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Computer-Aided Design 39 (2007) 245–257
COMPUTER-AIDED DESIGN
www.elsevier.com/locate/cad

System design and user evaluation of Co-Star: An immersive stereoscopic system for cable harness design

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Received 26 May 2006; accepted 8 December 2006

Abstract

The system design and results of a user evaluation of Co-Star an immersive design system for cable harness design is described. The system used a stereoscopic head mounted graphical display, user motion tracking and hand-gesture controlled interface to enable cable harnesses to be designed using direct 3D user interaction with a product model. In order to determine how such a system interface would be used by a designer and to obtain user feedback on its main features a practical user evaluation was undertaken involving ten participants each completing three cable harness design tasks with the system. All user interactions with the system were recorded in a time stamped log file during each of the tasks, which were also followed by questionnaire (5 point scale) and interview sessions with each participant. The recorded interaction data for the third task was analysed using functional decomposition techniques and used to construct a single activity profile for the task based on the mean results obtained from the participant group. The goal was to identify in general terms the relative distribution of user activity between specific purposes during practical system operation, and it was found that in this task Navigation accounted for 41%, Design 27%, System Operation 23% and looking at Task Instructions 9% of all user activity. The scored questionnaire data collected immediately after the completion of each task was used to rank the major features of the system according to user opinion. This was further enhanced by also collecting real interview comments from the user group about these same features. The combination of both quantitative performance analysis and subjective user opinion data obtained during a practical design exercise has enabled an in depth evaluation of the system, leading to a much greater understanding of many of the key user and interface requirements that should be considered during the development of immersive interfaces and systems for practical engineering applications.

Keywords: Virtual reality; Immersive design; Task analysis; User evaluation; Cable harness

1. Introduction

It is well known that computer-aided design (CAD) systems can bring significant benefits to engineering design through improved quality of output or improved efficiency of process; and that further improvements to current CAD systems may be possible, for example, by providing more intuitive interfaces that support the natural work flow of the user or through the appropriate use of new technologies. Such technologies include stereoscopic displays and motion tracking systems which together can provide the 'virtual reality' (VR) experience of being immersed in a 3D computer generated world. Typically VR systems are used to enhance a user's appreciation of a computer generated model by enabling them to view the model as though they are located within it; commercial applications include training (e.g. flight simulators) and visualisation (e.g. architectural-walk-through and automotive or aerospace vehicle mock-ups). However, there has also been significant effort to use various virtual [1] and augmented reality [2] 3D display and interface technologies as alternatives to more traditional desktop computer systems for a range of product development and related engineering tasks including concept generation [3,4], design [5], analysis and optimisation [6], manufacturing process simulation [7,8] and assembly planning and verification [9–13].

Indeed earlier work by Ng et al. [14,15] compared the performance of a VR design system with more traditional desktop CAD systems during cable harness design and demonstrated the potential for such an immersive system

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doi:10.1016/j.cad.2006.12.001

to impact upon the efficiency of design activity. However, the work was not able to identify which aspects of the software or technology platform produced this result nor how to develop the prototype into a practical system for VR-based engineering design. The Co-Star system described in this paper builds on this previous work by further investigating the major technological, human factors, interface design and other practical issues regarding the development and use of an immersive design system in engineering and specifically for cable harness design.

A demonstration system was developed incorporating the functionality needed to produce outline harness designs whilst also providing the interface feel of a larger and more comprehensive design platform. A detailed user evaluation of the completed system was undertaken with a small group of participants with the purpose of investigating how it was used during practical design work and to identify from a user perspective the key strengths or weaknesses of both the software interface and the technologies used. During the evaluation ten participants each used the system to undertake a series of three cable harness design tasks. All user interactions with the system were unobtrusively recorded in a system generated log file of each task; questionnaire and interview sessions also took place with each participant immediately after each task session. The user activity log files for the third (and final) task in the sequence were subsequently analysed to construct a single ‘typical’ user profile showing the relative distribution of user activity for the task based on the mean (average) activities undertaken by this user group during this task.

The questionnaire data obtained for each of the tasks was used to rank the major features of the software interface and system technologies. The feature questionnaires used a balanced 5 point scale to allow the users to score each feature, and in line with standard reporting techniques the mean and standard deviation of the scores obtained from the questionnaires for this sample group are reported. The mean value for each feature obtained from the questionnaires was used to rank the features and this process was further enhanced by the specific user comments regarding these same features made during the interviews that followed completion of the questionnaires.

Details of the Co-Star system design, the evaluation methods, the evaluation design task, the different analysis methods used and the results obtained are all presented in this paper, which therefore provides a valuable resource for anyone developing an immersive (or stereoscopic) design system or considering the practical application of one in an engineering environment.

2. Cable harnesses

A cable harness is an assembly of wires, connectors and other components that provides the electrical interconnectivity between different modules within a larger electromechanical product such as an automated-banking-machine (ATM), vehicle or aeroplane. Cable harnesses can follow complex 3D routes within a product and developing a harness design that fulfils all the electrical, mechanical, assembly and lifecycle requirements can present many challenges to the engineers involved. The rationale for the development of a stereoscopic system for this application is that immersing the engineer in a 3D product model and enabling direct interaction with it may provide a more natural and efficient interface, may increase the engineer’s spatial understanding of the product, and could potentially lead to better harness designs being generated in a shorter time by enabling more problems to be identified and corrected earlier in the design cycle. The practical realisation of this goal is perhaps some way off but the work described here represents a major step forwards in understanding the complex functional, user and system requirements needed to achieve it.

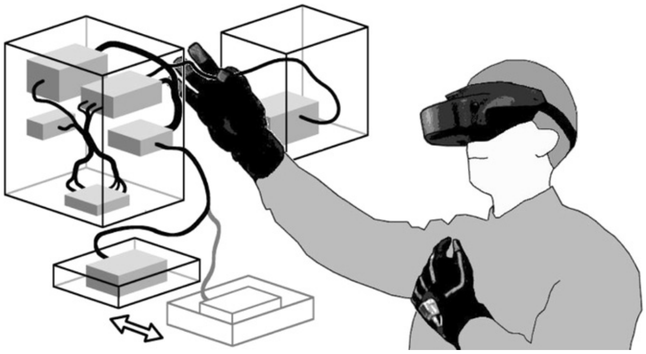


Fig. 1. Immersive design.

