Immersive Virtual Reality In Cable and Pipe Routing: Design Metaphors and Cognitive Ergonomics

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In recent years there have been moves in industrial engineering towards greater automation through intelligent systems and this has resulted in replacing human expertise. In many cases the potential of intelligent systems has yet to be realised. This paper presents and discusses an alternative technological approach, which uses immersive virtual reality (VR) to support engineering design tasks. The approach focuses on the human engineer and acknowledges the importance of human input to the design process. The development of a metaphor based VR system is reported along with initial field trials, which compare VR with conventional CAD systems. The results show advantages of using VR over CAD and these are discussed along with strengths, weaknesses and future work.
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Introduction

Past approaches to increased efficiency in manufacturing and assembly have often been characterized by deconstruction of activities into individual tasks and their separate automation. Such an approach increases knowledge and understanding of tasks and enables analysis and modelling from a work ergonomics perspective. However, it can also involve replacement of and in many respects the de-skilling of human contributors, such as design engineers, in favor of technology.

More recently, design engineering has been approached in a similar way with research into 'intelligent systems' and knowledge engineering involving, for example, expert systems or genetic algorithms. Expert systems are founded on the assumption that it is possible to capture and represent in software significant amounts of human expert knowledge. Although there have been some successes, the development of effective expert systems has been shown to be much more difficult than when such systems were first proposed. Genetic algorithms, despite considerable research efforts, have yet to make significant inroads into the practice of design and manufacture.

This paper proposes an alternative approach to enhancing design engineering that is enabled by the products of modern advanced information technology applied through Cognitive Ergonomics and Human Factors Engineering. In this approach, it is acknowledged and recognized that the involvement of the human engineering design expert is inevitable. Rather than seeking to reduce or even eliminate the expert with his or her knowledge, the aim is to provide the expert with interactive tools including immersive virtual reality (VR) so that explicit and implicit human expertise can be applied effectively in the engineering design cycle. The key issue here is the integration of the human expert into the 'system' by treating the operator as an integral part of that system [1].

The proposed approach is considered in the context of a particularly costly and difficult task, namely the design and planning for manufacture and assembly of cable harnesses for use in electro-mechanical artefacts. The work presented in this paper is also applicable to the routing of pipes as well as cables, although the rest of this article will refer solely to cables, as this is the particular application domain in which the work has been tested. The efficient and reliable manufacture of cabling systems for many such products in the aerospace, automotive and IT 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. Current practice often requires scaled or full-sized physical prototypes onto which the cable layout is constructed. This is the case even when advanced CAD systems are used for this and other parts of the design. Problems encountered at 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.

The paper commences with a brief review of prior work in the applications context of the current research and an introduction to the designer's workbench metaphor that underlies the authors' approach. This is followed by the description of a demonstration VR environment, embodying the workbench metaphor approach, which supports engineering design tasks. The system has been subject to extensive field trials with industrial engineers engaged in cable harness design tasks. The results of this experimental work are reported along with a discussion to conclude the paper.

Prior Work

Working in the early 1990s investigators in the United States set out to automate the choice of a cable harness route [2] in a system for use as a review tool after the equipment has been designed. It was not envisaged that this system would involve any form of interactive ability. Subsequent work by the same team was directed towards the use of a genetic algorithm approach for the automatic determination of cable routes [3]. Another approach [4] involved techniques for routing 'strings' around 'solid' parts. Some routing work has also been carried out based on robot path planning applied to piping systems [5]. More recent work has been carried out by a team at Iowa State University [6] who developed a prototype virtual reality system for routing flexible hoses. This system, known as VRHose, provides good integration with CAD and routes hoses along B-spline curves. The main focus of this research was to specify a route then view the rendered pipes in VR. The time needed to calculate B-spline interpolations and the additional time taken by the ADAMS package to analyze

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properties of the cable meant the system was constrained in its real-time design and editing ability. The VRHose work, although a very useful study, did not set out to address fundamental questions regarding choice of interface, navigation and interaction techniques: all areas where there is still scope for considerably more research. Other researchers who have looked at cable and piping systems include a group at MIT carrying out applications work on behalf of the US Navy, particularly relating to human factors issues and the use of VR for training. There is no evidence, however, that any of this previous research has been taken up by industry.

Following a slightly different line it has been suggested that non-immersive augmented reality could be used to allow operators to produce cable harnesses more efficiently [7]. This idea has not been followed up in later literature other than, some years ago, by Krumenaker [8] who gives a review of similar augmented industrial systems but concludes that all are at a very early stage.

An important aspect of previous work reported is the common theme running through all research in cabling system design of trying to find ways to automate the generation of routings using computer based techniques and a realisation, acknowledged in most cases, of how difficult this is given the open ended nature of the problem. There is some agreement that there is and still will be a need for human expert intervention to make fine adjustments and verify solutions.

The Designer's Workbench Metaphor

The VR, 'human in the loop,' metaphor described in this paper builds most closely on the prior research which explored the automatic generation of assembly plans based on operator assembly actions in an immersive VR environment using a system called UVAVU (Unbelievable Vehicle for Assembling Virtual Units) [9]. This system incorporated two special tools, namely collision snapping and proximity snapping to assist designers in assembling objects accurately. In a unique use of VR, this utilised its capability as a tool to observe users, in this case assembly planners, in a minimally intrusive way while assembling products modelled in virtual environment. This work targeted the delay caused in the time-to-market for new products that is inherent in the traditional process of generating assembly plans.

