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Design of a Virtual Reality framework for maintainability and assemblability test of complex systems

Adelaide Marzano[a], Imelda Friel[a], John Ahmet Erkoyuncu[b] and Samuel Court[b]

[a] *School of Mechanical and Aerospace Engineering, Queen's University Belfast, Belfast BT9 5AG, N. Ireland*
[b] *Manufacturing Department, Cranfield University, Bedford MK43 0AL, UK*

* Corresponding author. Tel.: +442890974034; fax:+442890974148.*E-mail address:*a.marzano@qub.ac.uk

Abstract

This paper presents a unique environment whose features are able to satisfy requirements for both virtual maintenance and virtual manufacturing through the conception of original virtual reality (VR) architecture. **V**irtual **R**eality for the **Ma**intainability and **A**ssemblability **Te**sts (VR_MATE) encompasses VR hardware and software and a simulation manager which allows customisation of the architecture itself as well as interfacing with a wide range of devices employed in the simulations. Two case studies are presented to illustrate VR_MATE's unique ability to allow for both maintainability tests and assembly analysis of an aircraft carriage and a railway coach cooling system respectively. The key impact of this research is the demonstration of the potentialities of using VR techniques in industry and its multiple applications despite the subjective character within the simulation. VR_MATE has been presented as a framework to support the strategic and operative objectives of companies to reduce product development time and costs whilst maintaining product quality for applications which would be too expensive to simulate and evaluate in the real world.

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*Keywords:*Virtual Reality; Assemblability; Manufacturing Systems

1. Introduction

This paper explores the use of virtual reality (VR) in manufacturing, specifically related to assembly and disassembly simulation and analysis. A unique environment is presented which satisfies the requirements for both virtual maintenance and virtual manufacturing through the conception of an original virtual framework, VR_MATE. This framework is used in two case studies to demonstrate the capability of the framework to applications of both maintainability and assembly analysis. The paper is structured as follows, Section 2 presents literature on virtual reality use in manufacturing and current frameworks to support application of VR in manufacturing, Section 3 describes VR_MATE, Section 4 presents the two case studies, Section 5 a discussion and Section 6a conclusion and future work.

2. Literature

2.1. Virtual Reality in Manufacturing

Virtual reality is a tool widely recognised in manufacturing sectors as a means to ensure quality whilst reducing development time and costs for a new product. It is often used as a visual aid to verify the design and function of a product during the concept design phase, with limited use beyond design. Research recognises the potential of virtual reality as a tool for assembly analysis, training purposes, process planning and path planning [1] and demonstrates its use as a prototyping system of a physical product for investigation and simulation of assembly and maintenance processes [2]. Further work has used virtual reality environments to obtain

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useful manufacturing information such as product maintainability from disassembly operation simulations [3], capturing design knowledge from assembly simulations [4], and analysing operator postures by simulation of assembly operations in aerospace manufacturing [5]. Researchers have investigated ways to improve the virtual environment to obtain more accurate information as reviewed in [6] with [7] and [8] improving the virtual environment for users by investigating physics-based modelling and motion tracking systems respectively. The latter work demonstrates how this motion tracking can create effective assembly planning. These examples illustrate the uses of virtual reality as a manufacturing tool, however do not provide knowledge on how to create virtual environments in order to implement the technology. This work presents the development and implementation of a new virtual reality framework that supports both assembly and maintenance operations within the manufacturing domain and has demonstrated its ability to provide system level information regarding optimisation of assembly sequence and timing for both disciplines.

2.2. VR Frameworks

Virtual reality frameworks have been developed and documented in literature to illustrate an overview on how to employ virtual reality. Many of these examples aim to exploit virtual reality as a training tool for manufacturing operations. Training in the virtual environments allows the user to develop skills needed for the operations and early identification of problematic areas which can be resolved prior to production where time and quality become constraints. A highly informed framework in [9] is implemented on a hydraulic winch example and creates a maintainability report of the operations. The framework includes a knowledge base of maintainability evaluation and product knowledge as well as the capacity to simulate and evaluate the maintenance operations through human-computer interaction. A collision detection report from the assembly analysis is obtained from the virtual environment in [10] whose framework combines CAD (Computer Aided Design) software and Virtools. The use of haptic devices within the virtual reality environment resulted in greater user satisfaction when assessing the environment as a training system [11]. VR_MATE, presented in this paper, allows users to perform both assembly and maintenance operations by combining the knowledge base developed for the product with the criteria required for the specific operations. Concurrently it will provide training for operators in assembly or maintenance tasks, as well as information for production engineers with regard to assembly/maintenance sequence planning, tooling requirements, time allocation for operations and importantly operator safety during production.

