Proceedings of IDETC/CIE 2006
ASME 2006 International Design Engineering Technical Conferences
& Computers and Information in Engineering Conference
September 10-13, 2006, Philadelphia, Pennsylvania, USA

DETC2006-99017

ANALYSIS OF USER ACTIVITY IN AN ENGINEERING DESIGN TASK DURING THE EVALUATION OF AN IMMERSIVE STEREOSCOPIC DESIGN SYSTEM

Graham Robinson
Heriot-Watt University
Edinburgh, UK

Phil N Day
Heriot-Watt University
Edinburgh, UK

James M Ritchie
Heriot-Watt University
Edinburgh, UK

Rick G Dewar
Heriot-Watt University
Edinburgh, UK

ABSTRACT

This paper describes the analysis of user activity during the evaluation of Co-Star, a demonstration immersive stereoscopic design system for cable harness design. During the study ten participants independently completed a sequence of three harness design tasks using the test system. All user interaction was recorded during each of the sessions and subsequently analysed to profile the distribution of user activity into five major activity classes: Design, System Operation, Navigation and Information, and Process Integration. The Design class was further sub-divided into Goal, Support, and Edit activities to produce a more detailed breakdown of this core activity. In addition measures of 'unproductive activity' and 'sequence breaks' (idle time) were used to identify relative performance within the different activities. The results clearly show the distribution of user activity for this task based on time and number of sequences of user activity and provide a compelling visualisation of this profile, with Navigation typically accounting for 41% and System Operation 23% of user activity whilst Design achieved 27%, in addition it was found that 7% of all activity was found to be unproductive, and 28% of system time was idle. Opportunities to improve operational design performance through targeted system developments can be clearly identified from these results.

INTRODUCTION

Engineering design is usually supported by computer-aided design (CAD) systems which can bring significant benefits through improved quality of the design output or improved efficiency of the design process. However, further improvements to current CAD tools may be possible, for example, by providing more intuitive user 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' experience of being immersed in a 3D computer generated world. Typically virtual reality systems are used to enhance a user's appreciation of a computer generated model by enabling them to view the model as though they were 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 such technologies as an alternative to traditional desktop computer systems for other engineering tasks such as manufacturing and assembly planning [1-4] and computer-aided design [5-7]. Indeed previous cable harness design work using an immersive system has demonstrated the potential to impact upon the efficiency of computer-aided design activity during comparative tests with desktop CAD systems but the research was not able to identify which aspects of the software or technology platform produced this result or how to translate this into a practical system [8, 9].

Hence, in order to ensure that such developments are worthwhile it is necessary to understand how users interact with and use design systems so that opportunities for improvements can be properly identified and measured. A challenge to doing this is that design is a complex sequence of activities involving problem solving and it can be difficult to investigate specific elements without fundamentally changing the nature of the activity.

This paper presents the user activity distribution obtained from analysing user interaction data for a cable harness design task during the evaluation of an immersive design system. The rational for using a stereoscopic system is that immersing the engineer in a 3D product model and enabling direct interaction with it provides a more efficient and natural interface and may also increase the engineer's spatial understanding of the product leading to better harness designs being generated in a shorter time by enabling more problems to be identified and corrected earlier in the design cycle (figure 1) [10].

CO-STAR

A cable harness is an assembly of wires, connectors, fasteners and other components that provides electrical

