Automated design process modelling and analysis using immersive virtual reality

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Abstract: This paper presents research which demonstrates how the detailed logging and analysis of a user's actions in a cable harness virtual reality (VR) design and manufacturing system permits automated design task analysis and process mapping, which facilitates information push. Based on prior research, which utilised user-logging to automatically generate assembly plans and time and motion study techniques to improve the system's efficiency, the research described here involves the extraction of design knowledge that is embedded within the log files. Once this has been extracted, it is then represented and formalised using IDEF0 diagrams, DRed graphs, PSL and XML information representations. Finally, using the design knowledge acquired, an online help system has been developed which aids a user to carry out design tasks that are similar to ones performed previously beforehand by expert users.

Keyword: Design task analysis, cable harness design, user logging, design rationale, knowledge capture

1 Introduction

Within product design and manufacturing, the cost of contemporary virtual reality (VR) tools is reducing and, in the near future, it is envisaged that they will become widely used throughout industry as a major part of the product life cycle process as computerised design interfaces. Due to this anticipated expansion, there is a need to investigate how such tools could have an impact on the various design and manufacturing processes. Due to the nature of VR systems, and the manner in which they are programmed, it is straightforward to implement routines which allow user actions to be logged unobtrusively. By analysing the information embedded in the logged data, it is anticipated that useful design knowledge can be extracted and used as a basis for interactive help systems within such design environments.

This paper focuses on utilising and expanding the capabilities of a well tried and tested cable harness VR design system as a tool for the analysis of industrially equivalent harness routing and assembly planning tasks [1]. Prior research demonstrated that the user-logged data can be used to automatically generate assembly sequence plans and IDEF0 diagrams. This has subsequently laid the foundations for design rationale capture through identifying methods for recognising signature patterns relating to subtasks within the various design activities carried out for cable harness routing and assembly planning. In this paper, a prototype information push system is demonstrated which offers automated assistance to users during a design task by combining the monitoring of user motions and activities and utilising design knowledge that has been previously captured to generate help and prompt advice.

The immersive VR apparatus is detailed in section 2 whilst the experimental methodology used to investigate this design domain is presented in Section 3. In Section 4 the various formal representations that have been used to represent the design knowledge extracted from the log files are presented while in Section 5 an overview of how the design knowledge has been used to develop an online push help system is detailed. Finally, a discussion of the results and future work is presented in Section 6 before ending with some conclusions.

1.1 User logging and design knowledge identification

The identification of design knowledge is a key issue for modern companies because if this can be captured with the minimum of overhead, vital knowledge will not be lost from a company if an engineer were to retire or move to another job externally [2]. Another key reason is the need to identify and store design knowledge in a neutral format due to, say, the use of CAE (Computer-Aided Engineering) systems which have closed proprietary file formats and new revisions of such a package may not be able to read files generated from previous software versions [3]. The simple solution would be for the engineer to manually-log all the associated actions and reasoning during a design session; however, this would be time-consuming, costly and disruptive to the design process. Therefore, to overcome this problem, automated and unobtrusive logging of the engineer could potentially be utilised to reduce these burdens on the process and virtual design environments provide an ideal platform on which to investigate this due to the ease of adding user-logging functionality to the design environment. The authors also contend that immersive VR provides considerable potential for the non-intrusive analysis of design tasks and, through the detection of associated patterns of actions, the user's behaviour can be recognised in context; this is even more so the case in well-structured downstream manufacturing planning activities, such as assembly planning.

Wyatt et al. [5] analysed the log files from a VR geotechnical laboratory to help create a more interactive design tool. Brough et al. [6] and Schwartz et al. [7] presented a virtual environment, called Virtual Training Studio (VTS), where users are trained to perform assembly tasks and assistance is offered to them if requested or if errors are made. VTS is one of a few the state-of-the-art user-logging VR systems in the current research field and many of its features are available in the VR system presented in this paper. However, the major difference between the two systems is that VTS is aimed at manufacturing tasks whilst the system presented in this paper concentrates on both design and assembly tasks, automated user analysis, behaviour detection and automated information/knowledge push.