3. Co-Star system design

Co-Star uses a stereoscopic head mounted display (HMD), body motion tracking and pinch gloves to immerse a user in a design model and allow them to use normal upper body motions to create and edit cable routes directly within the 3D model space (Fig. 1) [16]. The system was developed using commercially available technologies including the Sense8 World-Tool-Kit development environment running on an SGI Octane2 computer with two graphics pipes. These were used to provide ‘left’ and ‘right’ eye views on a Virtual Research Systems V8 HMD which enabled a user to see a stereoscopic image of the model. 3D user interaction with the model was supported using a pair of Fakespace Pinch Gloves for gesture based interaction and user motion tracking with an Ascension Technology Corporation Extended Range Flock of Birds. Motion tracking sensors were fitted to both of the pinch gloves and the HMD enabling the position and orientation of the user’s head and hands to be measured in real-time. The Fakespace gloves have conductive pads at the end of each finger and Co-Star is controlled by natural user motions involving arm motion to locate the design cursor within the model and simple hand gestures to communicate commands to the system. These hand gestures bring specific pads into contact, usually a thumb against a finger on the same hand or touching opposite fingers on each hand and are illustrated in Fig. 2. It is this potential for the user to use normal body motion such as looking and reaching towards an object in the 3D model environment combined with a few simple gestures to operate the system that

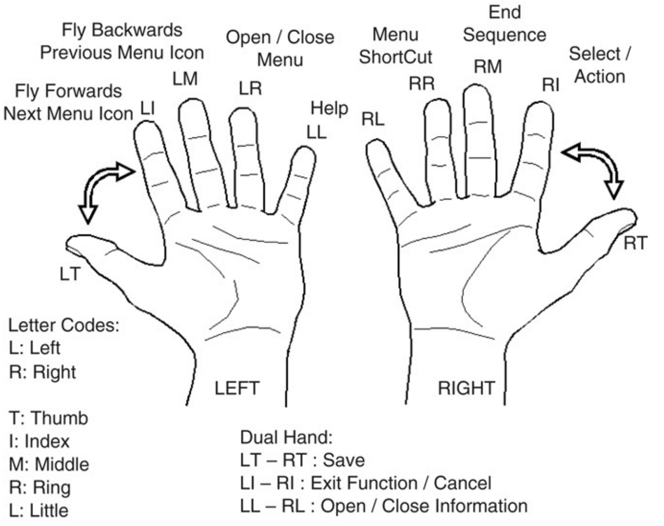


Fig. 2. Co-Star pinch glove hand gestures.

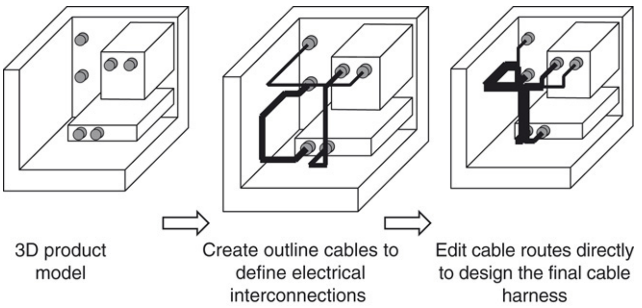


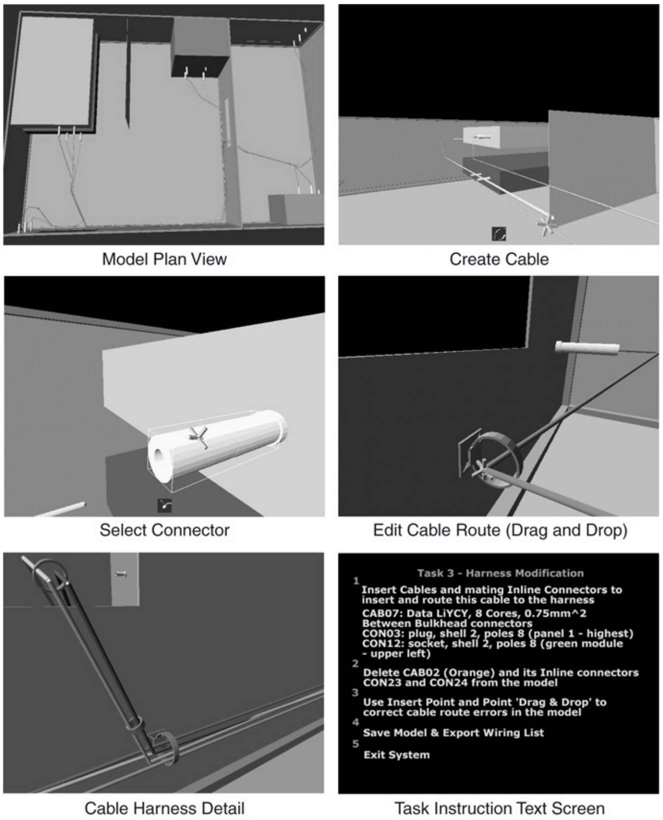
Fig. 3. Cable harness design with Co-Star.

is one of the major attributes of the technologies used in this system, and one which this research is working to exploit within practical engineering applications.

The process of designing cable harnesses using Co-Star is outlined in Fig. 3. Cables are created by inserting connectors into the model from the parts library and then using the 'create cable' function to generate an outline cable between the connectors by directly creating points in space that define the cable's route through the model. Subsequently, the paths of individual cables can be edited by adding or moving points on the cables to define the final form of the overall cable harness in the product model.

The system has three different interface modes; model, menu and text screens. The model environment is the main operation mode and where the design activity occurs; here the user is immersed in a first person stereoscopic view of the model on which he or she is working (Fig. 4). Body motion tracking is used to control the local model view with the user moving their head to control their viewpoint, whilst the location and orientation of the design cursor is controlled by the position and orientation of their right hand. Hand gestures are used to control the global location of the user within the model and they are able to 'fly' forwards or backwards through it using simple hand gestures.

Users are able to interact with objects in the model by reaching towards the object with their right hand which also moves the design cursor towards the object in the model. When the cursor collides with the object a bounding box appears around the object indicating that it is available for selection. It is selected by the user pinching their thumb and index finger together on their right hand ('action' gesture). Objects can be moved by holding this gesture whilst the user moves their hand (and the object) to a new location in the model, where it is placed by letting go of it.