2.2.1. VR environment development

Work has also been done on extending the virtual environment for multiple users training simultaneously. Both [12] and [13] aim to facilitate collaborative training environments for multi-operator use, with the former focusing on using a gaming environment to develop a framework to support learning of assembly and potentially disassembly operations. The latter has extended previous immersive Virtual Maintenance Training System (VMTS) to allow multi-operator use which results in reduced training time and improved maintenance efficiency when demonstrated. The framework includes a central supporting system which contains an extensive knowledge base and a human-computer interactive control model (HCICM) which supports real time motion control and evaluation. A remote training system in [14] which aims to break the limits of equipment, time and space by connecting the knowledge base to a server accessible to users for the development of a virtual assembly environment. The system demonstrated in an educational environment allows expansion of knowledge of maintenance whilst maintaining this data for future use. The environment presented in [15], DPVAE (Distributed Parallel Virtual Assembly Environment) is an internet based system that supports geographically dispersed teams during product assembly at early design stages. The technologies within the framework allow multiple user assembly operations on a complex product to determine visually collisions and optimized assembly path and sequences. However this framework has only supported assembly operations. In other work, virtual environments have been developed to allow user interaction during simulation to improve understanding [16] and as a collaborative design platform for manufacturing systems [17]. The ability to alter parameters within the simulation in [16] allowed identification of problematic areas to improve the manufacturing system design and ultimately reduce the costs associated. A framework that supports manufacturing system design and illustrates the use of a single framework capable of performing multiple analyses at various manufacturing system levels within an immersive CAVE environment is presented in [17].

The literature presented has validated the capabilities of using virtual reality within manufacturing to aid in assembly and maintenance procedures through the development of frameworks which include a knowledge base to support accurate simulation and evaluation of operations. This paper presents a unique environment whose features are able to satisfy requirements for both virtual maintenance and virtual manufacturing through the conception of original virtual reality (VR) architecture. VR_MATE encompasses VR hardware and software and a simulation manager which allows customisation of the architecture itself as well as interfacing with a wide range of devices employed in the simulations. Two case studies are presented to illustrate VR_MATE's unique ability to allow both maintainability tests and assembly analysis of an aircraft carriage and a railway coach cooling system respectively.

3. VR_MATE Development

The framework developed in this work, VR_MATE, shown in Figure 1, satisfies the requirements for the realisation of an immersive virtual environment for maintainability tests and manufacturing systems simulations. These requirements include:

- A powerful graphic and calculus system able to manage a great amount of data
- A large screen to visualise complex systems in full scale
- Input devices allowing the user of the virtual experience to easily navigate and interact with the virtual scene and other members of the team to share experience and review it
- Software tools for collision detection, motion programming, kinematics simulation, 2D distance measurements, virtual mark-up and path recording
- 3D audio output device increasing the immersion of the virtual environment.

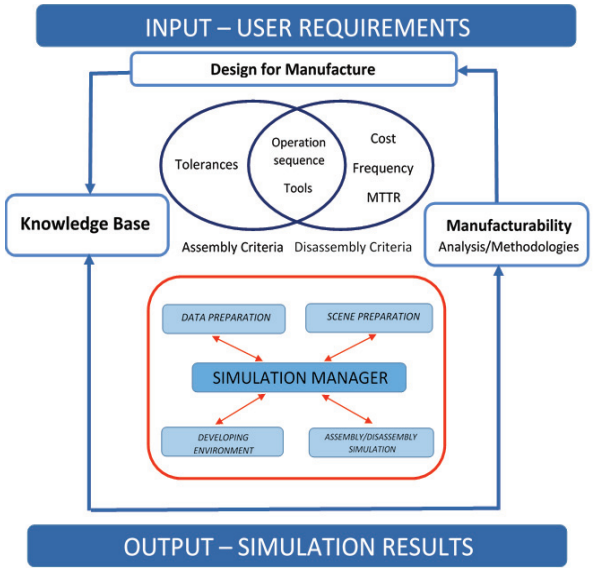

Fig. 1 VR_MATE Framework

The framework includes a simulation manager platform, Visionary Render 2. It is an extensive tool cotaining many functions for product development, from creation of virtual environments to the assembly simulation or ergonomics analysis. The Application Programming Interfaces (API) provided by the software allowed customization of the simulation manager for maintainability tests and manufacturing simulations, not currently provided by commercial, off the shelf (COT) software. It is also possible, using this platform, to interface with and manage a range of input and output devices, such as those available at the Operation Excellence (OpEx) laboratory at Cranfield University. The lab offered the following capabilities:

