaks existed within the navigation of the model, which points to the need for more effective navigation tools as well as an analysis of what is happening when these breaks are taking place. In addition, this time could indicate areas in the process where the designer is thinking about the design. This prompts the research question, "Can thinking time be identified and analysed in some way in order to evaluate design intent?"

Around 27% of the time within the system was spent on design-related tasks. Although a high percentage of the time, it was apparent from our research that there were opportunities to improve the interface in terms of navigation and menu interfaces to free up even more time for creative design. In this paper, we deliberately do not report on the findings and recommendations prompted by our usability and system functionality data for brevity and to maintain a focus on activity categorisation issues.

Furthermore, it was important to understand how much time was being spent by designers in unproductive activities and when there were breaks in the actual process of interfacing with the system, whether in design, menu operation or navigation. In order to do this two supplementary categories were developed which were generic across the all of the design categories, namely:

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

(b) ***Sequence Breaks:*** abeyance in activity between the end of one action sequence and another with no input from the user. For instance, user thinking time, or an activity that did not register as an interaction, such as a head or hand movement.

The results of these further subdivisions applied across all of the existing categories across all of the experimental tasks are shown below in Table 3.

Table 3: Supplementary category subdivisions

	Activity Category	
	Unproductive Activity	Sequence Breaks
Mean Time (s)	70	356
St.Dev.	51	110
Mean Time (%)	6	28

What these data highlight is that there are substantial parts of the process during which the users are taking breaks from carrying out any form of activity (28%). Although this time may illustrate when they are simply resting, it is apparent that with the task duration being so short this time could be associated with thinking time about, for instance, menu interfacing, design, design modifications, etc. These issues will require further investigation; however, this analysis shows that utilising a design categorisation scheme and having the ability to carry out the detailed monitoring of activity in a computer-aided engineering environment could potentially provide a means of non-intrusively analysing design intent.

Another major outcome of having the ability to carry out the detailed analysis and categorisation of a design process in this way is the ability to investigate statistically the cause and effect relationships between the various categories and subcategories. Consequently, tests were carried out to see if any significant relationships could be identified. This 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>0.1). 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. Because of this finding, 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 4, where significant was defined as *p*<0.05 and tending-towards-significant was defined as *p*<0.1. The majority of comparisons showed no significance and have been omitted here for brevity.

Table 4: Nonparametric correlations for activity and environmental categorisations

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 used within the experimentation and give an interesting and novel insight into the cable harness design process itself as well as the functionality of the immersive virtual reality design system.

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). Although this might initially appear to be an obvious statement, this result validates the approach and categorisation comparative structure used because it reflects the ***actual*** system usage observed and reflects opinions expressed by designers in the post-experimental interviews. 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) which shows the usefulness of the categorisations applied for analysing a cable harness design task. This stresses the need to design menu, help and support information and their associated interfaces as efficiently as possible to maximise creative design time and to minimise menu interaction and support tasks; something which was apparent from the basic categorisation analysis but is strongly supported by the statistical comparison. Less time in the menus means more time in the model, i.e. carrying out productive design (Pair 4: $\rho=-0.89$, $p<.05$). Similarly, less time in help means more time doing productive design (Pair 5: $\rho=-0.90$, $p<.05$); two strong negative correlations and, again, perhaps obvious observations; however, the relationship between these is now quantifiable using the approach developed in this work.

Continuing through Table 4, when the designers spend more time carrying out un-productive activities, they were most likely to be in the menu environment than doing other activity (Pair 6: $\rho=0.69$, $p<.05$), which implies that users are at their most productive in the modelling (design) environment. This supports the categorisation scheme developed because it numerically confirms a previously subjective judgement when observing such a design task. Tending towards significance, drag-and-drop is also shown to be an important productive design activity (Pair 7: $\rho=-0.61$, $p<0.1$) because the designer is ‘improving’ the design and justifies the categorisation because it identifies the drag-and-drop task as important to the design activity itself and justifies it inclusion in the VR interface; a functionality that is missing in CAD systems. 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: $\rho=0.59$, $p<0.1$). This is explained in terms of designers being interrupted by un-productive activity and then having to revaluate what they are doing before continuing with the design process [35].