Model Plan View
Create Cable
Select Connector
Edit Cable Route (Drag and Drop)
Cable Harness Detail
Task Instruction Text Screen

Task 3 - Harness Modification
1
Insert Cables and mating Inline Connectors to insert and route this cable to the harness
CAB07: Data LiYCY, 8 Cores, 0.75mm^2
Between Bulkhead connectors
CON03: plug, shell 2, poles 8 (panel 1 - highest)
CON12: socket, shell 2, poles 8 (green module - upper left)
2
Delete CAB02 (Orange) and its Inline connectors CON23 and CON24 from the model
3
Use Insert Point and Point 'Drag & Drop' to correct cable route errors in the model
4
Save Model & Export Wiring List
5
Exit System

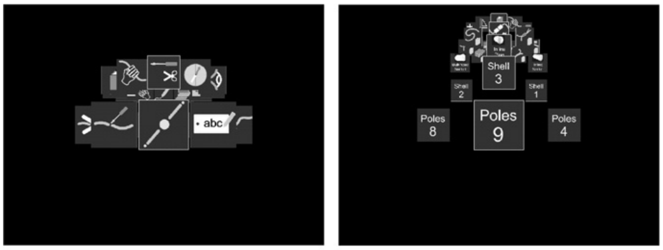
Fig. 4. Co-Star model environment and text screen.

The main harness design functions are 'create cable', 'join cable to connector', 'delete object', 'insert connector', 'insert cable point', 'save model', 'mate connectors', 'drag and drop cable editing', and 'export documentation'. When a function is active a small icon for it is shown in the centre lower edge of the display. There are also several text screens, including help screens and a summary task list, which can be accessed from any point in the system.

Similar to typical graphical user interfaces Co-Star has an icon based menu system (Fig. 5) this uses a gesture controlled hierarchical ring structure that is accessed using a dedicated 'menu' gesture. This gesture displays the top level menu ring which can be rotated, using the same gestures that are used to fly in the model environment, until the required icon is at the front of the ring. Selecting this icon causes the next menu-ring to be displayed and the previous level moves up the screen showing the menu hierarchy. The process is repeated through sequential ring layers until the desired function or option is reached. Menu levels can also be 'cancelled' to move up through the structure. The menu automatically exits to the model environment when

Action Gesture

Cancel Gesture



Tools Menu

Connector Library

Fig. 5. Examples of actual user hand gestures and the ring menu system.

a specific menu operation has been completed, or alternatively the ‘menu’ gesture can be repeated to close it.

Each menu ring contains a maximum of 12 icons and typically selection is complete within 2 to 3 layers, although the parts libraries have up to 5 menu levels to define all of a part’s parameters. The menu hierarchy contains icons for about 130 different functions and library options providing the feel of a reasonably comprehensive design system, although only about half of these were active on this test system. This approach was used to ensure that some of the operational complexities, such as menu navigation, that would be encountered in a full system were recreated so that a realistic evaluation of an immersive design platform would be achieved. The ring menu is similar to that described by Liang and Green [17] and Gerber [18] but unlike these which used wrist orientation to rotate the ring, this version is entirely gesture controlled. Gesture control was used to reduce the requirement for wrist rotations during operation and allow user’s to position their hands comfortably.

In order to reduce any delays between user tracked motion and the display updating, a system of object selection filters was used. These significantly reduced the model data that the programme had to search for object collisions during each cycle but also meant that the user had to tell the system (via the menu) what type of object they were currently wishing to interact with (although the filter setting only had to be changed when interaction with a different object type was required). This ensured that a real time environment was maintained which was important in minimising any user discomfort from using the stereoscopic display. User discomfort from stereoscopic displays can include headaches, nausea, and eye fatigue and is collectively known as ‘simulator sickness’ [19]. Another aspect of reducing computational overhead was that dynamic mating of objects by dragging them through other objects was not used and object mating also occurred indirectly via menu functions.

4. System evaluation

The system evaluation had two main objectives:

(1) To investigate how an immersive design system was used during a practical engineering design exercise and identify in general terms the relative distribution of different types of user activity within this use.
(2) To identify and rank the main features of the software interface and the technology platform and identify the main reasons behind these user opinions.

Central to this was developing an evaluation that involved realistic and practical design exercises with the system being used to undertake the key stages of cable harness design. The detailed nature of the evaluation, the need to train each participant to use the system and allow each a sufficient amount of time using it to develop a reasonable level of competency, and the amount of data to be collected and analysed from each session, required a realistic trade off to be made between the experimental ideal of having a large sample size and the resources available to achieve the goals of the evaluation. Hence, the system evaluation was undertaken by a small group of ten participants who each independently used it to complete a sequence of three design tasks plus an initial training session.

All of the participants were volunteers, two were university staff, seven were engineering students, and one was from a partner company. All were male and right handed; eight were aged 20–29, two were aged 30–39; eight had normal vision, whilst two wore glasses. All had previous CAD experience.

Each evaluation task took approximately 20–30 min to complete and represented a stage of a cable harness design in a relatively simple product model. End-to-end the three tasks included all of the activities required to complete a harness design using the method outlined in Fig. 3. All of the tasks took place in the same model environment with only the state of the harness model changing between them. The first task involved the creation of some outline cables to define the harness connectivity; the second involved detailing the routes of the cables to complete a harness design; and the third involved making some revisions to a completed harness design. Participants completed each task at a different session and the performance task results presented in this paper were obtained in the third task. This task had five main sub-tasks:

(1) Add cable 1: Add a cable of a specified type connecting two specified connectors.
(2) Delete cable 2: Remove a specific cable and its in-line connectors from the model.
(3) Fix cable error: The model included an undefined change to it that meant that the harness design was no longer appropriate. Participants had to redesign the harness to fix this issue.
(4) Save model and export documentation: Save the revised model and export an updated wiring list.
(5) Exit system: Exit the immersive design environment.

Each session began with a briefing using a summary of the task goals and a desktop VRML viewer showing the model environment. The briefing ensured that the participant understood the objectives of the task and any constraints but at no stage was a solution suggested to them. The immersive design session followed during which the participant completed

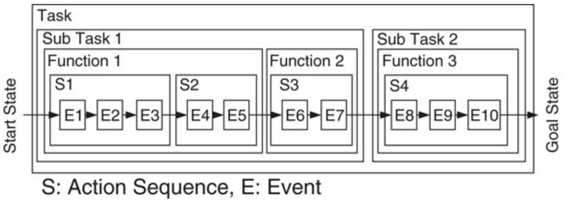


Fig. 6. The principle of task functional decomposition into hierarchical units of design activity.

the design exercise using the head-mounted display and motion tracked interface. Details of all the user's interactions with the system (including all gestures, menu interactions, functions used, object interactions, and navigation) were unobtrusively recorded in a time-stamped log-file of the session. The immersive design session was immediately followed by a questionnaire and interview session.