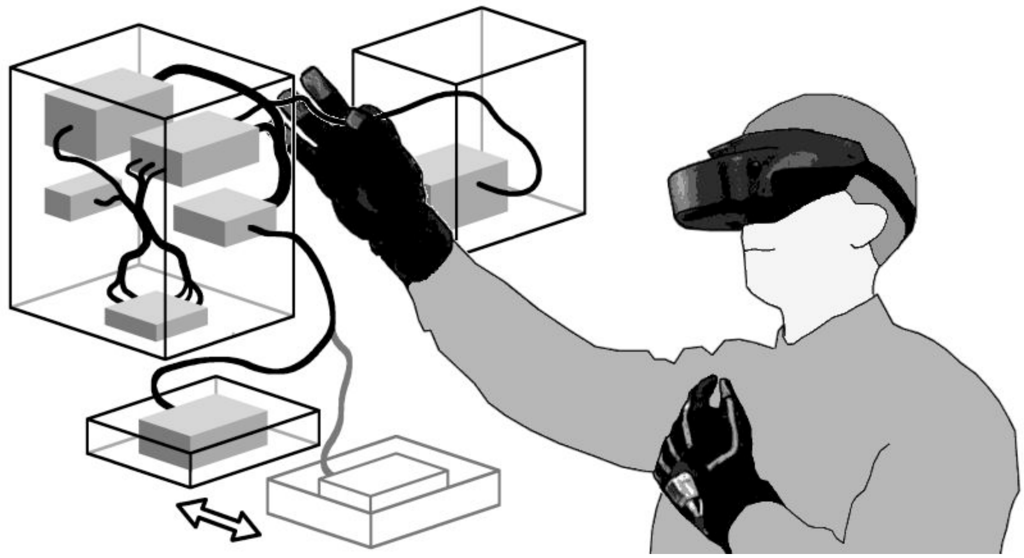


Figure 1: Immersive cable harness design

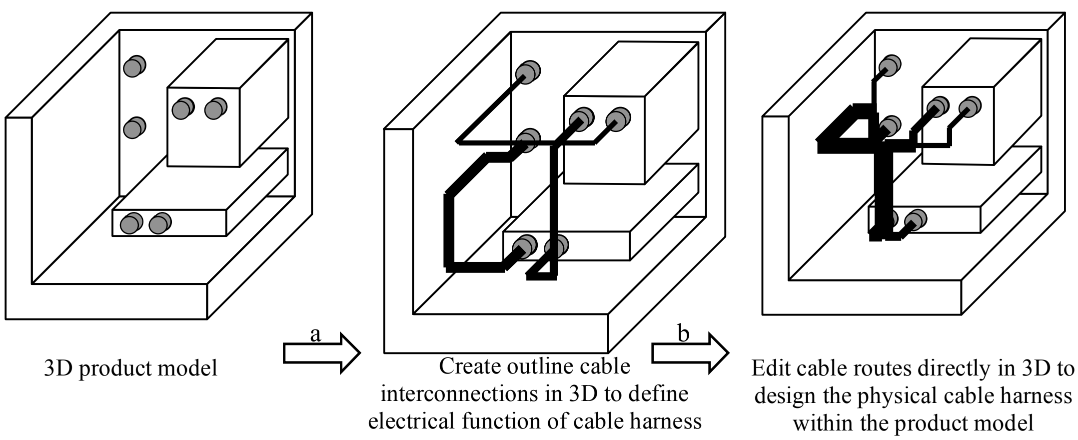
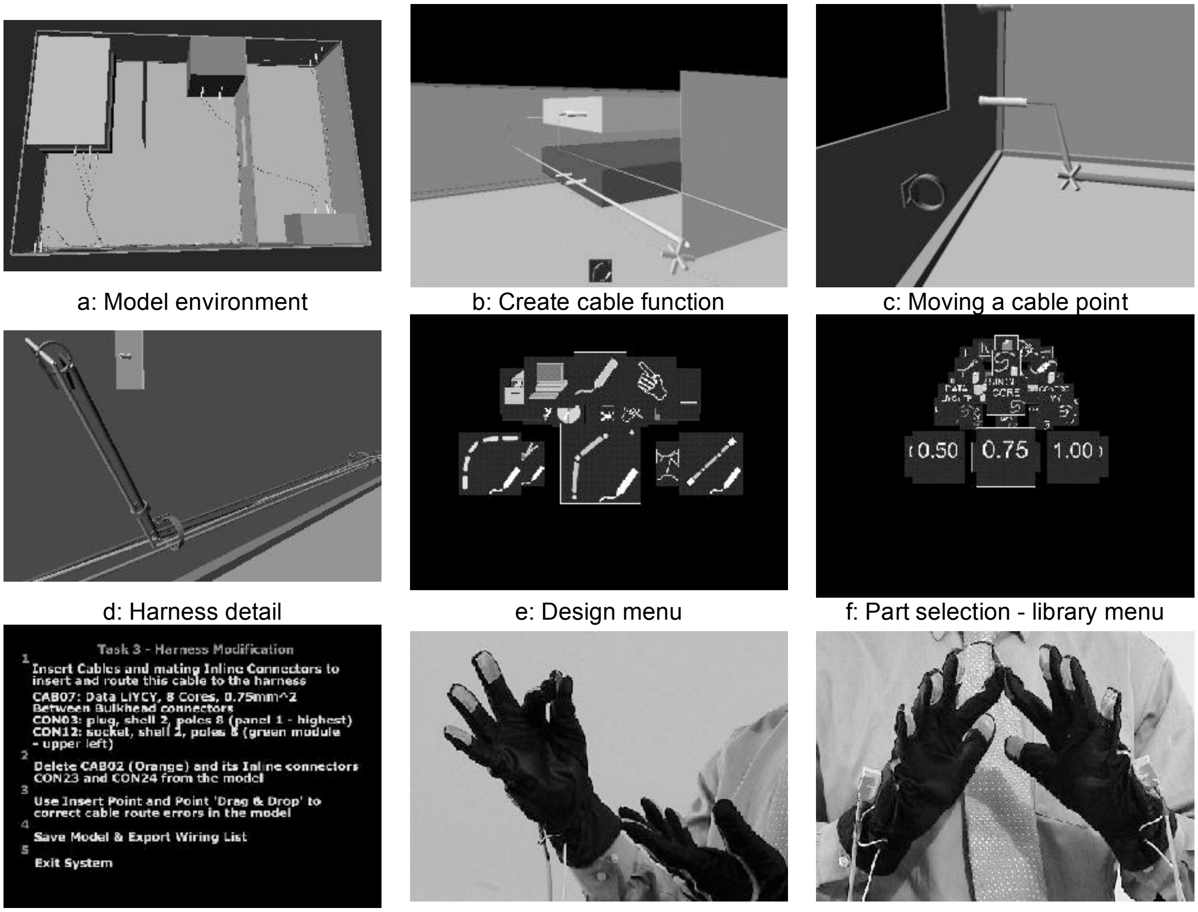


Figure 2: Cable harness design with Co-Star

interconnectivity between different modules within a larger electromechanical product such as an 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 and assembly requirements of the product can present many challenges to the engineers involved. The Co-Star system allows an engineer to be immersed in the 3D product model and use normal upper body motions to create and edit the cable harness design directly within the model space. Designing a cable harness using Co-Star is a two stage process (figure 2). Firstly, the electrical connections are defined by creating outline cables between connectors within the model (arrow 'a'). Secondly the physical cables routes in the product are detailed to complete the harness design (arrow 'b').

Co-Star was developed using commercially available virtual reality 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 Head Mounted Display which enabled a user to see a stereoscopic image of the model. 3D interaction with the model was supported through a gesture controlled interface using a pair of Fakespace Pinch Gloves and user motion tracking (head and hands) with an Ascension Technology Corporation Extended Range Flock of Birds. The Fakespace gloves have conductive pads at the end of each finger and the system is controlled by simple gestures that bring specific pads into contact; usually pressing a thumb against a finger on the same hand, or touching opposite fingers together from each hands.



a: Model environment | b: Create cable function | c: Moving a cable point
d: Harness detail | e: Design menu | f: Part selection - library menu
g: Task instruction screen | h: Action gesture | i: Cancel gesture

