<Review Paper>

The Application of Virtual Reality to Tasks in Manufacturing and Assembly Engineering

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Virtual Reality is a developing technology for which a range of applications are being explored by different international research groups. This paper describes recent research in the application of Virtual Reality to two important manufacturing and assembly tasks which have a direct influence on the speed of introduction of new products. The tasks are the production of planning documentation for assembled products and the design and planning of the cable harnesses which form part of all electro-mechanical assemblies. The research completed so far demonstrates the potential of Virtual Reality, even at its current stage of technological development, to make a significant contribution in both these cases.

Key Words: Virtual Reality(VR), Assembly, Manufacturing

1. Introduction

Virtual Reality (VR) is an emerging technology which has received much publicity and an increasing amount of academic attention in the past few years. Application areas have exploited the interactive, visualisation capability of VR and include computer games, architecture, molecular modelling and micro-surgery. Significant recent research has also been undertaken for military simulations of warfare situations. Applications in manufacturing engineering to date have been less frequent. This is partly because of the lack of computer power to handle the level of detail required for engineering tasks and partly because of the absence of effective haptic (the sense of touch) necessary for many human oriented tasks.

It is likely to be some time before affordable, effective haptic feedback systems are available, capable of managing a useful range of single and double handed tasks. On the other hand, computer power is expected to continue to decrease in price and it is certainly possible to look forward to yet more powerful computer systems in a few years time. In these circumstances it is vital to explore the potential of the current generation of VR technology to make useful contributions to manufacturing engineering. The purpose of this paper is to review some of the research in this area which has been undertaken at Heriot-Watt University over the past two years. There are two major aspects to the work. The first concerns the planning of manual assembly operations where manufacturing experts can interact with new products in the virtual environment well ahead of physical prototypes being built. If it is possible to generate assembly planning documentation automatically at this stage, there will be a direct impact on the time it takes to bring many new products to market. The second area of research concerns the design and planning of cable harnesses in electro-mechanical devices. Cable harnesses are complex systems which regularly receive attention at the end of the product development cycle and are the source of many delays and late design changes. These problems can be addressed by the use of VR which is ideally suited to enable

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cable and wiring arrangements to be considered concurrently with the overall product design.

2. Assembly Planning

2.1 Background

Conventional assembly planning is a lengthy and costly task which can be performed by a combination of examining design data and carrying out assembly tests on actual prototype components. The output of the assembly planning function is a complete set of instructions that precisely describes the assembly sequence, joining methods and materials, tooling, fixturing and any relevant testing or inspection procedures.

This paper proposes that immersive VR can be used as an aid towards more efficient assembly planning of electro-mechanical products. The virtual assembly system includes some novel techniques to assist users in carrying out assembly operations.

Since forty percent of a product's cost can be attributed to assembly (Bullinger & Richer, 1991) much research has concentrated on this topic. However, attempts to automate assembly planning have had limited widespread appeal outside the research community (Homem de Mello & Lee, 1991). Automation is computationally expensive and most of the work in this field has concentrated on lessening this burden (Lin & Chang, 1993). In general, however, systems that have been developed still rely on a large amount of data being provided by the user, such as precedence relations and liaison information (De Fazio et al., 1989) or even base parts (Henrioud & Bourjault, 1992). After the automated planning has been carried out, the user is then required to shift through a large number of possible sequences to select the best one. This user interaction, both before and after the computer's analysis, dilutes any benefits claimed for improving the efficiency and objectivity of the planning process. Indeed, Maropoulos (1995) contends that more work is necessary in the area of assembly planning and that VR is set to play an important role in process planning.

Whilst VR has, to date, been a tool best suited to visualisation, it is recognised that the sense of touch (also known as haptic feedback) is important to the accuracy and speed with which humans undertake assembly tasks in virtual worlds (Hirata et al., 1994; Gupta & Zelter, 1995). Connacher et al. (1995) propose a system for assembly and design which includes some haptic feedback, whereas Lee and Hahn (1995) report that their virtual assembly system will require the assembly plan as an input rather than an output and do not mention haptic feedback. However, the hardware to facilitate haptic feedback is still the subject of current research (Taylor, 1995; Caldwell et al., 1996; Tateno & Igoshi, 1996) and is not readily or economically available. Therefore the system developed for the work described here makes use of commercially available hardware and software, which relies on visual and audio cues but without haptic feedback.