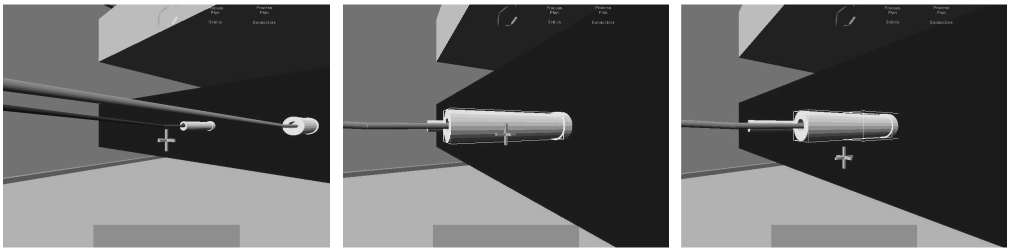
Pair 9 demonstrates that the designers were actually referring to the task information instructions rather than general help about the system when in the menu (Pair 9: $\rho=0.70$, $p<.05$). This supports interview feedback from the designers in which they said that the VR system was intuitive and easy to learn since they were focussing on the task in hand. 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 (Pair 10: $\rho=0.64$, $p<0.05$) and 11 (Pair 11: $\rho=-0.83$, $p<0.05$) show that more time in the model usually means more time carrying out drag and drop activities (i.e., amending the design) and more time in the menus means less drag and drop time, respectively. However, more time operating the system, e.g. menu navigation, filter selections, etc., negatively impacted on creative design time (Pair 13: $\rho=-0.79$, $p<.05$) which suggests the need for well designed and specialised task-specific interfaces for all system operations within immersive VR HMD design applications. 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: $\rho=-0.67$, $p<.05$).

5. Cable Harness Assembly and Cable Harness Installation Planning

One of the major benefits of any computer aided design (CAD) system is the generation of downstream manufacturing information; however, in the area of assembly planning there is a considerable need for direct user assembly instruction data input. The nature of a typical CAD interface is such that there are considerable interruptions to the assembly planner's creative thought processes as they are generating these sequences which could affect the quality of the assembly plan output. What is required is a more intuitive method of generating plans in which the user can describe their assembly activities intuitively through actions and demonstrations of processes rather explicitly describing them. It is within this context that immersive VR has an important role to play. Therefore, subsequent to the analysis of the design data in this study it was decided to investigate the possibility of automatically generating useable assembly plans using the immersive VR interface by firstly allowing the manufacturing planner to intuitively explore the cable harness and associated connector geometries to demonstrate a cable harness assembly process planning and then to follow this up by indicating the 'installing' of the cable harness in a virtual model. As the user is logged, this automatically generates an installation assembly plan from the data which requires no interactive creation of instructions or subsequent amendments from the user.

This approach supports the work carried out by Ritchie *et al.* [36] which demonstrated that it was possible to produce production assembly plans via an immersive VR interface. However, work by Dewar *et al.* [37] showed that the time achieved for virtual assembly planning were quite different from those obtained in the real world. This is a major disadvantage in virtual assembly planning environments. Therefore, to overcome this, the system was extended to demonstrate how real world assembly times can be cross-referred onto virtual equivalent tasks in a virtual planning environment. Tables of standard assembly times for fitting connectors to harnesses and fitting harness connectors into bulkhead connectors were tabulated from real world method studies and applied to the equivalent virtual tasks as an expert assembly planner built the virtual product. Non-intrusive logging of the planner enabled the development and generation of production-readable assembly plans without the need for human intervention; a major benefit over CAD methods. As well as this, harness access could be checked ergonomically.

Once the domain expert was immersed in the virtual environment they were able to navigate around the cable harness and ergonomically and chronologically choose which connectors and cables to join together, thus facilitating actual harness build. As this was being carried out, the user was non-intrusively logged in the normal way, connectors and cables identified and real world times automatically allocated to the sequence of build detected by the system. A similar approach was used when installing the cable harness into the actual assembly itself. The interface for assembly planning is shown in Figure 11 and the assembly plans automatically generated for both the harness itself and its installation, along with the corresponding real-world assembly times for each operation, are shown and Figure 12.



Select Cable Select Connector Select Bulkhead

Figure 11: VR User Interface for Assembly Planning

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CABLE HARNESS BUILDING SEQUENCE
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Op Num	W/Centre	Assembly Instructions	Tooling	Assembly Time (s)
10	Cable Bench	Connect cable CAB02(Type: CONTROLCY Number of Cores: 7 Core Cross-Section: 1 Colour (RGB): 225,125,0) to inline connector CON23 (Type: plug Shell size: 2 Number of poles 7)	Hand Assembly	10.3
20	Cable Bench	and inline connector CON24 (Type: socket Shell size: 2 Number of poles 7)	Hand Assembly	27.18
30	Cable Bench	Connect cable CAB01(Type: SINGLECORE Number of Cores: 1 Core Cross-Section: 4.8 Colour (RGB): 255,0,0) to inline connector CON22 (Type: plug Shell size: 1 Number of poles 2)	Hand Assembly	15.70
40	Cable Bench	and inline connector CON21 (Type: socket Shell size: 1 Number of poles 2)	Hand Assembly	14.24