Figure 3: Co-Star interface

The demonstration Co-Star system enables users to produce outline cable harness designs whilst also providing the interface feel of a much larger design platform. There are three different modes; model, menu, and text screens. Example screen images from these are given in figure 3. Images a-d are of the model environment, e-f are examples of the ring menu structure, g is of the task text instruction screen, and h-i are examples of gesture inputs used to control the system. The model environment is where the stereoscopic model image and body motion tracking are used and the user is immersed in a first person stereoscopic view of the model on which they are working. The user's viewpoint is controlled by their head-motion and the design cursor by the position and orientation of their right hand. The user is able to fly forwards or backwards through the model using left hand gestures. The user interacts with objects in the environment by reaching towards the object with their right hand. The user's physical hands are motion tracked and this reaching action moves the design cursor (b) in the model towards the target object. Once the cursor collides with an object a bounding box appears indicating that the object is available for selection; it is selected by the user pinching the thumb and index fingers on their right hand together (action gesture) (h). If the user has selected a point on a cable then it can be moved by simply holding the pinch gesture whilst they move their hand (and the point) to a new location in the model, where it is released by letting go of it (c).

The design functions are selected through a hierarchical ring menu system. The menu is navigated by rotating the menu-ring; using the same gestures that are used to fly forwards or backwards in the model environment. The user moves to the next menu level by rotating the ring so that the required icon is at the front and selecting it using the action gesture. The next sub-menu ring is displayed and the previous level moves up the screen showing the hierarchy. Menu levels can be exited using the cancel gesture (i); and the menu automatically exits to the model environment when a specific menu operation, such as activating a design function, has been completed. When a function is active a small image of its icon is shown on the lower edge of the display (b). Functions remain active for repeated use and are ended using the cancel gesture. The main Co-Star cable harness design functions are Create Cable, Join Cable to Connector, Delete Object, Insert Connector, Insert Cable Point, Save Model, Mate Connectors, Drag & Drop Cable Editing, and Export Documentation.

CO-STAR SYSTEM EVALUATION

The system was evaluated using ten participants who each independently completed a sequence of three design tasks plus an initial training session with it. 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 task took approximately 20 – 30 minutes to complete and represented a stage of a cable harness design; the whole including all of the activities required to complete a harness design using the methods outlined in figure 2. All of the tasks took place in the same model (a) 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 some outline cables in a model to complete a harness design; whilst the third involved making some revisions to a completed harness design. Participants completed each task at a different session and the results presented in this paper were all obtained from the third task. This task had five main sub-tasks (table 1).

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 the model that meant that the harness design was not longer appropriate. Participants had to locate this problem and redesign the harness to fix it
4	Save Model & Export Documentation	Save the revised model and export an updated wiring list
5	Exit System	Exit the immersive design environment

Table 1: The evaluation task

Each session began with a briefing using a summary of the task goals and a desktop VRML viewer displaying the model environment. The briefing was used to ensure 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 the design exercise using the head-mounted display and motion tracked gesture interface. During this session details of all the user's interactions with the system were unobtrusively recorded in a comprehensive time-stamped log-file. It is the data from these log files that has been analysed to produce the activity distribution profiles. The immersive session was immediately followed by a questionnaire and interview session; the results of which are not included in this paper.

DESIGN ACTIVITY CATEGORISATION

During analysis the task activity was broken down into meaningful sequences of actions using functional decomposition using the principle that larger activities (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 (figure 4). Functional decomposition is a standard engineering approach the basics of which are described in any good engineering design textbook [e.g. 11, 12]. However, the specific methods must be developed for the application being investigated 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.

Function	A composite sequence of user activity that achieves a single purpose within the system. Typically functions correlated with items on the menu system, and the use of several functions would be 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. Typically several action sequences would be required to complete a function.
Interface Event	A single user input.