An additional aim was to evaluate the possibility of eliciting 'expert' knowledge about the design process itself. The very use of a VR system in this way potentially provides valuable data about design. During the industrial trials engineers' actions and decisions were observed and for example, assembly sequence plans were automatically generated by the system for later study. In a more formal setting, knowledge elicitation studies were then carried out; the knowledge elicitation methodology being successfully was applied in four stages:

1. Define salient attributes using Repertory Grid Analysis. (Repertory Grid Analysis is a technique originating in Kelly's Personal Construct Theory but has been extensively used to model human knowledge as part of knowledge engineering [10].)
2. Evaluate the attributes manually and automatically.
3. Record expert usage data in the VR environment.
4. Generate design rules through induction.

From the data collected, rules were extracted and later validated in consultation with expert designers in the partner organisations [11]. The work to develop UVAVU demonstrated that immersive VR had the potential to be both a 'manufacturing' tool and a tool for the elicitation of implicit design knowledge. Subsequent feasibility work, including significant industrial input, successfully demonstrated that VR technology has the potential to play a valuable role in speeding up the design and planning of cable harness routes [12,13].

Taking this previous work forward the authors hypothesised that an identifiable metaphor was possible to support the generation of design solutions by engineers working in such environments. In this context a metaphor is something, which represents or stands for something else and in the design of interactive systems, metaphors have been designed, implemented and applied very successfully. The best-known metaphor in IT is the "Desktop Metaphor," which underpins all modern graphical user interfaces such as Microsoft Windows and the Apple Macintosh user interface. Without doubt the development of the "Desktop Metaphor" has been responsible for the migration of computers from specialised laboratories to common every day use in offices, schools, homes, etc.

In the work reported and discussed in this paper, the approach to the investigation of the cable harness design process is based on a visual metaphor. This is a 'Virtual Workbench' abstracted from the "natural" work practices normally used by designers who use a combination of drawing and CAD. The metaphor, entitled 'Electrical System Diagram to 3D Volumetric Distribution' is illustrated in Fig. 1. Here the cable harness is considered as an integral and important component of the final product right at the beginning of the design process. It is assumed that the conceptual, ergonomic and mechanical design of the product proceeds in parallel with the electrical system design in the early stages of the product development process. However, the need to have an effective cable harness design is recognized as an essential component of the final product. Cognitive engineering technology and methods are proposed to enable the designer to visualise, design and develop the final product in the following manner:

- At the stage when the system design is approaching completion, VR is used to 'grow' the volumetric representation of the electrical modules with their interconnecting cables as a solid model within a virtual workbench.
- When the workbench model is complete, the designer positions the modules assuming 'elastic' cables within the prototype mechanical structure.
- When the 3-D volumetric distribution of the modules is complete, the immersed VR designer can then 'grab and smooth' the cables into appropriate groups and channels to form the cable harness.
- The cables are now fixed in space to define the geometrical structure within the volumetric distribution of the modules.

Application to the Industrial Design and Manufacturing Process

The reported research and development has involved close participation of industrial partners in the main aspects of the complete design-to-manufacture process. Analysis of the wide range of products and the different cultures of the industrial sectors from which the partners are drawn, has highlighted important common areas of concern in cable harness manufacture. In addition, a typical structure to represent the design-to-manufacture process has evolved as illustrated in Fig. 2.

Here the typical design process follows the sequential steps of initially designing the harness and its assembly system. Very often, a prototype harness is assembled within the structure of the product to form the basis of the assembly planning and production systems; this is tested to verify production feasibility. The typical CAD system approach to produce design and manufacturing information for a harness is to interact with the CAD 3D visualisation to produce the basic cable layout and then produce a physical layout of the prototype cable form. Design evolution creates the design model that interacts with the prototype design and change section of the process system as shown in Fig. 5. It can be argued that the introduction of harness design within a VR Environment can give several benefits. When the geometric layout of the product is defined in a virtual space, the designer immersed in the virtual space can rout the cables using the available software tools. The prototype harness can be simulated and manufacturing

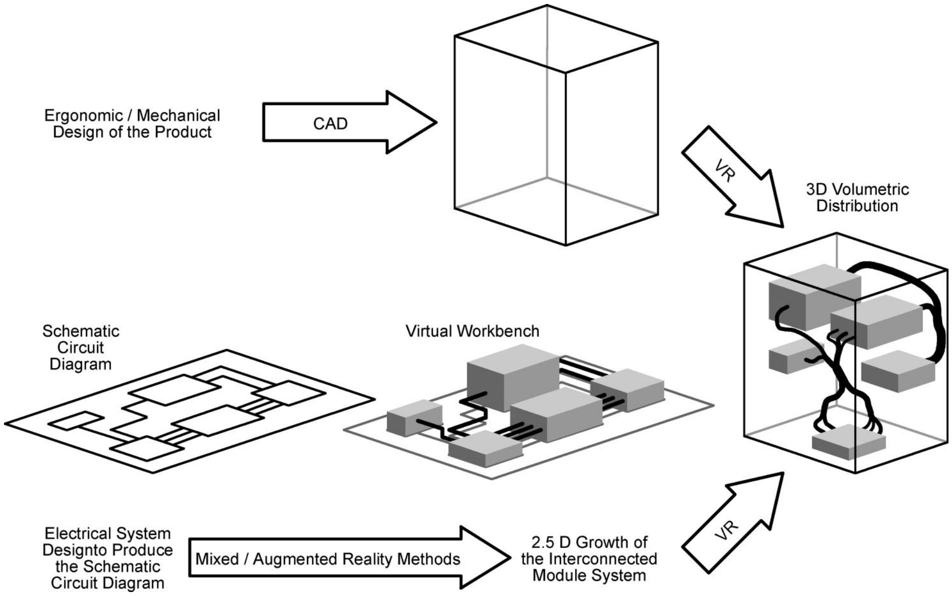


Fig. 1 The Designer's Workbench Metaphor

details can then be extracted from the simulation without relying on the physical manufacture of the prototype harness.