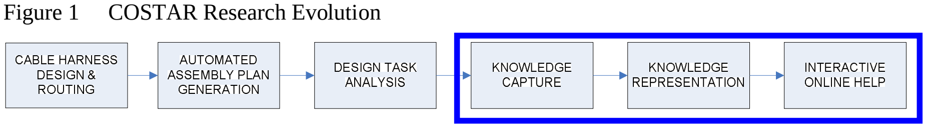
Research into user-logging and knowledge capture in a 2D CAD environment has also been carried, as presented in [8]. In this paper, a plug-in has been written that allows the user's actions to be logged and then specific sequential patterns are searched for using a pattern-recognition system. In [9], two tools are presented which aim to capture tacit or implicit knowledge which is generated during meetings and design sessions. The first tool is used to capture the audio and video of a meeting, as well as recording the decisions made, and the activities that were carried out that led to the decision. The second tool presented records the activities that take place during a design session and the data is saved in an XML file.

As can be seen from this brief review, there is still a gap in understanding how product design and manufacturing processes can be analysed in detail so that the design knowledge can be extracted semi-automatically or automatically from the user's actions. Therefore, as well as extracting the design knowledge, the aim of the research in this paper is to represent the knowledge in a formal way which can be used to aid new users.

VR's unique capability, and the manner in which the user can interact intuitively with 3D data, makes it a powerful tool with which to carry out detailed design and manufacturing studies. The main benefit of using this in cable harness design is that the task itself is flexible enough to allow some form of limited variety to be built into user trials but is restricted enough to carry out detailed analysis of what the designer actually does.

The work presented in this paper takes advantage of previous work in user-logging in VR assembly planning and user-motion analysis [4] by extending the research into the domains of capturing the embedded knowledge in the log files and formalising it. Finally, by using this knowledge, an information push system is presented which aims to aid a user during particular design tasks; the evolution of the research is summarised in Figure 1 with this paper focussing on the activities highlighted on the right of the diagram.

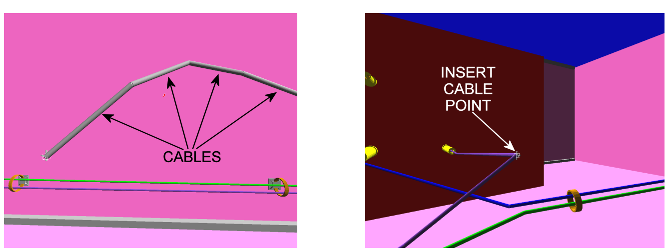
Figure 1 COSTAR Research Evolution



2 Apparatus and methodology

The experimental cable harness design platform developed for this research, called COSTAR (Cable Organisation System Through Alternative Reality), comprises an SGI® Octane2™ with V12 dual head graphics driving each eye on a V8 stereo head-mounted display (HMD). Peripherals include a Flock of Birds® motion tracking system and Pinch® Gloves with the system software platform being SENSE8®'s WorldToolKit® .

Figure 2 Creating a cable from point to point (left) and inserting a cable point (right)

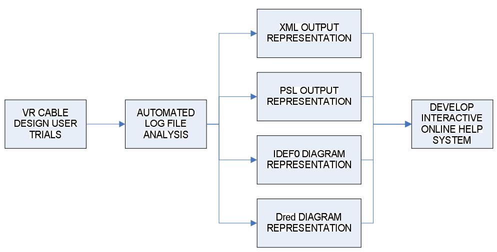


Using COSTAR, the engineer can design and assembly-plan cable harness assemblies within the VR environment with all of design functions being performed whilst they are immersed in the system, as shown in Figure 2. As the user operates the system, COSTAR logs all of the user's cable harness design and assembly activity-related actions and stores these in a log file

3 Experimental method

In previous work, three constrained design tasks were developed and implemented to evaluate each designer's time on the system [4]. These covered common harness design activities such as routing, bundling, cable modification and choosing connectors. Ten participants were then asked to perform these three tasks, whilst their actions were logged in the background. The log files were subsequently analysed, with the aim to extract important user actions that were performed during the design sessions.