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--------------------------------------------------------------------------------
INSTALL CABLE HARNESS ASSEMBLY INTO EQUIPMENT
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Op Num	W/Centre	Assembly Instruction	Tooling	Assembly Time (s)
10	Assy Station	Connect inline connector CON21 (Type: socket Shell size: 1 Number of poles 2) to bulkhead connector CON01 (Type: plug Shell size: 1 Number of poles 2) located at position (3250,- 500,3725) and Orientation (0,-0,0.707107,0.707107)	Hand Assembly	7.17
20	Assy Station	Connect inline connector CON22 (Type: plug Shell size: 1 Number of poles 2) to bulkhead Connector CON04 (Type: socket Shell size: 1 Number of poles 2) located at position (2250,-500,325) and Orientation (-0,-1,-0,4.37114e-08)	Hand Assembly	6.75
30	Assy Station	Connect inline connector CON23 (Type: plug Shell size: 2 Number of poles 7) to bulkhead connector CON05 (Type: socket Shell size: 2 Number of poles 7) located at position (1750,-500,325) and Orientation (-0,-1,-0,4.37114e-08)	Hand Assembly	4.58
40	Assy Station	Connect inline connector CON24 (Type: socket Shell size: 2 Number of poles 7) to bulkhead connector CON10 (Type: plug Shell size: 2 Number of poles 7) located at position (-2250,-500,-2175) and Orientation (-0,-1,-0,4.37114e-08)	Hand Assembly	7.69

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-------------------------------------------------------------------------------------------------
STANDARD REAL WORLD ASSEMBLY TIMES FOR EACH COMPONENT
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Component	Assembly Time (s)	Component	Assembly Time (s)
CAB02	10.30	CON22	22.44
CON23	14.88	CON21	21.42
CON24	34.87	CON01	7.170
CAB01	15.70	CON04	6.74
CON24	34.87	CON05	4.58

Figure 12: Assembly Plans for Building Cable Harness and Installing Cable Harness Generated from Assembly Planner Logging in the Virtual Environment

These outputs show that real world plans can be generated automatically from user interaction within immersive VR design and planning systems. However, the matching of real world times with the virtual-equivalent activities demonstrates wider and more profound concepts. For example, interactive systems of this kind could be used in generic project planning domains by carrying out interactive assembly/disassembly in exactly this way [38] and demonstrates the potential for generating data which could form the basis for formalizing manufacturing intent.

6. Conclusions

The novel outputs from this research have shown that it is possible to design and plan the assembly and installation of cable harness assemblies in immersive VEs using HMDs. It is also possible to examine, categorise and measure the wide range of design activities carried out by cable harness design engineers; something which has not been done to this level in the past. These novel categorisations, along with their subsequent analyses, have provided a more detailed understanding of design methods in this domain and a detailed outline of which aspects of VR are being used and where to focus future system development effort to improve performance. A numerical and statistical breakdown of activities has also shown to be possible which has given an insight into the cause and affect relationships taking place within the cable harness design process itself. The bona fide nature of these comparisons, expressing some of the oft-stated folklore relating to the design process, establishes that it is possible to quantify the extent of the relationship between two or more subtasks. In the context of cable harness design, this analysis indicates 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 these findings, this research is being extended to apply the 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 approach might prove useful is that ‘thinking time’ could be extracted from the data, which in turn may spawn a capability to imply design intent from actions leading up to and after a decision making event. For cable harness routing, VR can give productivity gains over CAD [22]; however, a more detailed investigation of cable harness design activities will be necessary to determine which tasks are best suited to VR and which are best suited to CAD. The design categorisation developed and successfully tested as part of this research, is central to such an investigation.

Areas for interface improvement have been identified from these experiments in terms of improving navigation and menu design, although they are not reported in detail in this paper. Once improvements have been implemented, the affects of these changes to the system's usability and functionality can be measured against the benchmarks reported here by reusing the categorisation scheme.

Finally, assembly planning sequences along with the novel application of associated real-world assembly times can be generated by non-intrusively monitoring and logging the user. From this study, improvements in assembly planning interface design are being planned to make the assembly and disassembly of cable harnesses more realistic.

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