In the first phase of this research program it was decided to produce a VR based toolset, which concentrated on routing cables through a generic assembly representing the main sub-system of a product as shown in Figs. 3, 4 and 7. This addressed routing through confined spaces and through bulkhead holes into multiple compartments. In designing the VR toolset, the focus is on providing engineering designers with a software environment, which represents or "mimics" the actual design tasks in a virtual world. The initial research system is called CHIVE or "Cable Harnessing In Virtual Environments." CHIVE was implemented on a Hewlett-Packard 725/75 workstation incorporating the HP-UX 10.01 operating system. Additional VR hardware and software was used which was supplied by PTC (then Division Ltd) with models of a prototype assembly imported directly from proprietary CAD systems. The user interacts with the data by means of a head mounted display (HMD), a 3D mouse and pop-up menus. The general algorithmic structure of the system is illustrated in the flow diagram in Fig. 8.

In the follow-on research, there is a greater emphasis on interacting with the design process as shown in Fig. 6. Here, the designer is immersed in the virtual environment with the capability of arranging the sub-systems under design and development. Moving the sub-system modules into place, with the "elastic" cables taking a route defined by the designer, forms the cable harness. The VR system not only produces manufacturing information but also gives further detail of the assembly method, planning and production system. VR is not only used to "present" information in a highly interactive manner but is used as a powerful tool for collecting data. A key characteristic of this work is the development of the "Workbench Metaphor," which is intended to provide a much-enhanced mapping between the VR environment and tasks performed by engineering designers. This should also facilitate more effective human-computer interaction.

An Exemplar Generic Task

In order to contextualise cable harness design, an exemplar generic task is provided with three constituent groups identified in defining the task. These are the *cable* technologies, the *geometry* of the product and the production *process*. The primary elements in each of these groups are shown in Table 1 and represented in the schematic diagram in Fig. 3.

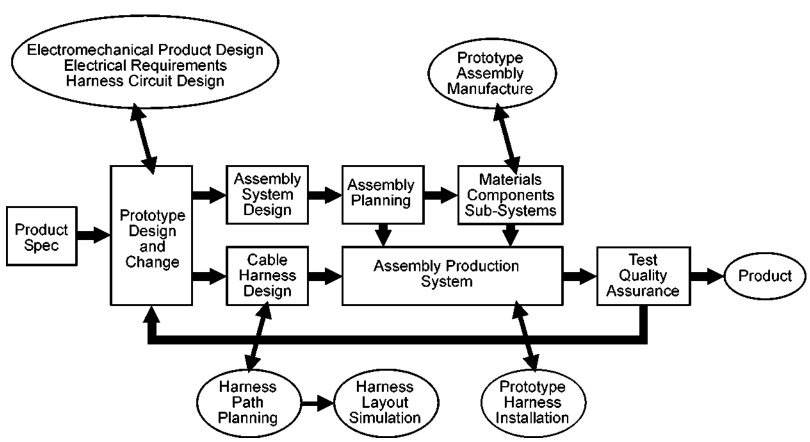


Fig. 2 Schematic Model of the Design-for-Manufacture Process

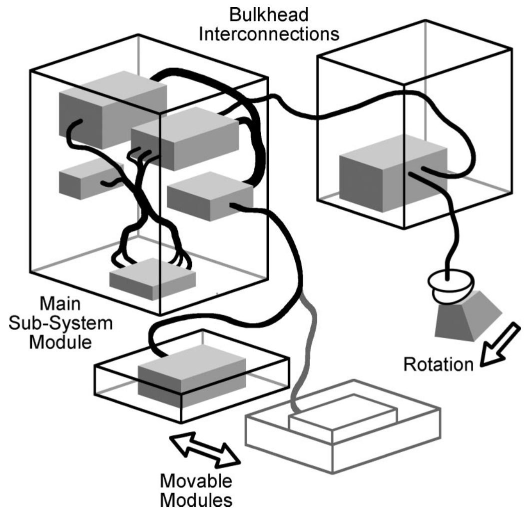


Fig. 3 Schematic Representation of an Exemplar Generic System

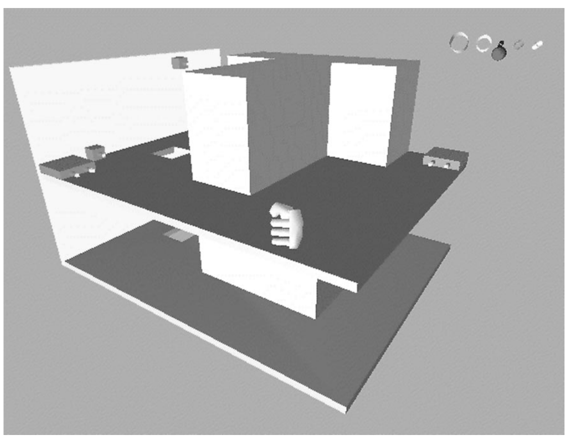


Fig. 4 The virtual environment representation of the main subsystem module of a generic assembly

Experimental Methodology and Preliminary Results

The initial phase of this research program demonstrated that immersive VR appears to have an important role to play in the design of cable harness designs [12,13].

The system enabled the user to identify the most appropriate routing strategies and harness configurations to determine cable routes through the product and then select the relevant cable types. The operator then uses interactive routing tools to produce different types of wire harness such as single wire layouts, branched multiple wire layouts to bundle wires layouts. Once the harness layout is completed, a wiring list is generated. In order to test the VR system in an industrial setting, field trials were carried out to investigate the effectiveness of creating cable harnesses using immersive VR; and to compare the cabling capabilities of the VR system with established commercial CAD cabling systems.

This type of field-testing would ideally involve a substantial number of users to comply with statistical parameters set by experimental designs involving human users. However, this approach is not possible here since, typically, the number of design engineers available for participation is small and is, in itself, a sample drawn from a small population. Hence, a variation on the ''single-case experiment'' was adopted and no statistical testing was performed on the data. (Such methods have been applied successfully in Clinical Neuropsychology and are referred to as *ideographic* approaches [14].)