Figure 3 Overview of Experimental Method



Once the design information was extracted, they are formalised using several different representations, as shown in Figure 3. The next section will cover these various representations in greater detail.

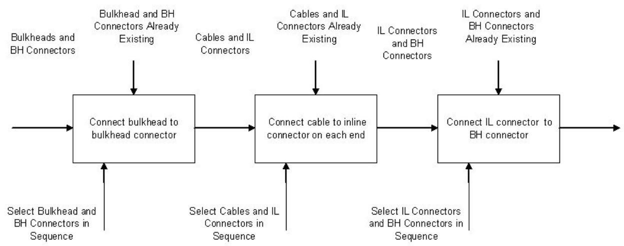
4 Formalisation of design knowledge

Prior work, presented in [1] and [4], had demonstrated preliminary steps in extracting the design knowledge deemed to be important and then representing them in a formal way. To allow this knowledge to be more easily viewed, analysed and imported into other knowledge-based systems, it is important that the information is represented in a formal format that is supported by applications used in industry. That was why the formal representation types that were chosen are IDEF (Integrated computer-aided design DEFinitions) diagrams [12], DRed graphs [13], PSL (Process Specification Language) [14] and XML (eXtensible Markup Language) [15]. In previous work, preliminary results were presented which showed these representations. In this paper, more detailed results will be shown together with how the representations have been used to support the creation and implementation of the online help system presented in Section 6.

4.1 IDEF diagrams

IDEF0 diagrams were developed to give a visual representation of the processes which have occurred in the modelled system. For this research, IDEF0 diagrams are used to give a formal representation of the user's actions during a design task in the COSTAR environment. To generate them, the user log files were imported into a spreadsheet and a macro was run, which parses the log file and automatically plots the IDEF0 diagram representation, as shown in Figure 4.

Figure 4 Assembly Planning IDEF0 Diagram

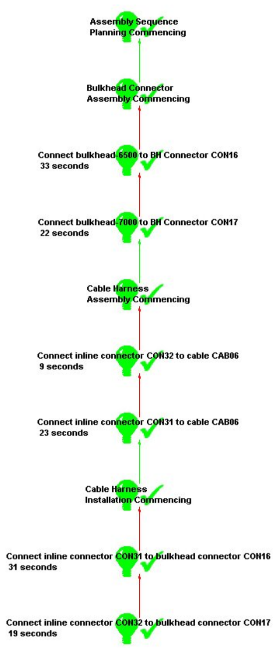


This IDEF0 diagram shows the steps that the user is required to perform to successfully complete a full assembly sequence plan for a cable harness. Also, by viewing these diagrams, it can give an expert user a quick way to identify the important processes that have occurred during a VR session, which can then be isolated and used to train new users.

4.2 DRed graphs

As a way of mapping the design rationale that is created during a design session, DRed (Design Rationale Editor) was developed by Kim et al [13] in collaboration with some aeronautical companies.

Figure 5 DRed Graph of Assembly Planning Process



The purpose of this tool is to allow the engineer to manually log all the design decisions that have occurred as a design progresses; however, for the research in this paper the generation of these graphs have been automated by creating a parser to parse the COSTAR log files and automatically output a DRed graph. In Figure 5, the DRed graph that represents the processes that have occurred during an assembly sequence plan task is shown. In this figure, each logged user action is represented by a green symbol (called an element), and each of these elements are connected with a colour-coded arrow. If the time in-between a task is quick (less than 5 seconds, for example), then the arrow is coloured green. However, if the time is more, the arrow will become amber and, eventually, it will be red to indicate the user has spent a long time on a particular task. This will aid in the identification of problems that have occurred during a design session and what areas is requiring attention. As can be seen from the figure, each element also includes a detailed description of the user action and the duration of it. Since this is only a preliminary result, the times intervals that are currently used to represent each arrow colour have not yet been finalised, so these may change in future research.