5. User activity categorisation

A method of categorising design activity was developed to analyse the user activity log file data and produce a distribution profile for the average (mean) user activity for the participant group based on both time and number of action sequences used to complete the task. During analysis the task activity of individual participants was broken down into meaningful sequences of actions using the principle that larger activities (such as sub-tasks) are made up of composite groups of actions (functions), which are in turn made up from smaller sequences of actions and individual interface events (Fig. 6). Functional decomposition is a standard engineering approach the basics of which are described in any good engineering design textbook (e.g. [20,21]) and a recent detailed review of the development and use of the methodology in ergonomics is given by Stanton [22]. However, the specific methods must be developed for the application under investigation and those described here were appropriate for the Co-Star system evaluation, although they are also applicable to the analysis of design and design systems in general. The following definitions were used during this work:

Function: A composite sequence of activity that achieves a single purpose. Typically functions could be identified as items on the menu system and the use of several functions was required to complete each sub-task.

Action sequence: A single sequence of user activity that produces a single identifiable action or operation within the system.

Interface event: A single user input (or gesture).

A useful analogy to illustrate the relationship between these different activity descriptions is a comparison with the language constructs 'letter', 'syllable', 'word', 'sentence', etc. In language the simplest words are one syllable long and contain one letter e.g. 'a' or 'i', but words can also be more complex with many syllables and letters and may also include the letters 'a' and 'i'. At a higher level groups of words are used to produce sentences that convey a specific meaning or purpose. Similar relationships apply to 'action sequences', 'interface events' and 'functions' which combine in different ways to deliver the purpose of the user's current sequence of activity.

After task decomposition, the action sequences obtained for each participant were grouped into activity classes based on purpose to determine for how long (time) or how often (count) a particular type of activity had occurred during the task. All action sequences were considered to belong to one of five classes:

Design: All activity that causes the design model or design documentation to be changed under the control of the user.

Information: All activity relating to the user obtaining information from a text screen.

System operation: All activity needed to operate the system but which does not usually cause a change in the design model.

Navigation: All activity leading to a change in the model viewpoint but which does not usually change the design model.

Process integration: All activity that interfaced with the wider product development process. In this case 'save' and 'export' of design data.

Since design is the core function of the system this class was further sub-divided to obtain more detail regarding this aspect of its use:

Design goal: Actions that produce an immediate change in the design model and which advance the design towards the goal state (completed design).

Design support: Actions that do not produce an immediate a change in the design model but enable the user to subsequently carry out a design goal activity.

Drag and drop (position edit): The action of moving an object from one location to another by direct interaction with it in the model environment.

The distribution of task activity was profiled by using these definitions to determine which class any particular unit of user activity within the session log-file belonged to (Fig. 7). System operation included all interactions that were required to operate the system but which would not necessarily be needed to complete the design if a different system was used. This included all menu activity except setting library part parameters which was classified as design support. Design support activity only included activity that directly allowed a subsequent design goal activity and did not include any activity that was only needed to support the operation of the system. 'Drag and drop' point editing was used to move the location of cable points and modify the cable paths in the model, this action often involved concurrently navigating within the model and is classed as design because moving the cable-point changes the design model. However, any travel that occurred in between moving points was classified as navigation.

Finally, two additional aspects of the task, unproductive activity and sequence breaks, were also identified as relative measures of operational performance.

Unproductive activity: All activity from any category that can be removed from the process without affecting the outcome of the task, i.e. any activity that has not added-value to the design process.

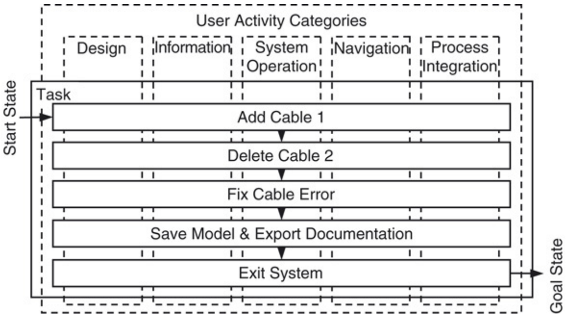


Fig. 7. Task decomposition into five user activity categories.

Sequence breaks: Pauses in user interaction activity between the end of one discrete action sequence and the beginning of the next.

The objective of identifying and measuring unproductive activity was to quantify how much effort was spent doing work that did not add value to the design process and the typical activities that this involved. A more detailed classification of unproductive activity into user ‘errors’ or ‘slips’ (such as described by Norman [23]) was not considered necessary in this work.

Similarly any breaks in the sequence of design activity were identified in order to quantify how much of the task time was ‘inactive’ and the distribution of this between the activity classes. In this context a sequence break is simply a gap in user interaction between the end of one identifiable action sequence and the start of the next on the basis of user gesture interaction. Non-gesture based activity such as head and hand motion (e.g. looking around or reaching towards an object) that produced only motion tracking data was not analysed and is included in the different activity categories.

A single profile representing the average user activity distribution for this user group in the analysed task was obtained by calculating the mean value (time or count) obtained for each class of activity for the participant group. This produced a generalised profile of system operation for this user group and this task; and it is this profile that is used in the following results and discussion sections regarding system operation.

Task analysis such as this is a general technique and indeed earlier work, for example, by Chu et al. [24] uses task decomposition to identify ‘planning’ (inactive) time, ‘operational’ (active) time, with both time and count being used to quantify specific interface events during the comparison of virtual reality and traditional interfaces using a series of constrained set-sequence geometry tasks. However, the techniques detailed here go further and describe a hierarchical structure of activities from the top level task through to individual interface events, and more importantly define a set of activity classes that enable the operational analysis of practical or unconstrained design tasks.

6. User activity results

From the experimentation, the total task times and sequence counts for each participant were determined as shown in Table 1. From these data, the operational results from the participant group are reported as the mean and standard deviation (st dev) using both time (seconds) and a count of the number of action sequences. The results include overall task data, the distribution of the task activity into the main activity classes, and the amounts of unproductive activity and inactive time.

Table 1
Total task times and sequence counts for the individual participants

Participant	P01	P02	P03	P04	P05
Task time (s)	1307	1433	1242	1271	1881
No. sequences	323	276	306	227	215
Participant	P06	P07	P08	P9	P10
Task time (s)	1125	693	1099	1549	963
No. sequences	179	160	142	229	179

6.1. Task results

The mean task completion time for the third task obtained from all participants was 1256 s (st dev 326) with the fastest individual time being 693 s and the longest 1881 s. The average number of action sequences used to complete the task was 224 (st dev 62) with the lowest being 142 and the highest 323. No significant correlation was found between the number of sequences used by individual participants to complete the task and the time taken.