Five experienced cable harness designers from four industrial collaborators participated in the research. They were all considered as experts in the use of their respective CAD systems for routing cable harnesses. Their CAD experience ranged from three to fifteen years and none of them had used an immersive VR system before. The user denoted as experimenter, was a researcher with three years experience in using and developing the VR system [15] and acted as a control. The comparisons between the industrial designers and the experimenter are at the process level rather than at the cognitive level but do provide a useful contrast within the confines of the measures used.

The cable routing modules that were tested in the trials were from the following packages: Pro/ENGINEER™, SolidDesigner™ and CATIA™ (the piping module). The industrial partners for the design of harness assemblies for use in their products currently use these cabling systems. The generic assembly used during these tests is shown in Fig. 4 with examples of routing at various stages of the process given in Fig. 9.

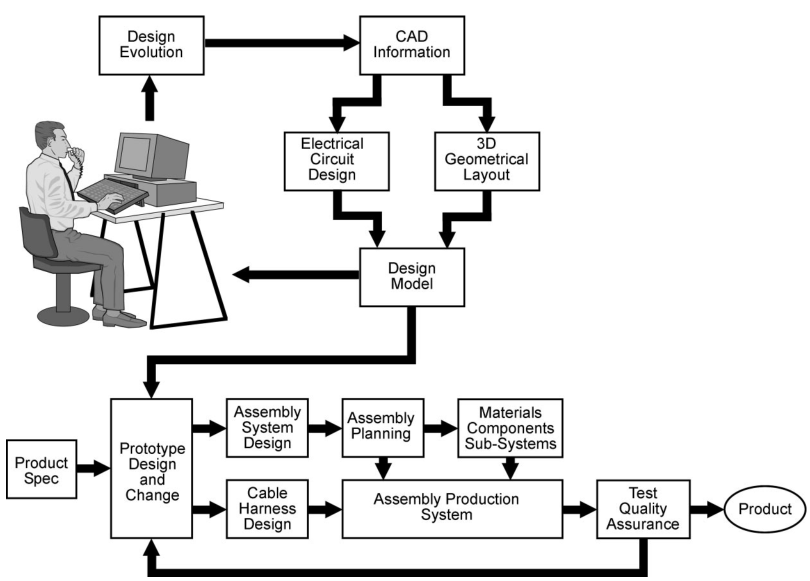


Fig. 5 CAD interaction with the Design-for-Manufacture Process

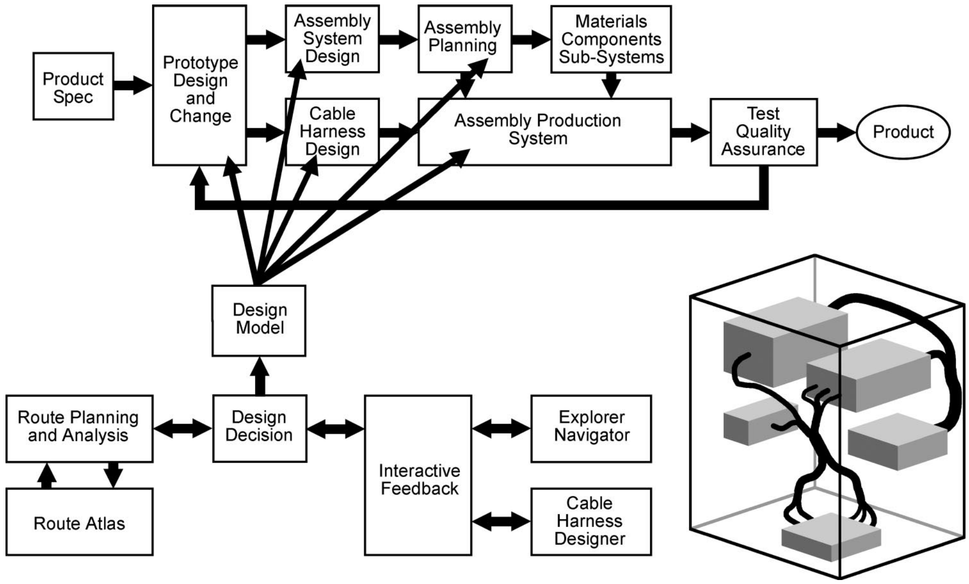


Fig. 6 Immersive Virtual Reality interaction with the Design-for-Manufacture Process

By comparing Task Completion Times (TCTs) it was found, for a simple single-level layout, that the participants took between two and four times longer to complete the routing task using the proprietary CAD systems (see Table 2). Here, the five industrial designers used both the VR system and conventional CAD. The experimenter (control) did not participate in these trials.

Direct observations and video analysis showed that only half of the participants made errors in VR compared to using CAD. Multilevel assembly routing was compared in a second set of trials; the TCT comparison depicted in the bar chart (Fig. 10) showed that VR gave productivity gains of between 3:1 and 5:1.

Other measures used were the number of mouse clicks, the number of mouse clicks per minute and keyboard entries. Tables 3 and 4 show a comparison between industrial designers using CAD and the experimenter (control) using the VR system. The measures were obtained through video analysis and from these it can be seen that the VR system requires significantly less mouse clicks than the CAD systems for both tasks.

A questionnaire was also given to participants after every VR and CAD trial which was used to compare the ease of using VR with the established CAD cabling tools as well as its suitability for carrying out harness design in the immersive VR system. These data showed that the VR system is comparable to conventional CAD systems in the domain of harnessing and that immersive VR can be used as a more effective tool for routing cable harness assemblies.