4.3 PSL and XML representation

Whereas IDEF0 diagrams give a visual representation of the design processes, PSL and XML give a coded representation which is in a format that is supported by many industry applications. PSL is used to model processes used in many situations, such as manufacturing and production. PSL consists of only the constants, functions and variables to describe the processes but needs a language to connect them into a formal structure. One language used is known as the Knowledge Interchange Format (KIF) and is designed to allow straightforward translation between different software packages.

Table 1 PSL Representation of 3 Design Tasks

	Drag and Drop	Create Connector	Assembly Planning
PSL	(activity CableDragDrop) (subactivity PickCable CableDragDrop) (timestamp 1227126621.614398 CableDragDrop) (subactivity DragCable CableDragDrop) (timestamp 1227126624.802401 CableDragDrop) (subactivity ReleaseCable CableDragDrop) (timestamp 1227126624.802436 CableDragDrop) (cablepointname A01H01C01S01P02 currentcable) (occurrence_of physicalObstruction) (timestamp 1227126627.617288 CableDragDrop) (accepted_solution Physical_CableDragDrop) (timestamp 1227126631.97959 CableDragDrop) (rejected_solution PhysicalReposition) (timestamp 1227126631.97995 CableDragDrop)	(activity CreateConnector) (subactivity SelectConnector CreateConnector) (subactivity PositionConnector CreateConnector) (connectorname A01B18 CurrentConnector) (connectorpositionx -850.586 CurrentConnector) (connectorpositiony -602.371 CurrentConnector) (connectorpositionz 1399.8 CurrentConnector) (bulkheadname BH-850.586 CurrentBulkhead)	(activity AssemblyPlanning) (subactivity AssembleBulkheadConnectors AssemblyPlanning) (componentname -6500 CurrentBulkhead) (componentname CON16 CurrentBHConnector) (assemblytime 33.1256 CurrentBHConnector) (componentname -7000 CurrentBulkhead) (componentname CON17 CurrentBHConnector) (assemblytime 22.3956 CurrentBHConnector) (subactivity AssembleCableHarness AssemblyPlanning) (componentname CAB06 CurrentCable) (componentname CON32 CurrentInlineConnector) (assemblytime 8.95224 CurrentInlineConnector) (componentname CON31 CurrentInlineConnector) (assemblytime 22.6301 CurrentInlineConnector) (subactivity InstallCableHarness AssemblyPlanning) (componentname CON31 CurrentInlineConnector) (componentname CON16 CurrentBHConnector) (assemblytime 31.2889 CurrentBHConnector) (componentname CON32 CurrentInlineConnector) (componentname CON17 CurrentBHConnector) (assemblytime 19.4891 CurrentBHConnector)

Therefore, this will allow user activity patterns to be imported into other knowledge or design packages. The PSL sequences can also be translated into human-readable instructions as well as UML or IDEF0 diagrams. In Table 1, the PSL sequences that are automatically generated, in real-time, when performing three design tasks is shown.