6.2. Activity distribution

The results for the activity profiles for the individual participants were used to construct a single ‘average’ profile for the task using the methods outlined in Section 5. The objective for this was to determine in general terms the relative distribution of different types of user activity within the task and the results are given in Table 2. On average it was found that the largest activity was model navigation which accounted for 41% of task time and 42% of the identified action sequences, followed by design (27% time, 25% count) and system operation (23% time, 24% count) and obtaining information about the task (9% time, 8% count).

The design category was further divided into three sub-categories detailing more specific elements of design activity (Table 3). On average it was found that 10% of the total task time had involved activity that had directly resulted in progression of the task towards completion (15% of activity by sequence count). 5% of the task time and counted activity sequences was design support activity (e.g. setting part parameters or interrogating objects) that enabled some goal activity to subsequently take place, and 12% by time (5% by count) had involved editing cable routes by moving cable-points using direct ‘drag and drop’ object interaction in the model.

However, not all of this identified activity added value to the design process and it was found that all participants carried out some unproductive activity. Typical examples include opening and closing the menu system or a text screen without using it, activating a design function and exiting it without using it,

Table 2
Distribution of task time and count data into the main activity categories

	Design	Information	System operation	Navigation	Process integration	Total
Time (s)						
Mean	343	106	293	509	5	1256
St dev	164	36	76	160	2	
Percentage of task	27	9	23	41	0	100
Sequence count						
Mean	55	18	55	94	2	224
St dev	14	6	16	36	1	
Percentage of task	25	8	24	42	1	100

Table 3
Further breakdown of task time and count data for the design class

	Design goal	Design support	Drag and drop	Total
Time (s)				
Mean	129	57	157	343
St dev	53	21	130	
Percentage of task	10	5	12	27
Sequence count				
Mean	35	10	10	55
St dev	12	3	7	
Percentage of task	15	5	5	25

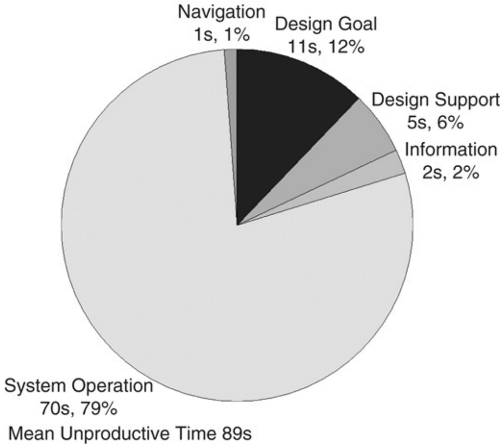


Fig. 8. Distributed of mean unproductive activity by time.

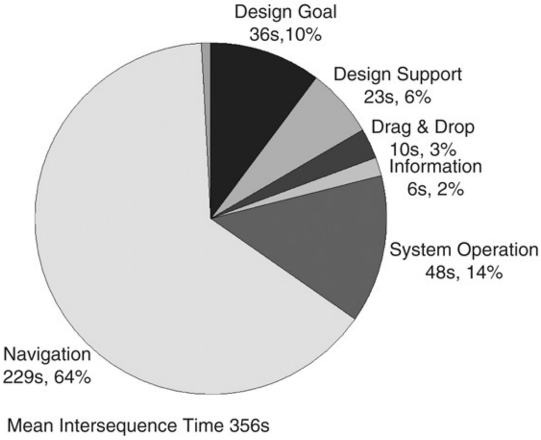


Fig. 9. Distribution of mean inter-sequence time.

inserting a wrong part and having to delete it, or setting one of the system parameters to its current value. (Navigation was only counted as unproductive if it occurred within an erroneous sequence of activity). On average participants made 20 (std dev 12) unproductive sequences of activity during the task totalling 89 s (std dev 64 s), which accounted for 7% of mean task activity by time. Distributing this unproductive activity into the different activity categories found that the majority of this, 79% by time, was due to unnecessary system operations and that overall 24% of system operations were not needed (Fig. 8). No significant correlation was found between the proportion of unproductive activity and the overall task completion time for individual participants in the group.

The action sequences identified in this analysis are discrete series of actions and there is often a short pause between the end of one and the start of the next. These pauses have been called sequence breaks and it was found that on average there were 180 such pauses in the task with a mean duration of 2.0 s (std dev: 0.6 s) which accounted for 28% (356 s) of the mean task time. Distributing these breaks between the different activity categories shows that 64% of this break time occurred during navigation and that this accounted for 45% of the total navigation time (Fig. 9). No significant correlation was found between the proportion of the task that was inactive and the overall task completion time for individual participants within the group.

7. Questionnaire and interview results

The immersive design session was immediately followed by a questionnaire and interview session. The questionnaire listed 54 features of the Co-Star software, technology or task, and the participant was asked to rate their opinion of each listed feature as 'very positive/very good' (++),

Table 4
Selected positive features of the system identified by the Co-Star user questionnaire

	Task 1			Task 2			Task 3			All tasks	
	Mean value	Std dev	Score	Mean value	Std dev	Score	Mean value	Std dev	Score	Mean value	Score
'System average':	3.7			3.8			3.9			3.8	
Results for individual features:											
Cable point 'drag and drop'				4.4	0.5	0.6	4.4	0.5	0.5	4.4	0.6
Being immersed in the design data	3.9	0.4	0.2	4.2	0.4	0.4	4.4	0.5	0.5	4.2	0.4
The pinch gloves	4.1	0.7	0.4	4.2	0.4	0.4	4.1	0.7	0.2	4.1	0.3
Accessing menus	4.1	0.7	0.4	4.2	0.4	0.4	4.0	0.8	0.1	4.1	0.3
Insert point into cable tool				4.1	0.3	0.3	4.1	0.3	0.2	4.1	0.3
Method of global model navigation	4.0	0.7	0.3	4.1	0.6	0.3	4.1	0.3	0.2	4.1	0.3
Your understanding of the task goals	4.0	0.8	0.3	3.8	0.9	0.0	4.4	0.5	0.5	4.1	0.3
3D object interaction	3.9	0.4	0.2	4.1	0.3	0.3	4.2	0.4	0.3	4.1	0.3
Creating cables in the model environment	4.1	0.7	0.4				4.0	0.5	0.1	4.1	0.2
3D object creation	3.9	0.3	0.2	4.1	0.3	0.3	4.1	0.3	0.2	4.0	0.2
Spatial awareness	3.9	0.7	0.2	4.0	0.7	0.2	4.1	0.3	0.2	4.0	0.2
Gesture control	3.9	0.6	0.2	4.0	0.0	0.2	4.0	0.0	0.1	4.0	0.2
Inserting connectors into the model environment	4.0	0.5	0.3				3.9	0.3	0.0	4.0	0.1
Mate connectors tool	4.2	0.6	0.5				3.7	0.7	−0.2	4.0	0.1
Menu structure	3.8	1.0	0.1	4.2	0.7	0.4	3.8	0.8	−0.1	3.9	0.1
Depth perception	3.7	0.8	0.0	4.0	0.5	0.2	4.1	0.3	0.2	3.9	0.1
Sense of direction	3.7	0.8	0.0	3.9	0.3	0.1	4.0	0.0	0.1	3.9	0.1