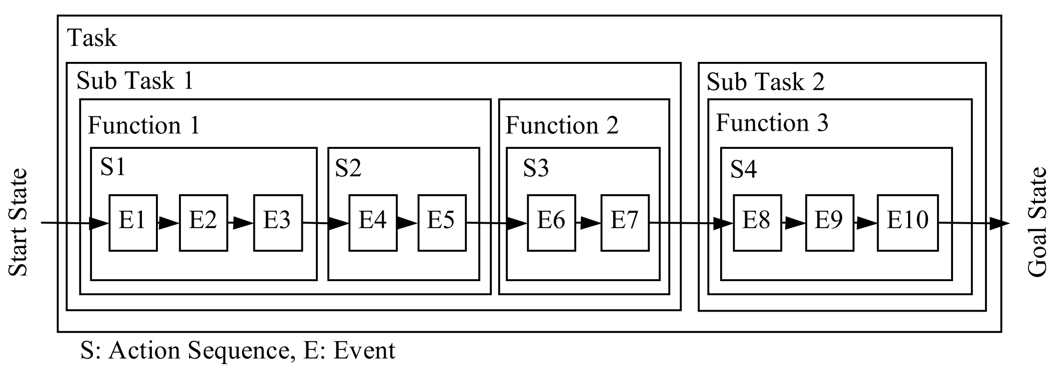


Figure 4: Principle of task decomposition into units of activity

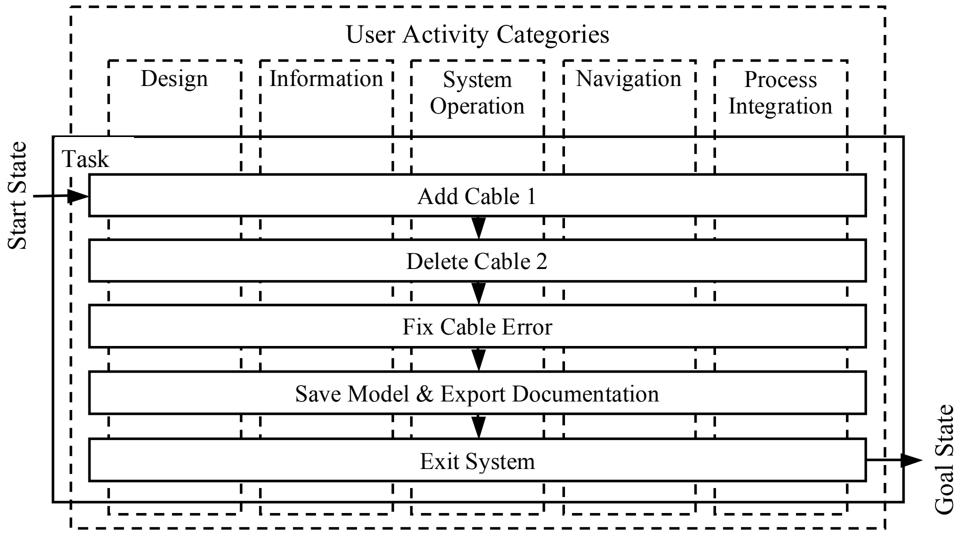


Figure 5: Task decomposition into five user activity categories

An analogy with the language constructs 'letter', 'syllable', 'word', 'sentence', is useful to illustrate the relationship between these different activity descriptions (table 2). 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 exist in different combinations to deliver the purpose of the user's current sequence of activity.

Activity Construct	Language Analogy
Task	Paragraph
Sub-Task	Sentence
Function	Word
Action Sequence	Syllable
Interface Event	Letter

Table 2: Language analogy

After task decomposition, the identified action sequences were grouped according to their purpose to determine for how long or how often a particular type of activity had occurred during the task. All action sequences were considered to belong to one of five classes (figure 5).

Design — All activity that causes the design model or 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 change the model.

Navigation — All activity leading to a change in the user's viewpoint but which does not usually change the model.