Table 2 XML Representation of 3 Design Tasks

	Drag and Drop	Create Connector	Assembly Planning
XML	<?xml version="1.0" encoding="UTF-8" ?> <costar_events> <cable_drag-drop> <pick_cable>1</pick_cable> <drag_cable>1</drag_cable> <release_cable>1</release_cable> <cablepointname> A01H01C01S01P02 </cablepointname> <cable_move_reason> Thermal Interference </cable_move_reason> </cable_drag-drop> </costar_events>	<?xml version="1.0" encoding="UTF-8" ?> <costar_events> <create_connector> <activate_connector_menu>1 </activate_connector_menu> <select_connector>1 </select_connector> <position_connector>1 </position_connector> <connector_name>A01B18 </connector_name> <connector_position_x>-850.586 </connector_position_x> <connector_position_y>-602.371 </connector_position_y> <connector_position_z>1399.8 </connector_position_z> <bulkhead_name>BH-850.586 </bulkhead_name> </create_connector> </costar_events>	<?xml version=1.0 ?> <costar_events> <assembly_planning> <assemble_bulkhead_connectors>1 </assemble_bulkhead_connectors> <bulkhead_name>-6500</bulkhead_name> <bulkhead_connector_name> CON16 </bulkhead_connector_name> <assembly_time>33.1256 </assembly_time> <bulkhead_name>-7000 </bulkhead_name> <bulkhead_connector_name>CON17 </bulkhead_connector_name> <assembly_time>22.3956 </assembly_time> <assemble_cables_harness>1 </assemble_cables_harness> <cable_name>CAB06</cable_name> <inline_connector_name>CON32 </inline_connector_name> <assembly_time>8.95224</assembly_time> <inline_connector_name>CON31 </inline_connector_name> <assembly_time>22.6301</assembly_time> <install_cables_harness>1</install_cables_harness> <inline_connector_name> CON31 </inline_connector_name> <bulkhead_connector_name> CON16 </bulkhead_connector_name> <assembly_time>31.2889</assembly_time> <inline_connector_name>CON32 </inline_connector_name> <bulkhead_connector_name> CON17 </bulkhead_connector_name> <assembly_time>19.4891</assembly_time> </assembly_planning> </costar_events>

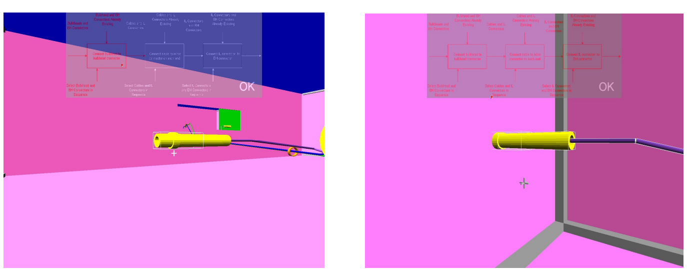
In addition to the PSL representation, XML outputs are also automatically generated in real-time, during a VR session. Since XML is widely supported in many applications, it would allow the data to be easily imported. The XML representation for three design tasks is shown in Table 2.

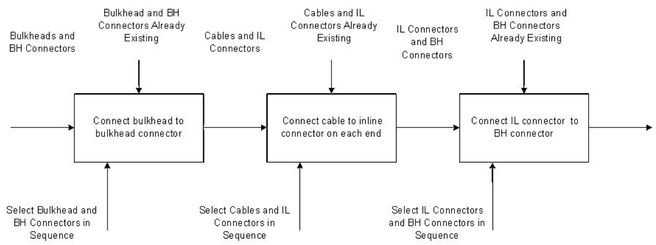
By analysing the PSL and XML sequences that are generated by several expert users, it is proposed that by looking for repeating patterns of action sequences, the 'best practice' for each specific design task can be isolated and then used to train new users. Furthermore, by having a database of these PSL and XML fragments, and then constantly monitoring a user's PSL or XML, output during a task, the system can identify when a user is carrying out a recognised task in real time. When this happens, an online help system is automatically activated to offer relevant help to the user, if required; this is detailed in the next section.

5 Interactive online help

As mentioned in the previous section, the COSTAR system has a database of PSL and XML fragments that were generated by analysing the logged output of expert users whilst carrying out specific design tasks.