2.2 Virtual assembly planning

Any virtual assembly planning tool needs to capture at least two major attributes-the assembly sequence and the methods of joining components together. The system described in this paper uses the top level algorithm given in Fig. 1. Here a user selects and moves a virtual component until it has either touched, or is reasonably close to, another virtual object whereupon the user decides if the two objects are to be joined and by what means. This assembly information, namely the sequence and method of joining is captured and

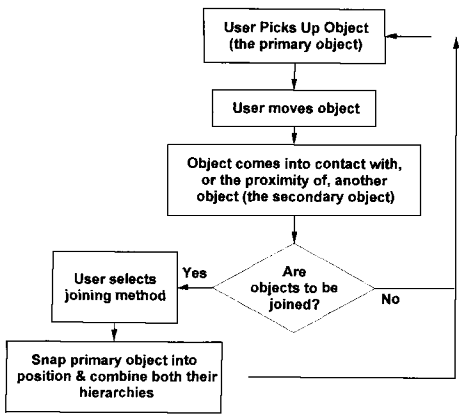

Fig. 1 Top level assembly algorithm.

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Event Pick was received for component RedStrut_0 @ 277.8 secs.
Event Collide was received for component RedStrut_0 @ 279.3 secs.
Event Collide was received for component Block @ 279.3 secs.
Event Drop was received for component RedStrut_0 @ 279.3 secs.
Toolbox: Join Started @ 279.3 secs.
Toolbox: Join Stopped @ 290.0 secs.
Toolbox: JoinType Started @ 290.0 secs.
sub001 was created @ 302.0 secs.
JOINT: RedStrut_0 was Screwed to Block @ 302.0 secs.
Toolbox: JoinType Stopped @ 302.0 secs.
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Fig. 2 Extract from assembly plan.

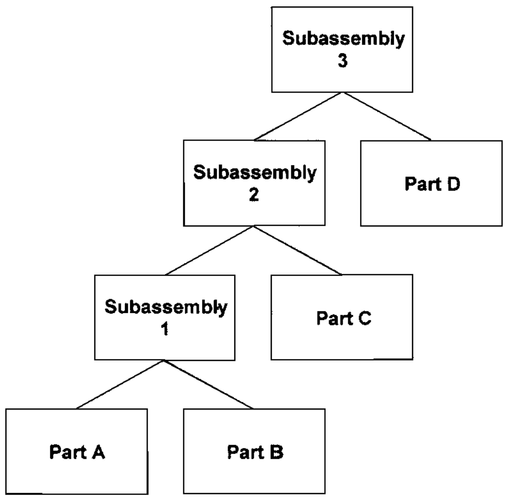

Fig. 3 Family tree assembly structure.

an assembly plan automatically produced.

An extract from an actual plan produced by the system is given in Fig. 2. Although relatively verbose, it shows two examples of how a component was picked up then collided with another component. The two components are then joined together.

Event Pick was received for component RedStrut_0 @ 277.8 secs.

Event Collide was received for component RedStrut_0 @ 279.3 secs.

Event Collide was received for component Block @ 279.3 secs.

Event Drop was received for component RedStrut0 @ 279.3 secs.

Toolbox: Join Started @ 279.3 secs.

Toolbox: Join Stopped @ 290.0 secs.

Toolbox: JoinType Started @ 290.0 secs.

sub001 was created @ 302.0 secs.

JOINT: RedStrut 0 was Screwed to Block @ 302.0 secs.

Toolbox: JoinType Stopped @ 302.0 secs.

The hierarchies mentioned in Fig. 1 are the internal representation of the subassemblies in the virtual world and depict the transient states that components have evolved through on their way to being incorporated into a final assembly. Fig. 3 shows a portion of such a family tree with four parts (A, B, C and D) and three subassemblies. This type of binary structure has been chosen to represent the joined objects in the virtual world since it gives historical information about the assembly sequence. For example, the first join in the sequence was between parts A and B and the most recent join involved part D. This representation allows the last joining operation to be readily undone.