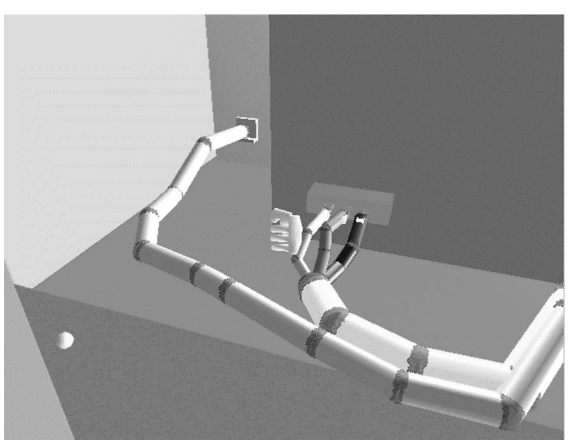


Fig. 7 A user utilizing the VR system for routing a cable harness in the virtual world

Figure 11 shows the complete multi-level routing outputs developed in both VR and the associated CAD systems.

This preliminary work demonstrates that the TCTs obtained by the participants were between two and five times faster when using VR than current CAD systems, even though the experiments were heavily biased towards CAD. The VR interface, with fewer mouse clicks and keyboard inputs, appears to have a significant impact on TCTs and this, along with the results from the questionnaire, indicate that participants found the VR system comparable to current commercial CAD systems for the routing of cable harness assemblies. Although it is recognized that the VR system output takes more of a pipe form that what is finally output from commercial CAD packages, it should be noted that most of the latter types of system utilize pipe-form inputs and outputs with a 'curve fitting' option at the end of the design process. Therefore, it was decided to compare the systems in terms of actual cable route generation via pipe forms and not include the superfluous 'finishing' of curve-fitted cables.

Park [16] states that harness design requires in-depth three-dimensional spatial reasoning, which, as stated by Kloske [17], CAD systems tend to lack due to their conventional flat screen display. These results have shown evidence that the two or three degrees of freedom of movement on a flat screen provided by current CAD cable harness routing systems inhibits the designer's ability to route cable layouts especially in complex 3D assemblies. Immersive VR on the other hand gives users the ability to change their viewpoint quickly and provides six degrees of freedom of movement thus showing great promise as a suitable environment for routing cable harness assemblies.

It also demonstrates that, in general, immersive VR can be used as an interactive design tool as well being useful in the actual routing of cable harnesses. However, there are several limitations to the field trials and these must be highlighted. Ideally, good experimental design involves the manipulation of independent variables while keeping all other potentially confounding variables under control. In the work reported here it is problematic to separate the influence of the graphical user interface of the VR system from the influence of the cable harness toolset. What this means is that while it is arguable that the positive aspects of the VR system in comparison to the CAD systems are due to the virtual software tools provided to the designer then the influence

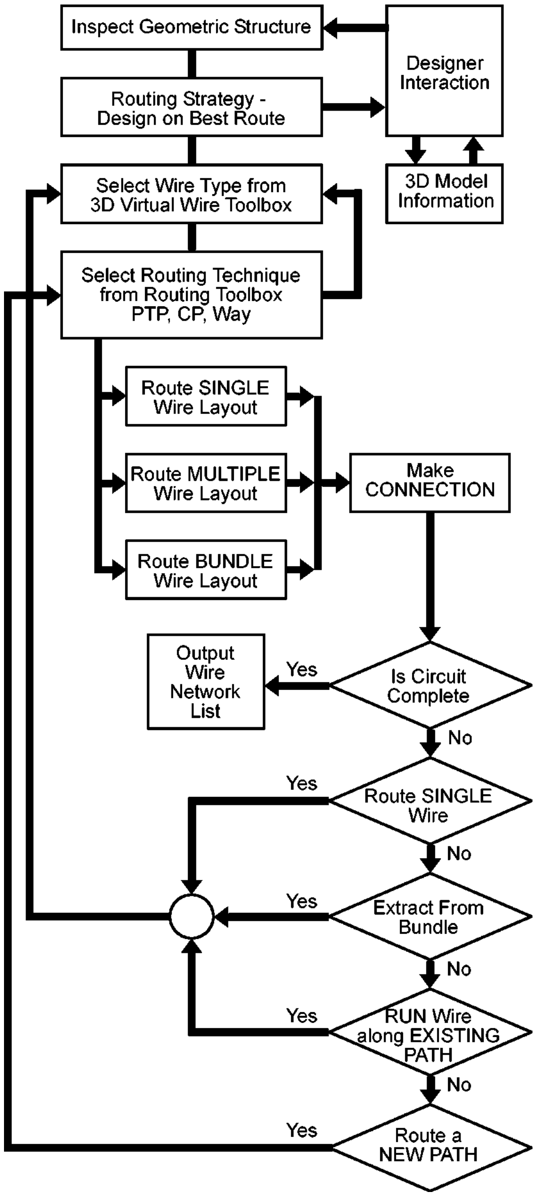
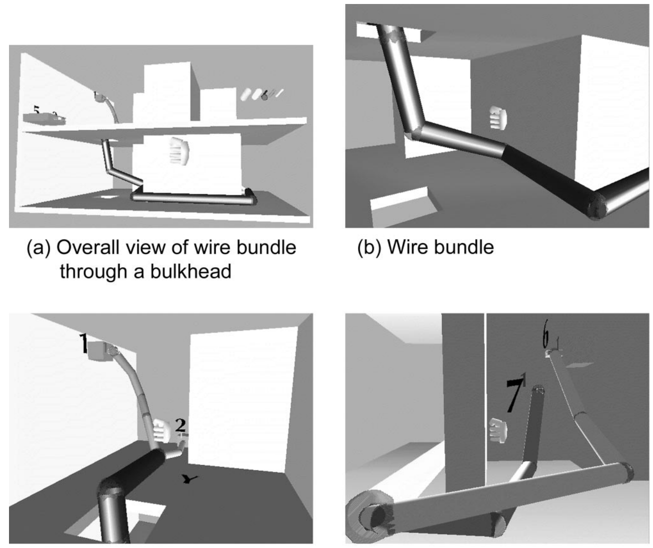