'positive/good' (+), 'neutral/average' (0), 'negative/bad' (−), and 'very negative/very bad' (−−). For analysis purposes these questionnaire results were converted to a five point numerical scale, with 1 representing 'very negative' and 5 'very positive'. Similar feature questionnaires were used at each task session with the listed features changing slightly depending on the system functionality needed to complete each task. Other techniques such as Kalawsky's usability questionnaire [25], Witmer and Singer's presence questionnaire [26] or Sutcliffe and Gault's heuristic approach [27] were not used because many of the generalised questions were not relevant and the approaches did not achieve the detail required about specific system features. Also, the completed questionnaires in this study were intended to provide a basis for more detailed discussion with each participant rather than produce a single 'usability' rating for the system as a whole.

The questionnaire results obtained for each of the three tasks and the mean value obtained across all three tasks for the main system features are given in Tables 4 and 5. Blank squares indicate that the particular feature was not used in that task. In line with normal reporting practice the mean and standard deviation has been reported as the result of each feature (question). (Whilst this is a convenient method of reporting value and spread the reader is reminded of the small number of participants that took part in this study when using these statistics).

When the mean value for each of the features listed in the questionnaires was calculated across all of the tasks all of the features achieved a score of 3 (neutral) or higher indicating that, in general, the system received a positive review from the participants and indeed the 'system average' or the mean value obtained from all responses in all of the questionnaires was 3.8, where 4 was equivalent to 'positive/good'.

However, it is perhaps more useful to use this 'system average' of 3.8 as a reference value for the system against which to rank the individual system features, as this more easily enables features that were perceived by the users as strengths or weaknesses of the system compared to the average performance for the system to be identified. Evaluating systems or concepts against an average reference value in this way is a standard engineering technique described in many good engineering design books such as Pugh [28]. The main benefit of the approach is that features that are better than the system average (strengths) receive a positive score, whilst those that are worse than the system average (weaknesses) receive a negative score. When used in conjunction with more descriptive user comments regarding individual features, such as those obtained during the interview sessions, this approach provides a very useful method of identifying good or bad aspects of a system.

In Tables 4 and 5 columns headed with the term 'mean value' contain the mean value calculated for the listed feature from the responses of the ten participants in each of the three tasks. The standard deviation for this result is given in the next column with the heading 'std dev'. The first results row of Table 4 gives the 'system average' or the mean value obtained for all of the questionnaire responses for that task. In task 1 the system average was 3.7, in task 2 it was 3.8, and in task 3 it was 3.9. The mean 'system average' value obtained across all three tasks was 3.8 and this is the value given in the 'all tasks' 'mean value' column. The subsequent rows of the table give the equivalent result for the listed system features.

The 'score' column for each feature simply contains the 'mean value' obtained for each feature minus the overall 'system value' obtained in each task. As an example, in task 1 the participants gave 'being immersed in the design data' an individual feature value of '3.9', whilst the overall system

Table 5
Selected average or negative features from the Co-Star user questionnaire

	Task 1			Task 2			Task 3			All tasks total	
	Mean value	Std dev	Score	Mean value	Std dev	Score	Mean value	Std dev	Score	Mean value	Score
Your previous experience with the VR system	3.3	1.2	−0.4	3.8	0.8	0.0	4.3	0.5	0.4	3.8	0.0
Menu operation	3.6	1.2	−0.1	4.1	0.6	0.3	3.7	1.1	−0.2	3.8	0.0
Sense of scale	3.6	0.7	−0.1	3.8	0.4	0.0	4.0	0.0	0.1	3.8	0.0
Task instructions	3.7	0.9	0.0	3.9	0.8	0.1	3.8	0.9	−0.1	3.8	0.0
‘Superscale’ model presentation	3.6	0.5	−0.1	4.0	0.0	0.2	3.7	0.7	−0.3	3.8	−0.1
The head mounted display	3.2	0.8	−0.5	3.9	0.7	0.1	4.1	0.6	0.2	3.7	−0.1
Sense of motion	3.6	0.5	−0.1	3.8	0.4	0.0	3.8	0.7	−0.1	3.7	−0.1
Realism of environment	3.6	0.8	−0.1	3.7	0.7	−0.2	3.7	0.7	−0.2	3.7	−0.2
Menu icons	3.6	1.2	−0.1	3.4	1.0	−0.4	3.9	0.7	0.0	3.6	−0.2
Speed	3.6	0.7	−0.1	3.4	0.7	−0.4	3.9	0.3	0.0	3.6	−0.2
Your comfort	3.6	0.8	−0.1	3.6	0.7	−0.2	3.7	1.3	−0.3	3.6	−0.2
Depth perception when selecting objects	3.4	0.7	−0.3	3.2	1.3	−0.6	3.8	0.6	−0.1	3.5	−0.3
Join cable to connector tool	3.5	1.2	−0.2				3.4	1.0	−0.5	3.5	−0.4
Graphical feedback when selecting objects	2.9	0.9	−0.8	3.9	0.3	0.1	3.5	0.7	−0.4	3.4	−0.4
System mode feedback	3.1	0.8	−0.6	3.5	0.8	−0.3	3.7	0.5	−0.3	3.4	−0.4
Finding inserted cable points				2.5	1.0	−1.3	3.6	0.9	−0.4	3.0	−0.8
Object selection filters	2.5	1.0	−1.2				3.4	1.0	−0.5	3.0	−0.8

average for this task was found to be ‘3.7’, leading to a positive score of ‘0.2’ for this feature. On the other hand, participants gave the ‘object selection filters’ a value of ‘2.5’ in task 1 leading to a negative score of ‘−1.2’ for this feature. Hence, ‘being immersed in the design data’ has been identified as a strength during task 1, whilst the ‘object selection filters’ were considered to be a weakness of the system.

The final ‘All tasks’ ‘Score’ column in the table gives the overall score obtained for each feature from the data obtained in all three tasks and is calculated by subtracting the ‘All tasks system average’ (3.8) from the ‘All tasks mean value’ for each feature. As an example ‘being immersed in the design data’ produced an ‘All tasks mean value’ of 4.2, which leads to a score of 0.4. This ‘All tasks’ score for each feature has been used to order the list within Tables 4 and 5 so that the most positive features or key strengths of the system are listed at the top of Table 4, whilst the most negative or weakest features are listed at the bottom of Table 5. The split between the tables occurs at those features which received a zero score during the analysis indicating that they were found to be about ‘average for the system’.