In this system, subassemblies are created online as objects in much the same way as components, except that they have no visual attributes

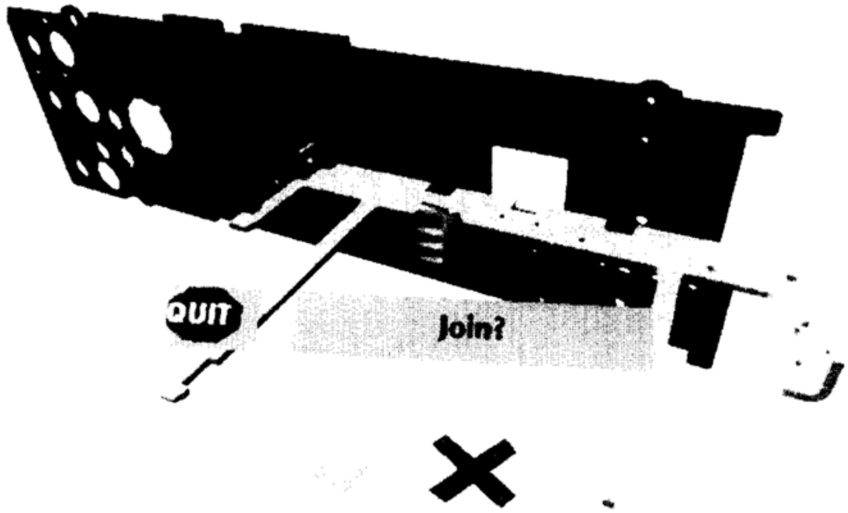

Fig. 4 Two sheet metal components, a virtual hand and a virtual toolbox.

associated with them. The topmost subassembly in any grouping of objects is called the Root Parent. Those objects below the root parent are called its Children and objects at the same level, say Subassembly 1 and Part C, are called Siblings. All the objects can be made to behave as if they are joined together by fully constraining the children of a root parent in position and orientation and leaving the root parent unconstrained.

2.3 Joining tools

The relatively poor visual resolution of most immersive head mounted displays, coupled with the lack of haptic feedback and low accuracy magnetic tracking, means that positioning a component exactly in an assembly is almost impossible in the system under consideration here. To assist users of the virtual environment place components in the correct position relative to their neighbours, two joining tools have been developed.

These joining tools use the idea of *snapping* as adopted by most CAD packages. Snapping in CAD is the assistance given to users when they try to pick, say, a line's end-point with their cursor and even though they may miss, the software's algorithm looks for the nearest vertex and takes that as the point at which to start/finish a new line. Without this assistance CAD drawings would contain gaps and inconsistencies which could cause problems with, for example, NC software and dimensioning. Thus, as a matter of course, CAD software allows users to position their cursor approximately whilst still ensuring the integrity of the geometry.

Furthermore, snapping is not the only parallel that exists between CAD and these joining tools. In many technical drawings, the visual representation of fasteners is not deemed necessary. Instead the fasteners are called up in notes and/or bills of material. To see their geometry would clutter the drawing and add little to the descriptive properties of the representation. The same argument can be applied to VR. Therefore, fasteners are not graphically represented in the virtual environment. Instead, when a user chooses a method of joining, this choice is simply recorded in the assembly plan.

Both joining tools described here are based on the assumption that the fully assembled position of each object is already known. This is a reasonable assumption since a designer will invariably have created a final assembly of the components in a CAD package during the design process. The positional information of the various components can be re-used in the VR system.

2.3.1 Collision snapping

Collision Snapping is the simplest joining tool available to assist the assembly planner in attaching two objects together in a virtual world. When a user picks up a component (the *Primary Object*) and moves it towards the component that it is to be mated with (the *Secondary Object*), then as soon as a collision is detected between them the user is asked, via the toolbox shown in Fig. 4, if the two components are to be joined. Since it may not always be immediately obvious what the primary object has collided with, the secondary object is highlighted by making it flash. The collision is also accompanied by an audio cue from the system in the form of a simple 'beep' to emphasise the event. If the two are to be joined then the method of joining is chosen from a toolbox which includes options such as gluing, welding, bolting, snapping, etc.

Once the means by which the two objects are to be joined have been chosen, the collision snapping algorithm repositions and re-orientates the primary object such that the relative position and orientation of the primary to the secondary object are the same as in the final assembled state. Since the primary and secondary objects may already be part of existing hierarchies, their two families of components are combined below a new subassembly object-as shown in Fig. 3.

2.3.2 Proximity snapping

Proximity snapping offers a more realistic approach to assembly than collision snapping since it does not call up the toolbox shown in Fig. 4 unless the primary object is sufficiently close to its final position relative to one or more of its neighbours, that is until it is in the *proximity* of a secondary object. This maps more closely on to the real world. Furthermore, while the user is manipulating the primary object to get it close enough to a secondary object for joining to take place, a large number of collisions are likely to occur. Whilst in the real world two solid objects will not readily pass through each other, in the virtual world they will unless some action is taken when a collision is detected. Thus, the algorithm has to be constantly checking to determine if the primary object is close to any of its neighbours and it must also deal with collisions as they occur to stop the boundaries of objects overlapping.