Fig. 8 The VR system algorithm

of the more sophisticated VR graphical user interface *per se* to enhanced performance remains to be clarified. It must also be noted that the industrial trials only compare CAD systems with the overall VR environment. The work did not analyze which elements within the virtual environment actually contribute to the

Table 1 An Exemplar Generic Task

CABLE Technologies	GEOMETRY	PROCESS
Flexible copper	Back-plane to display panel	Design
Hard copper	Interconnected modules	Manufacture
Ribbon	Movable modules	Assembly
Heavy screened	Rotating components	Reliability
Armoured	Multiple bulkhead compartments	Installation
Semi-rigid high frequency	Single conductors	Safety
Rigid high frequency	Conductor bundles	Maintenance
Optical fibre	Interconnected harnesses	Repair
Thermal effects	Confined spaces	Scale factors
Electromagnetic effects	Fixings	Communication
	Connectors	Testability
		Human factors



(a) Overall view of wire bundle through a bulkhead
(b) Wire bundle
(c) Single wires from a bundle above the bulkhead
(d) Single wires from a bundle below the bulkhead

Fig. 9 Examples of virtual cable routing in the VR system

improved performance. These results initiated in the development of the Designer's Workbench Metaphor as a possible vehicle for studying further cable harness design and to provide immersive VR support that is highly interactive in an industrial context.

Development of the Designer's Workbench Metaphor

The Designer's Workbench Metaphor is shown in Fig. 1 and is based upon recreating in VR a representation or metaphor, which captures as far as is possible the ''natural'' way design tasks are carried out. In order to achieve this a greater understanding of the design process and the cognitive processes which underlie design is required. The approach taken involves observing designers at work, using verbal protocols and extracting data from designs and design documents under the guidance of industrial cable harness designers. An important aspect of the resulting VR design is to produce a ''natural'' environment, which has features such as moving parts, cable sag and electromagnetic effects. A very important feature of the new VR system is the notion of ''tinkerability,'' which reflects the way designers like to make changes to prototypes, whatever the form of the prototype, to suit the final ''fitness for purpose.'' This process of interface design is analogous to the development of the Desk-Top Metaphor seen in modern windows systems.

The VR system is implemented on an SGI® Octane2™ (400 MHz IP30 processor, 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. 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

Table 2 Comparison of TCTs for VR and CAD for a single-level assembly

Participants	VR-TCTs (Mins)	CAD-TCTs (Mins)	Types of CAD Systems
Expert 1	6.58	13.52	Pro/ENGINEER™
Expert 2	7.57	12.83	Pro/ENGINEER™
Expert 3	6.8	20.1	Pro/ENGINEER™
Expert 4	5.10	12.52	SolidDesigner™
Expert 5	4.98	17.1	CATIA™

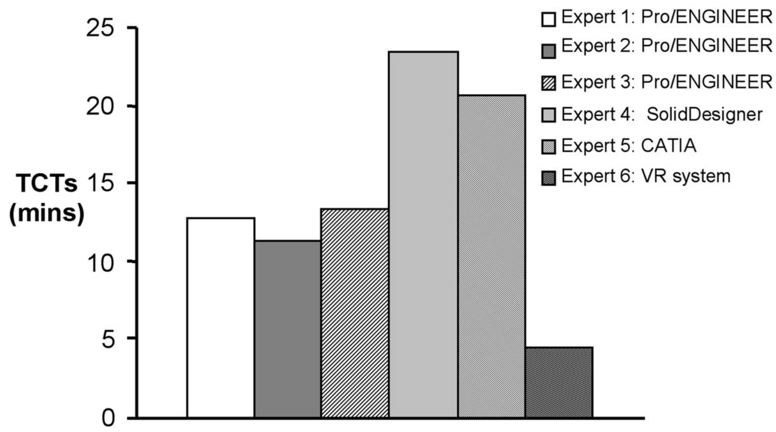


Fig. 10 Comparison of CAD and VR cabling systems for a complex multilevel assembly

(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 gloves with conductive cloth at the tips of each finger, with signals being 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 system enables the user to design cable harness assemblies within the immersive VR environment, with all design functions including the creation of new objects being performed while the user is immersed in the system. Interactions with the system are achieved by means a custom-built menu system and pinch gestures (combinations of two to ten fingers all touching each other) in addition to the spatial input afforded by the Flock of Birds system; see [18] for a more detailed discussion of the merits of using such an input device. Figure 12 shows the lightweight immersive helmet and the pinch gloves while Fig. 13 shows an example screen of the gestures used. Figure 14 shows the menu system in use for selecting the current cable type, Fig. 15 shows 2 cables being created in a bundle, and Fig. 16 gives an example of a cable being edited by translating a section.

Table 3 Other measures for CAD and VR system comparison for single-level assembly

Participants	No. of Mouse Clicks	No. of Mouse Clicks per min	No. of Keyboard Entries
Expert 1 (Using CAD)	266	20	30
Expert 2 (Using CAD)	153	12	15
Expert 3 (Using CAD)	527	26	13
Expert 4 (Using CAD)	195	16	30
Expert 5 (Using CAD)	406	24	66
Experimenter (Using VR)	30	10	Not Applicable

The initial results and feedback from the industrial partners are encouraging and support the theme of the current research paradigm illustrated in Fig. 17. A new system of routing "elastic" cabling is under development together with other editing tools. In addition, experimental methods to integrate CAD and Virtual Reality systems are under investigation. As stated earlier, the aim is to provide the expert with interactive tools including immersive VR so that implicit, human expertise can be applied effectively in the design cycle [19–21].