It can immediately be seen that ‘cable point drag and drop’ (direct object interaction) and ‘being immersed in the design data’, which are two of the core attributes of the immersive platform, received the most positive user evaluations in the questionnaires. Whilst two specific parts of the Co-Star software interface ‘finding inserted cable points’ and ‘object selection filters’ were identified as the worst aspects of the system. Summaries of key user interview discussions and comments corresponding to some of the ‘best’ and ‘worst’ features identified by the questionnaire analysis follow. These discussions place the questionnaire results obtained into the context of the participant’s verbal interview comments and provide a much greater insight into the reasons behind some of these scores.

7.1. *Direct object interaction*

Direct 3D editing of cable-point locations within the model using ‘drag and drop’ interaction received the highest user score (+0.6) in the system. During the interviews several users stated that the entire system would be much better and more enjoyable if it all worked by ‘drag and drop’ rather than using menu systems, with one user stating that using model selection and then having to use menu functions to work on some objects defeated the purpose of having a 3D motion tracked environment. Typical interview comments described 3D object interaction as ‘powerful and liberating’, ‘intuitive’ and ‘easy-to-use’ because it ‘worked like you would do it in real life’. This last comment was describing the fact that the arm and hand movements used to move objects within the computer model are very similar to those that you would use if the object had existed in the physical world. Importantly users considered that the real time motion of the object with their hand produced a ‘real feeling of interaction’ with one user reporting that this ‘made you feel like you were really doing something with your hands and building the environment’.

Participants also reported some difficulty selecting small objects in the model space. There was some feeling that the collision detection used had been too precise so that the accuracy required to pick up small objects was difficult to achieve; similar problems were not reported for larger objects. A particular problem was the location and selection of cable-points, which for aesthetic reasons had been made the same diameter as the cable, users found that locating these defining points was rather difficult unless they were located at a bend in a cable. As a result the act of locating and selecting a point on a cable received the lowest score (−0.8) on the ranked questionnaire data and users frequently expressed frustration about this during the interview sessions.

Another compounding factor during object selection was the quality of depth perception produced by the stereoscopic display. It is important to appreciate that the 3D image seen by the user is simply an illusion created by showing two slightly different 2D images to each eye and that any depth information is generated by the user from these two flat images rather than being accurately transferred from the 3D computer model. General depth perception received a mid rating (+0.1) in the user questionnaire data, but this decreased to a low ranking (−0.3) when users were specifically asked about the quality of depth perception when selecting objects. Such limitations on depth perception have also been found by other groups developing virtual reality based CAD systems and improving the accuracy of this has recently been described as a 'critical interface issue' for the field [29].

Several participants also expressed concern regarding the 'tidiness' of the harness design that they produced. Some specifically reported that it was very difficult to determine when cables where vertical or horizontal and requested additional design aids for this. Another described the output as 'messy' but thought that this was acceptable if the design generated in the immersive environment was part of a process of refinement and would subsequently be tidied up to achieve a final design.

7.2. *Being immersed in the design data*

The experience of being immersed in the 3D design model received a highly positive score (+0.4) in the user questionnaire ranking. Most participants felt that it had been useful to be immersed in the design data, although some thought that the evaluation tasks and model were not sufficiently complex to really benefit from this. However, some users thought that rather more movement (such as looking around or even turning round) had been required than they had expected in order to view or interact with this all encompassing model environment. This may have been due to the first person 'super-scale' presentation used whereby the participant was 'scaled down' to work inside the model. Most users were happy working like this but felt limited because they had not been given scale (or zoom) control and a mid rating (−0.1) was obtained for this aspect of the system.

It had been expected that users would develop a mental model of the environment in order to visualise and carry out the tasks. This process was aided by using the same general model in each task and using a VRML desktop viewer of it during each pre-immersion task brief. Users did not report getting lost but did admit to feeling a little uncertain at the beginning of each task until they recognised something to give them their position within the model. Users responded positively (+0.2) to their spatial awareness of the model, although two reported concentrating only on what was in front of them and having to turn round to see what was behind them rather than knowing what should be there. Additionally, one participant felt that they had not developed a good mental model of the environment until the third task and expressed disappointment in the time they had taken to do this. Most users requested access to additional navigational aids and thought that these would be essential for more complex models or tasks.

7.3. *Navigation*

Users responded positively (+0.3) to the method of head directed flying used to navigate the model and said that it felt natural. However, they also reported that their ability to move vertically (downwards) in the model was restricted by their physical ability to move in the real world, which was limited either by the HMD, its attachment cable, or their chair (or all three). In addition all users reported having to think about how to approach an object so that they reached it with a desirable working position and orientation. They found that if they did not arrive at an object in a good working position subsequently getting into a good one was harder and more time consuming than they imagined; additional navigation modes were requested to overcome this.

For simplicity a single flying speed was used during navigation and whilst all participants thought that the speed was perfect for local work they all thought it was too slow for global model navigation. In general users thought a variable navigation speed would be beneficial and suggestions included time dependent acceleration, a go-fast gesture, jumping, or being able to quickly go to a model overview and relocate within that. Typical interview comments on global navigation included 'it takes ages to get there', with one participant saying that they 'would like to be able to travel large distances in a single bound' whilst another described navigation as 'dead time'. However, users also suggested that faster navigation might produce motion sickness and that they might miss things if they travelled too fast. Overall the fixed flying speed received a negative score (−0.2).

7.4. *Menu system*

During the interviews participants reacted positively to the ring menu and liked its ease of use and consistency of operation, but a mixed response also revealed some dislikes leading to a mid ranking (+0.1). In particular users expressed a desire to be able to directly select a function they could see rather than have to step round the ring to get to it. It was also suggested that they would prefer to be able to see all the options at the same time and that the ring style of presentation gave insufficient information about what was on the next menu level. Users felt that the menu icons were satisfactory but could be improved and that some icons were not intuitive, although this improved with experience with the system. Some users also thought that the menu would benefit from additional text either on the buttons or as 'pop-up-tips'. Overall the menu icons received a lower ranking (−0.2).

It is also worth repeating that in general the participants thought that whenever possible direct interaction (drag and drop) within the model environment should be used in preference to using a menu system at all.