In the proximity snapping approach, a primary object is snapped to a secondary object if the differences between their positions and orientations are within certain tolerances of the values they have in their final assembled state. In the same manner as for collision snapping, the primary object is repositioned and reoriented with respect to the secondary object and the secondary object is added to the primary object's hierarchy.

The collisions that occur as a user manoeuvres the primary object into place are dealt with as follows. To prevent object boundaries appearing to overlap, as each new frame is rendered the position and orientation of the primary object are recorded. When a collision is detected, the primary object tracks back through these previous positions and orientations until an *uncollide* event is detected. At this point the user is then free to carry on manoeuvring the primary object. An alternative to this method is to record the time at which a position is recorded, note the time at which the collision occurred and reposition the primary object at some time before the collision.

2.4 A virtual assembly system

A computer aided virtual assembly system has been developed which consists of a suit of software functions, called actions, written in the C programming language. This system incorporates the collision and proximity snapping algorithms and has been integrated with a proprietary VR software package.

Each object in the virtual world has behaviour associated with it. This behaviour is based on the objects' response to a series of events. For example:

- *collide*-occurs when a collision is detected between components;
- *uncollide*-occurs when component boundaries are no longer in collision;
- *pick*-occurs when the user picks up a component.

When an object receives such events, the actions can be executed. These actions include making objects flash, setting variables and starting toolboxes. The system automatically produces a record of the user's activities in the virtual world in the form of an assembly plan, as in Fig. 2. The interface through which users communicate with the program is in the form of floating virtual toolboxes (Fig. 4). Generally these have annotated buttons which can be pressed to perform different functions.

A further feature of the system is that of *likely liaisons*. When manipulating a component there are often accidental collisions between it and other components. These collisions cause the toolbox in Fig. 4 to appear unnecessarily. To avoid this the system automatically assesses what are likely liaisons for each component by considering the components which are touching, or close to, each object in the final assembled state. Thus, the toolbox will only be triggered if a collision occurs and the secondary object has a likely liaison with the primary object.

2.5 Summary of virtual assembly

Virtual reality offers a wide range of applications in the automation of manual assembly planning. However, currently affordable VR hardware and software suffers from certain limitations that reduce the level of realism that is achievable when attempting complex assembly operations in the virtual world. This paper has described some novel approaches to reducing the impact of these limitations and producing a more intuitive and useful assembly environment. A method for combining virtual objects without redefining the internal object model has been discussed. Two methods for virtual joining have been presented, along with a brief exploration of approaches to the implementation of non-penetrating object collision.

3. Cabling

Cable harnesses, as shown in Fig. 5, are used to connect electrical/electronic modules in electromechanical devices. The design of such cables is typically thought of as an ancillary activity of secondary importance. The process is, in fact, a complicated design problem which is time-consuming and costly, leading to complex cable harness systems (as illustrated in Fig. 6) which can constitute a significant proportion of the overall product cost. Moreover, delays in the completion of the cable harness design can have a direct impact on the speed with which new products can be brought to market.

The complexity of cable harnesses in many products is such that designing the harness in the absence of a physical prototype is simply impractical. One only has to think of the difficulty in understanding the CAD wire frame representation of even a quite simple mechanical design to realise how difficult the design of a cable harnesses is given that they are comprised of principally of lines in three dimensional space. Common practise is for cable lengths, paths and fastener positions to be determined by hand at the prototype stage. The set of cables has to be arranged to provide the shortest paths between the various connection points commensurate with producing a single harness which can then be produced as a single subassembly in its own right.

A typical harness includes a variety of different

Fig. 5 Cable harnesses within an electro-mechanical assembly.

Fig. 6 An assembled cable harness.