- Immersion using 3D projection system
- See-through head-mounted display (HMDs)
- Ability to create virtual environments and import a range of CAD data
- Demonstration software, with emphasis on virtual training

A breakdown of the hardware and software that was used is as follows:

- ART Trackpack optical tracking system
- NVIS ST50 VR/AR headset
- Flystick2 3D mouse
- Dell NVIDIA Quadro K5000 workstations
- Optoma HD 3D stereo projector
- Dual screen displays
- Laptops, tablet devices
- Virtalis Visionary Render

There are two key devices used in this work for direct manual interaction:

- For navigation: a system of eight cameras for tracking position and orientation of the sensors attached to various human body points to transfer the real movements to the virtual scene
- For manipulation: flystick for the activation of motions by means of the events associated with each of the eight keys.

Although the simulation manager is fundamental to the framework, it is independent and the choice does not influence the framework. The simulation manager is responsible for data preparation, scene preparation, developing environment, and assembly/disassembly simulation. Previous work, [18], used Virtual Design 2 (by vrcom) as its simulation manager.

In order to support the maintainability analysis and manufacturing systems simulations a knowledge base is developed for this framework including the assembly and disassembly criteria. This knowledge base as well as manufacturability methodologies ensures that the framework achieves maintainability driven design for manufacturing. The criteria are illustrated in Figure 1 including specific parameters such as tolerances, as well as common parameters, e.g. sequences and tooling required for the analysis of the operations.

The framework has the capacity to use the knowledge base and methodologies along with the simulation manager to create the virtual environment for both maintainability analysis and manufacturing systems. It also supports immersive interaction with the user and creates output parameters such as collision detection, feasibility of operations, ergonomics evaluation and operation time estimation. The framework is validated through two manufacturing applications in the following section.

4. Case Studies

The VR_MATE framework has been implemented in two case studies to demonstrate its unique ability to allow for both maintainability tests and assembly analysis of an aircraft carriage and a railway coach cooling system respectively. The framework can be used according to the requirements specified by the user during development of the virtual environment, Figure 1.

The development of an interactive environment has been designed to take advantage of the VR instrument during *Design Review* sessions. In particular, the system was intended to be used even by inexperienced VR users, such as workers assigned to the maintenance operations. Moreover,

the environment was oriented to study complex systems with large dimensions, such as trains or aircraft in real scale: with this aim, for example, the possibility to select any component of the assembly, directly pointing it in the scene, is given.

4.1. Railway Coach Assembly

VR_MATE has been used to simulate the assembly operations of cooling systems on a railway coach. The assembly analysis is focused on specific components chosen from the list of assembly activities. In particular, operation 8, 'insert pipe' is described and illustrated in Figure 2.

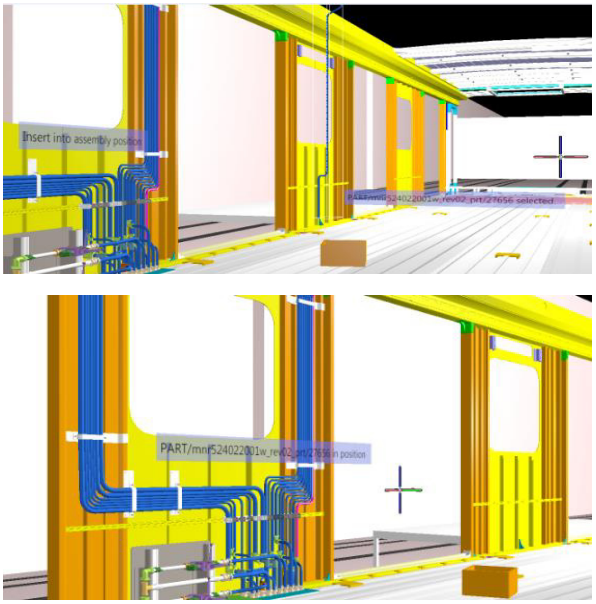

Fig. 2 Operation 8 - 'Insert Pipe'

The 3D models have been designed in ProEngineer (PTC) and imported to Visionary Render having prepared the scene and geometries for simulation. Light sources were introduced and materials associated to each part by means of colour and texture to improve the realistic effect of the scene. A small table was positioned near the railway coach where the tools used in the simulation have been placed.