Figure 6 Online Help During Assembly Planning (top) and IDEF0 Diagram (bottom)

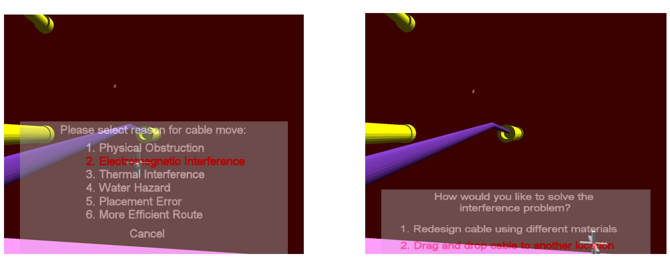




In subsequent design sessions, as a new user performs a design activity and PSL and XML data is output in real-time, the system can 'recognise' a particular pattern by matching it with one in the database. At this point, the system will know what particular design task is being carried out and offer assistance by displaying context-related instructions, as illustrated by the example in Figure 6. In the example, a user is carrying out an assembly plan, so as soon as the PSL output generated by the user matches the assembly planning PSL sequence in the database, an IDEF0 diagram that shows the processes that are required to be performed to give a correct assembly plan is displayed, as shown in more detail at the bottom of Figure 6. At this point, the user can click the 'OK' button to switch off the online help or just carry on working with the IDEF0 diagram displayed. Initially, the displayed IDEF0 diagram is completely white but, as each stage of the assembly plan is completed by the user, each corresponding section of the IDEF0 diagram will turn red to let the user know the current step has been completed and the next step can be started. As soon as the user completes the assembly plan the IDEF0 diagram automatically turns off.

Another example of the online help system is shown in Figure 7, which shows a user moving a cable. As soon as this happens, a dialogue box appears which asks the user the reason why the cable has been moved. When a reason is selected, which in the example is 'Electromagnetic Interference', the system then offers two possible solutions to the user's problem which were derived from previous experiences of expert users. In the example, the user has selected 'Drag and drop cable to another location' as the solution and this information is then stored in a number of formats for future referencing.

Figure 7 Proposed Online-Help System



6 Discussion & future work

A 3D immersive cable harness design system has been presented which integrates previously separate tools into a single application that allows several design stages to be carried out concurrently.

Several formal representations of the extracted design knowledge have been presented and used to create a prototype online help system to aid training of new users. To measure the effectiveness of the representations and the online help system, future work will involve running some user trials where the participants will carryout design tasks in the VR environment. After each design session, the participants will be interviewed and asked to fill out a questionnaire to give ratings on how useful the online help system had been. Furthermore, the participants will be shown the various forms of design decision representations and then interviewed to discover how clear and concise the representations are. Further experiments can also be carried out to determine whether the online help system and various design knowledge representations help reduce the task-completion times. This would involve comparing two sets of users carrying out a design task, but one set of users will have been shown the various design knowledge representations before carrying out the design task.

The authors envisage that the interactive online help system and the real-time log file analysis tools can be integrated into a 2D CAD system. One obstacle to this is the fact that many CAD packages used in industry usually have security or intellectual property restrictions to them so it is difficult to obtain access to the code in these CAD packages. However, one potential solution is to utilise a simplified design environment which will allow users to create a design and carry out a simulation to test out that design, as well as allowing log file analysis functionality to be added to it. Preliminary research work using this method has already been initiated and has been reported in Rea et al. [16]. When the tools, presented in this research, are finally integrated into a 2D CAD system, this will allow industrial-based, and hence more realistic, design tasks to be carried out and analysed.

7 Conclusions

A number of novel outputs from this research have demonstrated the potential for immersive VR in aiding the analysis of and supporting product engineering tasks.

The research presented in this paper has demonstrated the ability to log a user, whilst carrying out a cable design task in a VR environment, and then – in real time - automatically analysing the logged data and extracting the important design knowledge embedded within it. Next, the design knowledge has been automatically formally represented using several established formats, which include IDEF0 diagrams, DRed graphs and PSL and XML representations. Finally, by utilising the obtained design knowledge, a novel interactive online help design information 'push' system to aid users during a design task has been demonstrated which is triggered by solely monitoring and identifying the user's specific actions in real time. This system will not only instruct users on how to correctly carry out a task but will also help improve the efficiency of future designs. Once the research has been refined further, the next step is to embed these methods and similar solutions into industry-standard 2D CAD packages.

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