The initial work carried out by the authors using VR as an experimental research tool has shown the following advantages compared with conventional physical experimental methods. Firstly, experimental controls in terms of procedure (both presentation and measurement) are greatly enhanced. In addition, the data collected is less prone to errors of measurement, and potentially the amount of data collected is very high. (For example, in an experimental task lasting 5 minutes, with measures of position, orientation and time being taken every 10ms one obtains 90,000 measures from the VR system. This compares very favourably with a similar 5-minute task using physical equipment, which would only yield in the order of 10 measures). In addition to these advantages, VR provides flexible tools for altering experimental conditions and data collection allowing general experimental de-

Table 4 Other measures for CAD and VR system comparison for multi-level assembly

Participants	TCTs (Mins)	No. of Mouse Clicks	No. of Mouse Clicks per min	No. of Keyboard Entries
Expert 1 (Using CAD)	12.82	261	20	21
Expert 2 (Using CAD)	11.27	165	15	12
Expert 3 (Using CAD)	13.37	593	44	22
Expert 4 (Using CAD)	23.35	294	15	52
Expert 5 (Using CAD)	20.7	533	26	87
Experimenter (Using VR)	4.43	89	20	Not Applicable

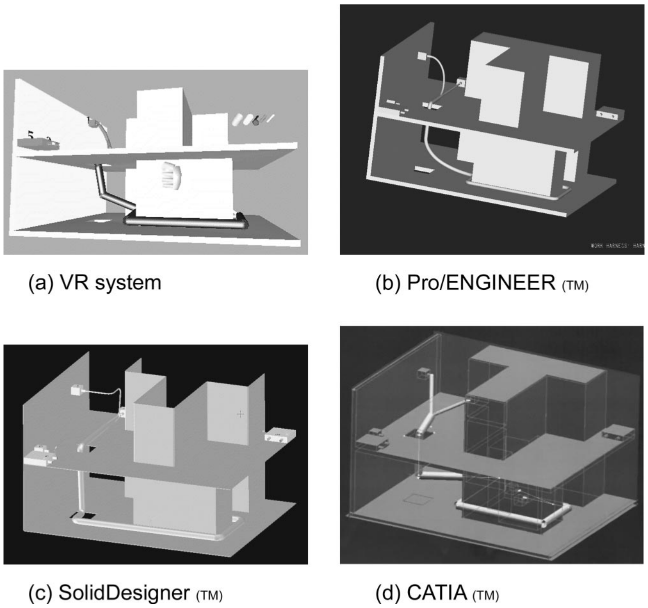


Fig. 11 The multi-level routing test on the associated CAD and VR systems

signs to be refined and reused as required. This is of particular use when testing and refining experimental hypotheses. However, the following disadvantages with using VR compared with conventional physical equipment have been noted. Firstly, and perhaps most importantly, in the experience of the authors, considerable skills and efforts in software design and development are required to use VR in experimental tasks.

Fig. 12 VR Helmet and pinch gloves

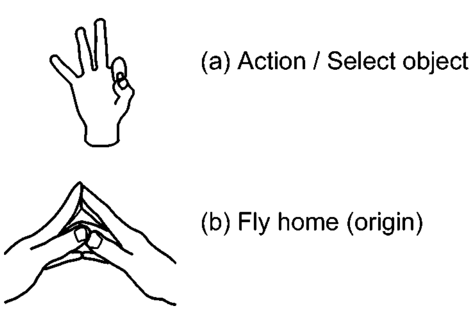


Fig. 13 Example control gestures

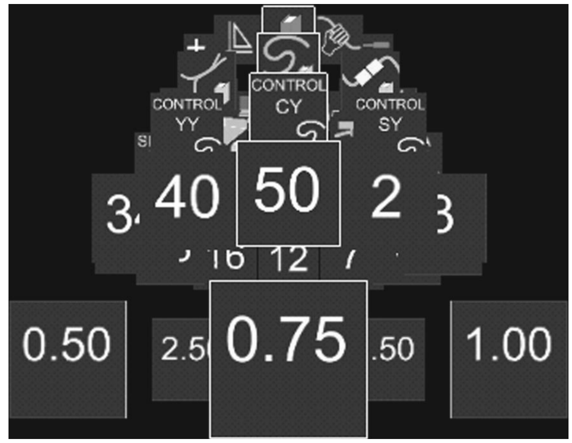


Fig. 14 Example menu-choosing cable type from library

Another significant consideration is that the equipment required for VR based experiments can be costly. As has already been mentioned, preparing immersive VR experiments was found to require a large investment in terms of resources. However, once a general experimental framework has been implemented it is relatively easy to produce variants allowing results to be replicated and experiments extended. Using VR means that the experimental procedure is automated and this yields data with low errors of measurement. This enables the experimenter to identify and control more readily the effects of experimental variables [22].

Discussion and Conclusions

The development of VR has been progressing for a number of years but with a focus on hardware and software technologies. It is only relatively recently that VR has started to be applied in real industrial settings, rather than using industrial exemplars, as is frequently reflected in the literature. The work reported here has focused from the beginning on applying VR in realistic industrial settings. This close collaboration with industry is what characterises our user centred approach and the results obtained have begun to demonstrate the potential advantages of VR. It was also demonstrated that the application of VR in manufacturing need not be deskilling, rather it can be supportive and can serve as a toolbench to enhance our knowledge of design, thereby allowing more effective designs, taking shorter times with less error, all of which has important economic consequences.