In order to assemble the pipes it is necessary to position and fix brackets to the chassis of the coach. The digital models of the tools used for this assembly were introduced from the box tools. The preliminary phase of the study has been focused on verifying the prescribed volume of access to allow the operator to perform the action of screwing the bolts. The assembly operations listed in Table 1 have been simulated in the virtual environment allowing the user to validate the feasibility of the entire compilation of sequences. Particular verification of detachability, accessibility and manipulability were achieved. The results of the assembly simulation in Jack software are presented in Table 1.

The predetermined time (PT) output from Jack has been corrected according to the number of 'breaks' in the simulation a time for each assembly sequence is calculated. A 'break' is a pause in the operations of the assembly. 'Cr' corrections are those which have been calculated according to the posture of the operator when completing the operation sequences. These corrective indices are developed from previous work on improving MTM-UAS [18]which account for the effect of critical postures of the operator on the time taken to complete an operation sequence. The cumulative total for the assembly operation, when posture and breaks in the operations were accounted for was 37min 05s.

Table 1 Assembly operations of railway cooling system

Seq. No	Description	PT (s)	Corrections Breaks (s)	Corrections Cr (s)	Time (s)
1	Pick up tools and components	12.7	1.1	2.8	16.7
2	Insert track	2.4	0.2	0.5	3.1
3	Secure with M8 bolt	351.2	31.6	84.3	467.2
4	Fix brackets with drill	36.7	3.3	8.8	48.8
5	Position brackets	14.1	1.3	3.4	18.7
6	Secure with huck rivet	31.0	2.8	7.4	41.2
7	Position brackets	49.8	4.5	11.9	66.2
8	Insert pipe	553.6	49.8	132.9	736.2
9	Test pipe alignment	2.8	0.3	0.5	3.6
10	Tighten band positioning	281.5	25.3	67.6	374.4
11	Tighten pip and joint	227.1	20.4	54.5	302.1
12	Insert pipe assembly	109.0	9.8	26.2	145.0
Total Time		1671.9			2223.1

This output result has been obtained having fully implemented the VR_MATE framework, using knowledge of the assembly process as the input, selecting correct assembly criteria, developing the virtual environment and simulating the assembly process. The assembly operation has been verified in terms of feasibility of operations and time to complete operations.

4.2. Aerospace landing gear disassembly

The case study is an aircraft (The Sukhoi Su-30), which has a twin-engine, two-seat super-maneuverable fighter aircraft. The fighter is designed for all-weather, air-to-air and air-to-surface deep interdiction missions. The case study was offered by an important aerospace company, to verify, in the preliminary design phase, the maintainability of components of service systems. VR_MATE has been used to define the

optimum disassembly operations of the landing gear. Figure 3 demonstrates disassembly of the wheel and the brake disks.

The disassembly specifically concentrated on the landing gear subsystem. The 3D models were designed in CATIA V5 by Dassault Systemes and imported to Visionary Render. In this process the scene and the geometries for the simulation were defined. Figure 3 provides an overview of the aircraft and the landing gear subsystem.

Visionary render allowed to breakdown the components represented in the digital model through the box tools. Each part removed was positioned near the aircraft on a small table. The preliminary phase focused on identifying the steps in disassembling the landing gear. The sequence involved the disassembly of the following components:

- Bearing
- Washer lock
- Rim cover
- Rim cover screw
- Tyre tube
- Inner axle inside
- Cooling fan dock
- Cooling fan
- Cooling fan cable
- Outer axle
- Brake pads
- Brake pad lock mount