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

Design is the core system function and this category was sub-divided into three additional categories to obtain more specific detail regarding this aspect of system operation:

Design - Goal — Actions that produce an immediate change in the design model and which advance the design towards the goal state (complete 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 & Drop (Position Edit) — The action of moving an object from one location to another by direct interaction with it in the model environment.

System operation includes all interactions that are 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 a 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 & 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 point changes the design model. However, any navigation that occurred in between moving points was classed as navigation. Finally, two additional classifications were used as relative measures of operational performance during the task and in the activity categories outlined.

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 did not add-value to the design process.
Sequence Breaks	Pauses in activity between the end of one discrete action sequence and the next.

The overall objective of the analysis was to determine the activity distribution for the participant group during the task and to develop an average profile for a typical user based on both time and number of action sequences. This profiling was used to investigate user activity for the overall task, different sub-tasks, and during the operation of specific design functions and model interactions, although only the task level results are reported in this paper.

RESULTS

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. Pie charts of the mean result for the group are also included.

In the task level profile (table 3, figure 6) '% Task' is the percentage of the mean total task that was allocated to each activity category, e.g. for design goal 129s is 10% of the 1256s mean task time and 35 action sequences is 15% of the mean task total of 224 sequences.

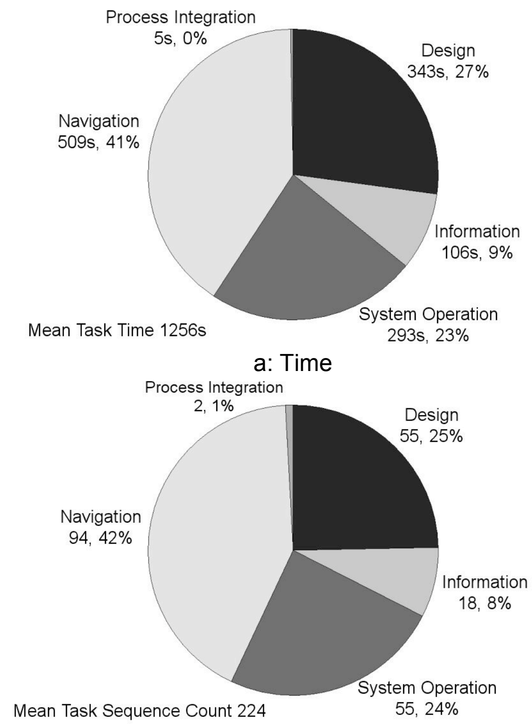
In the distribution of unproductive activity (table 4, figure 7) '% Un P' is the percentage of the mean unproductive activity allocated to each activity category, whilst '% Cat' is the percentage of each activity category that was unproductive, e.g. for design goal 11s is 12% of the unproductive activity total of 89s and 9% of the mean design goal category time of 129s.

In the distribution of inter-sequence break time (table 5, figure 8) '% Seq B' is the percentage of the mean total inter-sequence time allocated to each activity category, whilst '% Cat' is the percentage of each category formed by sequence breaks e.g. for design goal 36s is 10% of the total sequence breaks of 356s and 28% of the category total of 129s.

DISCUSSION AND CONCLUSION

All of the ten participants completed the evaluation task and the mean task completion time for the group was 1256s (std dev 326), the fastest individual time was 693s and the longest 1881s. The participants had been given the task of completing a cable harness design task using the system, having been told the design goals but not what the design should be or how to go about producing it. This freedom for the participants to work normally was central to the evaluation. However, the task goals were quite specific and participants were guided towards a solution by the inclusion of appropriate design cues in the model, although there was some variation in the solution produced and the methods used by different participants.