It is often assumed that VR Environments should reflect ''visual realism'' or the real world as far as is possible and that through achieving this the application of VR would become more effective. The work reported shows that it is wrong to assume that VR

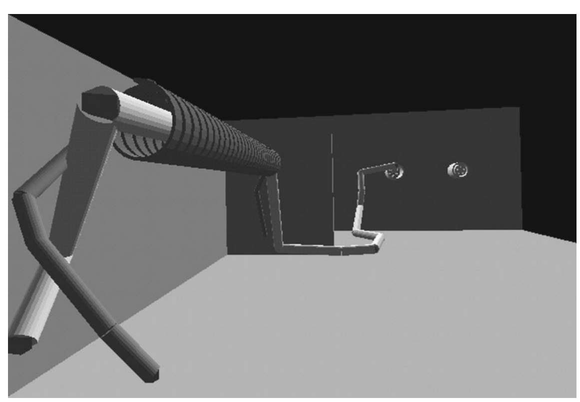


Fig. 15 Example of cable creation

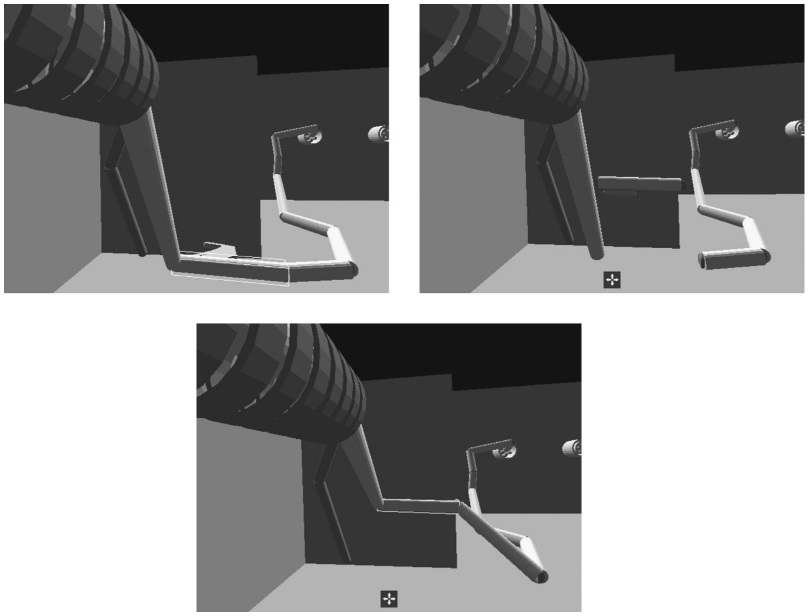


Fig. 16 Example of cable editing

Environments must represent visual realism to be effective. Rather, much like happened with the development of modern graphical user interfaces, abstracted metaphors, which are matched to tasks and allow users to work naturally is an important development of effective VR systems intended to support design in industry. Through this feasibility was established and important new knowledge was gathered about the design process and how VR might be used as a research tool.

As this research develops further, we face a number of challenges, which have been identified. The weakness of small samples of experienced engineering designers remains and will remain a problem. Further lessons from ideographic or single user experimental designs can be learned. A complimentary alternative is to abstract the design tasks to be more suitable for laboratory experimentation. This would involve simplifying and deconstructing tasks to be more suitable for experiments involving senior engineering students as users with the results from such work being compared to results obtained with small samples of experienced engineering designers in industry. This approach will also allow manipulation of experimental variables that is more detailed, thereby separating the effects of a graphical user interface as compared to immersive VR and the graphical user interfaces of CAD systems. Such experimental manipulation will involve making tasks more artificial as compared to an industrial setting.

Throughout the project, the VR equipment has been continuously upgraded. One important aspect of this is the nature of the Head Mounted VR displays (HMDs), which have become lighter, smaller and of higher resolution. Further work is planned to compare various types of display, e.g. HMDs, Semitransparent Displays (Augmented VR), Stereoscopic Displays and Desktop non-immersive displays. As part of this planned work, various ergonomic and health issues will also be investigated. The long-term affects of prolonged use of VR are not well understood and issues such as general fatigue, physiological affects on head, neck, shoulders, and back, motion sickness and eyestrain, and psychological implications, will be addressed.

It seems safe to conclude that applying VR in industry as part of a supportive toolset has begun to show positive results with economic implications. Integrating users into the total functionality of an integrated disciplinary system appears to be a promising way of supporting users, making use of their strengths while avoiding deskilling. The evolution of the concurrent engineering environment of the future will require a much deeper understanding of human factors and cognitive ergonomics issues to enable the effective creation of user-friendly, intuitive tools for the engineer of the future [21,22].

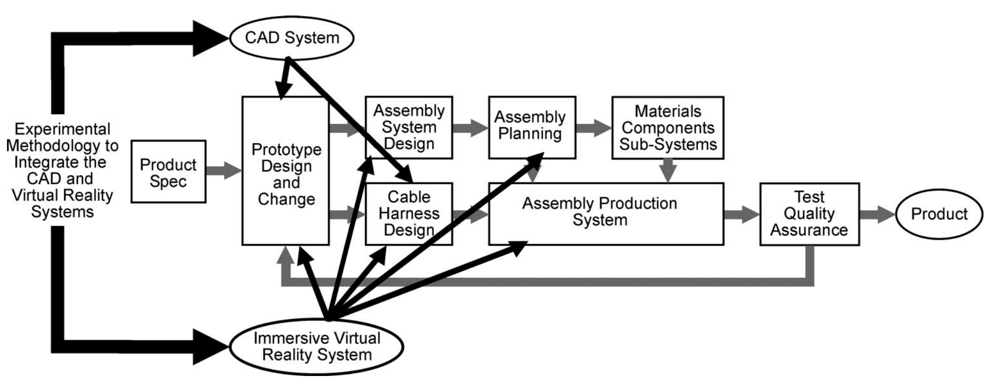


Fig. 17 The research paradigm is to include the expert designer within the cable harness Design-for-Manufacture loop

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