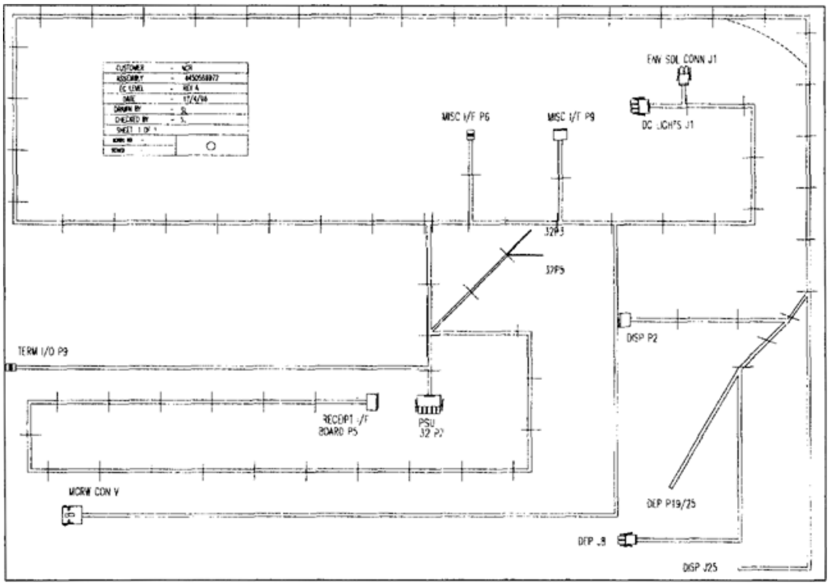

Fig. 7 An assembled cable harness associated layout drawing.

wires which vary in diameter and stiffness. These factors determine the mass distribution, minimum permitted bend radii and fastener distribution of the various arms of the harness. An important concern for harness designers is that of voltage drop (Kloske & Smith, 1994). Voltage drop is directly proportional to cable length and inversely proportional to cable cross-sectional area. Ideally, the designer must find a routing configuration which maintains a suitable voltage drop for all cables in the bundled harness. The cable harness is completed by end connectors which are determined by the type of socket provided by individual modules. Once a suitable harness is designed, all the necessary information including cable types, lengths, end connectors and fixing points can be entered in the database of a CAD system. The system converts the information into two dimensional drawings and parts lists, as in Fig. 7. It is vital that this information is accurate and proven since the actual manufacture of the harness assembly is often carried out by a specialist supplier.

The routing problem is further complicated by the vulnerability of the cable harness to decisions made upstream. In some cases a major cable harness reconfiguration may have to take place after only minor changes elsewhere within the prototype machine. The routing process can even result in the late and expensive re-design of the machine chassis to allow the cables to reach their terminal points.

3.1 Background

In spite of its industrial importance, cable harness design is not widely recognised as an area for academic research. Internationally most progress has been made in the United States. At Stanford University investigators have attempted to automate the choice of cable harness route in a non-immersive virtual space (Couru & Cutkosky, 1993). The system is a review tool for use after the equipment has been designed. It does not envisage the interactive capability which is seen as a key feature of this proposal. Subsequent work by the same Stanford team has been directed towards the use of a genetic algorithm approach for the automatic determination of cable routes (Conru, 1994; Park et al., 1994). Attempts have also been made, with partial success, at using genetic algorithms to automate cable layouts in power plants (Kloske & Smith, 1994).

Wolther and Croll have used a different approach which involved techniques for routing ' strings' around 'solid' parts (Woeter & Kroll, 1996). This work attempts to mimic two generic assembly operations for flexible components, namely pushing and pulling. This research, while directed more to flexible parts than to cabling, does offer some hints about interactive tools which might be developed to enhance an cable harness design system. Some routing work has also been carried out based on robot path planning and applied to piping systems by Zhu and Latombe (1991).

Although there are a few similarities with the cabling problem, the validity of this latter work is hard to assess since it does not appear to include any provision to alert the user when different lines or routes collide. While this might be satisfactory in a sparsely populated pipeline space, it will be unacceptable in a densely occupied environment.

Interestingly, an approach related to VR was advocated as early as 1992, not for the design of cable systems but rather for the actual fabrication cable harness assemblies (Caudell & Mizell, 1992). The investigators involved believed that augmented reality (projecting graphics on to real world objects) could be used to allow operators to produce cable harnesses more efficiently but failed to identify the wider design, manufacture and associated business issues related to this type of approach. Krumenaker (1997) gives a review of similar augmented industrial systems but concludes that all are at a very early stage.

A common theme running through previous research in cabling systems design is a desire to find ways to automate routings using computer based techniques and a realisation, acknowledged in most cases, of how difficult this is given the open ended nature of the problem. There seems to be some agreement reached that no matter how sophisticated a system might be developed, there will still be a need for a human expert's intervention to make fine adjustments and verify solutions. The most successful application of 'tracking' in this context is probably that of printed circuit board routing, however this is essentially a layered 2D problem whereas the types of environment being challenged by this research is very much 3D and much more difficult to visualise and tackle by computer analysis, especially when the end product is not as easily 'standardised'.