The system log files were a complete time stamped record of every user interaction with the system and contained all of the



b: Action sequence count

Figure 6: Mean task activity distributed into main activity categories

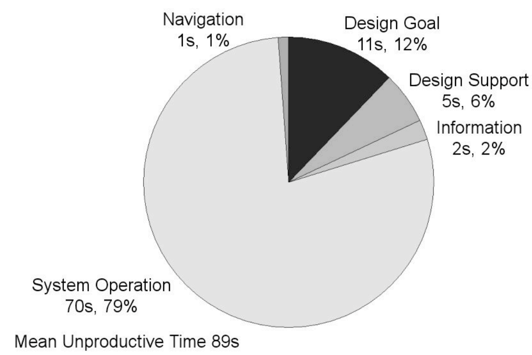


Figure 7: Profile of mean unproductive activity by time

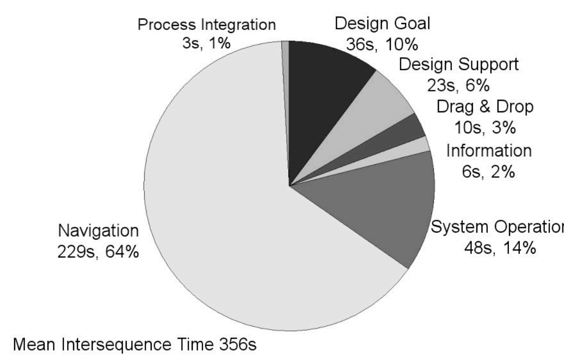


Figure 8: Profile of mean inter-sequence time

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

Distribution by Time (s)				Distribution by Action Sequence Count			
Mean	1256	St dev	326	Mean	224	St dev	62

	Design		Information		System Operation		Navigation		Process Integration	
	time	count	time	count	time	count	time	count	time	count
Mean	343	55	106	18	293	55	509	94	5	2
St dev	164	14	36	6	76	16	160	36	2	1
% Task	27	25	9	8	23	24	41	42	0	1

	Design Goal		Design Support		Drag & Drop	
	time	count	time	count	time	count
Mean	129	35	57	10	157	10
St dev	53	12	21	3	130	7
% Task	10	15	5	5	12	5

Table 3: Distribution of task time & count data into the six activity categories

Unproductive Activity by Time (s)								Unproductive Activity by Sequence Count							
Mean	89		St dev		64			Mean		20		St dev		12	
% Task	7							% of Task		9					
	Design Goal		Design Support		Drag & Drop			Information		System Operation		Navigation		Process Integration	
	time	count	time	count	time	count		time	count	time	count	time	count	time	count
Mean	11	3	5	1	0	0		2	2	70	14	1	0	0	0
St dev	14	3	7	1	0	0		3	2	47	8	3	1	0	0
% Un P	12	14	6	3	0	0		2	8	79	73	1	2	0	0
% Cat	9	8	9	7	0	0		2	9	24	26	0	0	0	0

Table 4: Distribution of unproductive task activity into the six activity categories by count

Total Sequence Breaks by Time (s)				Total Sequence Breaks by Count			
Mean	356	St dev	110	Mean	180	St dev	53
% Task	28						
	Design Goal	Design Support	Drag & Drop	Information	System	Navigation	Process Integration
	time	time	time	time	time	time	time
Mean	36	23	10	6	48	229	3
St dev	17	12	8	6	17	85	2
% Break	10	6	3	2	14	64	1
% Cat	28	40	6	6	16	45	70

Table 5: Distribution of task inter-sequence breaks into the six activity categories by time

data needed to reconstruct the design session activity. This was used to identify the specific action sequences that had been used to generate the design, operate the Co-Star system, obtain information, or navigate the model. These smaller units of activity were common across all users regardless of how they had undertaken the overall task and it is the analysis of these that has enabled the task profiling presented in this paper. Distribution of the average activity for the group during the task shows that the largest use of activity was navigation (41% time, 43% count), followed by design (27% time, 25% count) and system operation (23% time, 24% count) and finally obtaining task information (9% time, 8% count). The generation of design data was the core purpose of the user within the system and fact that this only accounted for a quarter of all activity was quite surprising considering a similar amount was devoted to operating the system and rather more was spent simply moving around the model. It may be deduced from this that the system would benefit from developments to increase the efficiency of model navigation and system operations so that less time is spent on these activities.