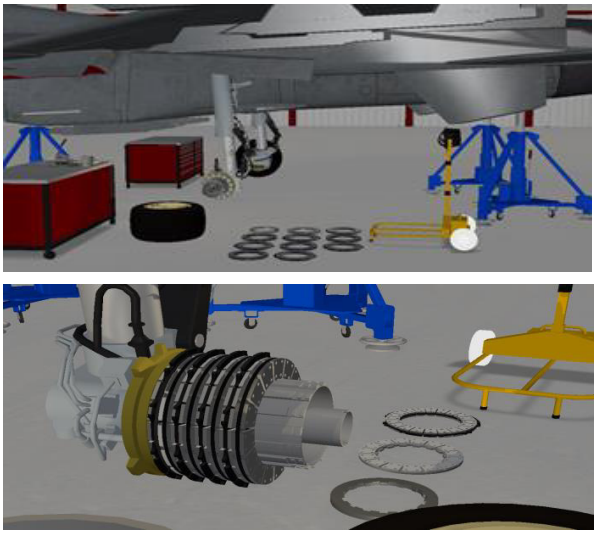

Fig 3. Disassembly of the wheel and brake disks

The simulation demonstrated the sequence that needs to be followed and that parts are detachable, and accessible. For this case study the VR_MATE framework was applied for disassembly purposes without prior knowledge of the sequences as in the previous case study. The simulation determined the optimum sequence of disassembly operations and verified them in terms of their feasibility.

5. Discussion

VR systems help designers analyse assembly and disassembly activities in the early stages of the design process and can support with saving resources for testing the real processes. The user interface for the assembly and disassembly allow users to operate in a natural manner.

The aim of this work was to examine the applicability of immersive virtual reality (VR) technology to early stage of assembly design and manufacturing process development. To successfully implement virtual reality in conceptual design required a considerable insight into the way that assemblies are designed, manufactured and modelled in industry. Gaining this insight established the underlying importance of automated modelling systems that can incorporate virtual reality as early as possible in product development. This approach offers a valuable link between design and manufacture, providing the design engineer with the valuable insight into knowledge of the manufacturing processes and vice-versa. This correlating design approach means that vital, early communication between engineers is possible and can reduce the number of errors in design between parts and fixtures for assembly and disassembly.

Virtual reality software is typically developed for the gaming industry where key operating functions differ significantly from those required to engineer complex systems. Significant effort was required to develop a realistic engineering environment for the purpose of evaluating product and process concepts.

The VR_MATE framework set for this work presents the following benefits:

- Uses knowledge base and design methods to create a virtual environment for both assembly and disassembly operations.
- Creates output parameters e.g. collision detection between parts and feasibility of operations.
- Supports immersive interaction with the users.
- Ergonomics analysis thought direct manual interaction and operation time estimation.

These early results indicate that by implementing the work-cell i.e. fuselage panel and assembly fixture into an immersive environment the process designer can learn more effectively through enhanced interaction functions. The CAD models provide sufficient data for an engineer to visually inspect part designs; virtual reality adds another dimension for the engineer to retrieve vital information as to the accessibility and reachability required for assembly. It is possible to quickly view and inspect the generated fixture design of a specified fixture dimension on a graphics screen for likely design issues such as interactions. A major advantage is that there are no knowledge or computer skills required to work within the immersive VR environment. Using HMDs offers a relatively high resolution approach that is sufficiently flexible for design purposes.

This paper adopts active VR interaction, which offers advantages in allowing humans to interact with objects. The immersive environment allows the engineer to analyse the

design of complex systems in the 3-dimensional environment. This means that the engineer can gain a better understanding of the designs as well as explore the available access required for assembly and disassembly operations.

6. Conclusion and future work

The VR_MATE framework has been implemented on complex systems, both the railway coach and the aircraft carriage to demonstrate its use within industry for multiple applications despite the subjective nature of the simulations. It has been demonstrated as a tool to simulate and validate both assembly and disassembly procedures. The framework has successfully facilitated system level investigations into assembly times and disassembly sequence planning identified as its unique feature.

The examples presented here are at a systems level and VR has been used in a top down approach to support that level of investigation. Future work can address product level investigations supported by the framework. This will require intelligent model creation that when integrated within the simulation manager will contain relevant product information to allow for more in-depth investigations, for example the effect of tolerances on product assembly. This incorporation of VR in early stage design will drive more cost efficient changes that promote better manufacturing scenarios.

Future work involves developing an approach to introduce mannequins to enhance the demonstration of industrial tasks. This could further help with meeting industrial targets around reducing product development cycles and cost. Use of mannequins is especially relevant when there is human involvement, which can help with demonstrating a range of factors such as safety, feasibility, cycle time, and the comfort. VR offers the opportunity for multiple people to interact within the same environment. Although, the presented simulation is designed for a single user, to interact with the virtual world, the authors acknowledge for future work the need for a number of users interacting in the same virtual domain for performing a common goal.

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