The proposal approaches the issue from the opposite direction by recognising that the involvement of an expert is inevitable, at least for the foreseeable future. Rather than seeking to eliminate the individual, the research is giving the expert tools so that their expertise can be applied effectively and at the right time in the design cycle. These may be used in two ways: (a) to develop a new design from scratch or (b) to employ them as a means of 'finishing off' and tailoring automatically generated solutions.

Although there has been little academic work in cabling systems, some proprietary computer -aided packages have been developed for use, such as contained within 'ProEngineer' and 'CADDS 5'. Investigations carried out prior to preparing this proposal suggest that current systems are not easy to use, particularly when modifications are required, and cannot always be relied on to come up with a suitable solution. It appears that a substantial amount of manual tailoring is generally necessary. As stated previously, prototype machines are often built without cabling. Only then will a harness be devised for that arrangement of components.

3.2 Cable layout using immersive virtual reality

The virtual design and planning cable routing system is implemented on a Hewlett-Packard workstation with additional VR hardware and software from Division Ltd., Bristol, UK. CAD models of a prototype assembly can be imported directly into the system which negates the need for any extra component modelling. The user interacts with the system by means of a Head Mounted Display (HMD). This provides a stereo image of the virtual environment. A three dimensional mouse (3D) is used as an input device. The immersive VR approach is the key to comprehending three-dimensional cable assemblies and it also overcomes the inherent difficulty of understanding cable layouts using flat screen conventional CAD systems.

NODE	Node Position	Connector Type	Liaisons/Cable Configuration
1	(1,1,1)	1	2A
2	(2,3,4)	NA	3B
3	(3,5,5)	NA	4A,5C,6B
4	(6,6,6)	4	NA
5	(8,-7,4)	NA	7A
6	(9,2,1)	NA	8C
7	(10,-4,5)	2	NA
8	(5,3,2)	3	NA

Fig. 8 An example of the output from the system.

The ability to touch and feel objects in the real world is one that is taken for granted. However, the development of viable systems to provide this haptic feedback in virtual environments is still the subject of much research (Caldweel et al., 1996; Tateno & Igoshi, 1996; Taylor, 1995). For this reason, the system described here makes use of alternative visual and audio cues to highlight collisions. A full polygonal collision detection algorithm is available in the Division software; thus, when a collision occurs, the system utilises messages sent from the algorithm to make objects in the virtual world turn to a wire-frame representation to highlight to the user that something is amiss. The visual cue is accompanied by an audio cue which takes the form of a simple 'beep'.

To lay cables, the user simply has to "click" points in space with the 3D mouse. Cables then appear between these points which can easily be edited by dragging and dropping. Cables can follow paths that closely follow the surfaces of existing components in the virtual world. This is achieved by using the aforementioned collision detection algorithm.

3.3 System architecture

The set of nodes and cable sections created by the user are stored in a multi-linked graph structure containing a linked list of nodes and a further linked list of joins for each node (Langsam et al., 1996).

At the end of the routing session, the system generates a text file by traversing the graph structure and extracting useful information which details the bills-of-materials and process planning information associated with the physical cable harness. These output include the types of end connectors and cable configurations selected as well as the positions and liaisons that exist between the virtual nodes as shown in Fig. 8. The connector type and liaisons/cable configuration indicated in the text file are specified by the user during the immersive routing session. The numbers indicated in the connector type list describes the physical configuration of the connector (i. e. actual size, number of crimps found on the connector). The liaisons/cable configuration, on the other hand, describes the types of bundles of wires that are specified for use within certain sections of the cable harness layout.

A post processor had been developed to convert the data within the text file into a two dimensional layout of the cable harness in a DXF format. This drawing can be use in the manufacture of the physical cable harness.

3.4 Summary of virtual cable routing

Current CAD cable harness routing systems are only able to provide users with two or three degrees of freedom of movement on a flat screen for tailoring of 'automated' cable layout designs or for designing cable layouts interactively from scratch. This inhibits the user's ability to recognise and edit flaws in a cable layout design. Augmented reality applications show promise in allowing assembly workers install the harnesses, but are at an early stage of development and still do not address the design and planing issues. Immersive VR, on the other hand, gives the user the ability to change their stereo viewpoint quickly and provides six degrees of freedom including the perception of depth which helps in the location of geometry and associated virtual bodies. Here, a VR system has been described which allows the user, in an immersive virtual environment, to perform the routing process intuitively and efficiently. This approach focuses on the user's expertise to complete the task rather than trying to automate the procedure. The system also automatically logs the details of the routing process which can be used to create a bill-of-materials and two dimensional schematics of the harness.

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