Unproductive activity was any sequence of actions that could be removed from the design process without changing the outcome. 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, 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 unproductive activity accounted for 7% by time (9% by count) of task activity. Distributing this into the activity categories shows that the majority of this unproductive activity was due to unnecessary system operations (79% of unproductive time, 73% count) and that overall 24% of system operations by time (26% by count) were unnecessary.

Individual action sequences 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 on average there were 180 pauses in the task accounting for 28% (356s) of task time (mean break 2.0s (std dev: 0.6s)). Distributing this between the activity categories shows that 64% of this break time occurred during navigation and that this accounted for 45% of the total navigation time. Whilst this also includes time looking around from a static location it also suggests that the system would benefit from developments to improve the flow of the navigation activity.

In general, the participants reported positively on the experience of immersive design using the Co-Star system and it received a good evaluation. The user activity profiling presented in this paper has been extremely useful in linking the subjective user feedback gathered during the interview sessions and actual performance and use of different aspects of the system. In particular the technique has clearly identified the opportunity to improve future systems by targeting research and development effort in a number of key areas, namely system operation and navigation, and also shows that efforts to improve other areas of the system are unlikely to yield similar improvements in operational performance.

ACKNOWLEDGEMENTS

This research was conducted in the Scottish Manufacturing Institute, Heriot-Watt University, Edinburgh, funded by the Engineering and Physical Sciences Research Council. The authors would like to acknowledge the project's industrial partners and thank the participants for their involvement in this work.

REFERENCES

1 Dewar RG.,1998, Assembly Plans from Virtual Environments, PhD Thesis, Heriot-Watt University, Edinburgh, UK

2 Ritchie JM, Dewar RG, Simmons JEL., 1999, The generation and practical use of plans for manual assembly using immersive virtual reality. Journal of Engineering Manufacture (Part B) (Institution of Mechanical Engineers, UK), 213:461-474

3 Weyrich M, Drews P., 1999, An Interactive Environment for Virtual Manufacturing: the Virtual Workbench. Computers in Industry Journal, 38:5-15

4 Gomes de Sa G, Zachmann G., 1999, Virtual Reality as a Tool for Verification of Assembly and Maintenance Processes. Computers and Graphics Journal, 23:389-403

5 Liang J, Green M., 1994, JDCAD: A highly interactive 3D modelling system. Computers and Graphics (ACM),18(4):499-506.

6 Dani TH, Gadh R., 1997, Creation of Concept Shape Design via a Virtual Reality Interface. Journal of Computer Aided Design, 29(8):555-563.

7 Fischer, A.G., Chipperfield K., Vance J.M., 2002, VR Hose: hydraulic hose routing in virtual reality with Jack™, Proc. AIAA/ISSMO Symposium on Multidisciplinary Analysis and Optimization, Atlanta, Sept 4 – 6.

8 Ng FM., 1999, Virtual Reality and Computer-Based Tools for the Routing of Cable Harnesses, PhD Thesis, Heriot-Watt University, Edinburgh, UK

9 Ng FM, Ritchie JM, Simmons JEL, Dewar RG., 2000, Designing cable harness assemblies in virtual environments. Journal of Materials Processing Technology, 107:37-43

10 Holt POB, Ritchie JM, Day PN, et al., 2004, Immersive Virtual Reality in Manufacturing: Design Metaphors and Cognitive Ergonomics. Journal of Computing and Information Science in Engineering; 4(3):161-170

11 Cross N., 1989, Engineering Design Methods, John Wiley, ISBN 0-471-92215-3

12 Otto K., Wood K. ,2001, Product Design, Prentice Hall, ISBN 0-13-021271-7