7.5. *Object selection filters*

A system of selection filters was used to reduce the computational overhead of the system and hence ensure that real-time interaction was maintained. However, this meant that users had to specify the type of object that they were currently interested in interacting with. None of the users liked this approach and all users felt that they should be able to interact with any object in the model without first telling the system what it was going to be and this received the lowest score (−0.8) in the user questionnaire ranking. Most users did not think that the filters supported them in their work and considered them a hindrance. Typical interview comments on this feature included ‘annoying’ and ‘could definitely be improved’.

7.6. System feedback

Two aspects of system feedback to the user also received low ratings (−0.4) in the user questionnaire rankings. The first of these was the level of graphical feedback when objects in the model environment were selected. Whilst a collision boundary box appeared when the design cursor collided with an object there was no additional feedback when the object had been selected (except in ‘drag and drop’ operations when the object attached to the design cursor). Users thought that such feedback would have been useful and could easily be provided by either the object or its boundary box changing colour. The second was due to the level of feedback regarding whether functions had successfully been performed. Design functions in the model were not considered to be a problem but insufficient feedback for behind-the-scenes functions such as save or file-export left users unsure whether these had occurred or not.

7.7. Technology

The main interface technologies were the HMD and the pinch gloves. (The motion tracking system was attached to these and head tracking was considered part of the HMD and the hand tacking part of the gloves.) Opinions of the HMD varied and the fact that the user score for it increased dramatically between the first task (−0.5) and the last (+0.2) indicates that participants got used to and accepted this technology; overall the unit achieved a mid position (−0.1) in the system ranking. Most users reported that it took several sessions before they felt they were able to adjust the unit properly but all had mastered this by the final task. Several users reported feeling that the HMD restricted their head motion and impeded their ability to navigate or explore the model environment, particularly when trying to look or move downwards and attributed this either to the weight of the unit or its attachment cable. Several users suggested it would be good if the HMD weighed the same as a pair of glasses and was wireless.

The HMD incorporated two 640 × 480 LCDs to produce the stereoscopic image and all users expressed disappointment with the colours and resolution of this display compared to the desktop display of the same model used during the session briefing. In general users thought that the field of view of the model provided by the HMD was adequate, although some reported feeling that they had to move around more than they should in order to see things; and one user suggested that the lack of peripheral vision had reduced their overall experience.

One user reported feeling disturbed by the level of isolation from the ‘real world’ caused by wearing the HMD although several others users liked this and thought the system had enabled them to concentrate more on the task by reducing external distractions. Additionally one user suggested that using CAD was quite an isolated activity anyway and wearing the HMD was no different.

In general all users responded very positively to the pinch gloves (+0.3) and liked the gesture control (+0.2). Users found that frequently used gestures became ‘easier’ and ‘more fluent’, whilst less used gestures were ‘a lot harder’ to remember. One participant described the gesture interface as ‘one of the best things on the system’ and another as ‘probably the best way to do it’; by the end of the final session most users had described feeling confident with this interface.

Seven of the participants (all male) reported that the gloves were too large for them and had had some problems with the touch pads coming off the ends of their fingers. This was particularly an issue with the thumbs which reduced confidence in some of the gesture operations and particularly when little additional feedback was given to the user. Users also reported difficulties with the glove attachment cables but did not find these as problematic as the HMD cable.

8. Conclusions

The design and evaluation of a demonstration immersive system for cable harness design has been described. The system was developed to enable the major technological, human factors, interface design and other practical issues regarding the development and use of an immersive design system in engineering and specifically for cable harness design to be investigated during a realistic design exercise. The system evaluation described in this paper involved ten participants using it to complete a series of three cable harness design tasks covering the major aspects of the cable harness design process. This relatively unconstrained approach was central to the evaluation and required the use of analysis methods that could cope with the variation in user activity that inevitably occurred.

Analysis of the user interaction log files for each participant during the final task has enabled a typical activity profiles for the task to be constructed using a process of activity decomposition and categorisation. Constructing this profile has enabled the relative amounts of different user activities that occurred during the task and provides a much greater understanding of how the system was used than simply looking at either the task or sub-task completion times. The profile constructed during this evaluation showed that almost half of user activity within the task involved model navigation (41% by time), whilst design activity (27%) and system operation (24%) each took up about a quarter of all activity, whilst accessing information required to complete the task accounted for 8% of all activity. Of this activity 7% (by time) was found to be unproductive (i.e. did not add value to the design process) including approximately one quarter of all system operations; and 28% of system time was classified as inactive with an average pause length of 2 s. In particular, many of these occurred within otherwise continuous sequences of navigation activity leading to almost half (45%) of this category being classed as inactive.

Access to this level of task activity data has enabled the Co-Star team to make strategic decisions regarding the priority and likely impact of redeveloping specific aspects of the system interface to improve operation. For example, there can be little argument that the system would benefit from efforts to increase the efficiency or reduce the requirement for both model navigation and system operation so that more time can be used for design centred work.

Combining this activity profiling with the user questionnaires and interview data presents a much more comprehensive picture of the system than using any one of the methods in isolation and this combined approach has enabled the key user requirements for an immersive design system to be identified along with the underlying reasons. For example, both navigation and system operation were also identified as issues during the user interview sessions with requests for additional methods of navigation and the replacement of menu based activities with direct object interactions in the model environment. Thus the results of the evaluation not only provides a compelling argument for addressing these two aspects of the system, but also identifies the user expectations from making such modifications along with real performance data that can be used to estimate the impact on system operation that such changes might be expected to achieve.

As such the task profile data and summary discussions of the major user requirements included in this paper provide a valuable resource to other workers in the field who are developing new immersive or stereoscopic design interfaces or considering the practical implementation of such a system for an engineering application.

Most encouragingly from the results is the fact that two of the defining features of an immersive design system, namely, user immersion in the model space and the ability to support direct 3D object interaction with the model were identified as the 'best' features of the Co-Star system receiving the highest scores in the ranked feature list. Meanwhile, the 'worst' features were a number of software elements that can easily be improved by making relatively simple changes to the system interface.

Overall, the results obtained and the positive experience of the participants indicate that 3D immersive design and direct body motion tracked interfaces do provide a very intuitive, easy to use, and useful addition to the technologies available to design engineers. However, the results also show that future immersive design systems must play to their strengths and make maximum use of direct 3D interaction with the model environment via a minimalist yet versatile interface which also reduces any requirement for complex system operations and unnecessary navigation.

Acknowledgements

The work described in this paper was conducted within the Scottish Manufacturing Institute at Heriot–Watt University, Edinburgh, which is one of the Innovative Manufacturing Research Centres funded by the UK Engineering and Physical Sciences Research Council. The authors would like to acknowledge continued involvement of the project's industrial partners to this research and thank the participants in the evaluation for their time and commitment to this work.

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