Description of a Haptic System for Virtual Maintainability in Aeronautics

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Abstract

This paper describes a Haptic system for maintainability simulation in Aeronautics, called REVIMA (Virtual Reality for Maintainability). In this project a software-hardware tool is designed and built to realistically simulate assembly-disassembly operations. It also helps to perform accessibility, interference and maintainability analysis by using virtual reality techniques without physical mock-ups. The system gives the user a reliable and realistic response. In order to achieve these requirements, the device has a workspace similar to the size of a turbo-engine. In addition this workspace can be placed in different positions to study ergonomics aspects of the simulated tasks.

1. Introduction

In the field of Aeronautics the term Maintainability is defined as “the ability of an element to keep in service or to be returned to adequate status in order to develop its function, after being maintained at conditions previously established, using the personnel, the means and adequate procedures”\cite{1}.

One of the most relevant aspects of maintainability concerns man and tool accessibility task analysis, which is undertaken in order to calculate paths and assembly-disassembly sequences and times.

Design based on electronic mock-up is widely used in the creation of engine externals (piping, harnesses and installations) by the aeronautics industry. Pipes and harness are routed over these parts and accessories are installed by means of a workstation network. This allows a group of designers to work quasi-concurrently over an assembly, copying and automating the original process. This technology is known in the industry as DMU/DPA (Digital Mock Up / Digital Pre-Assembly).

DPA/DMU technology has overcome the need for a hard mock-up for design purposes, significantly decreasing time-to-market and thereby saving money. However, nowadays the use of a physical mock-up is mandatory in order to evaluate the maintainability of externals during the development stage. Although these mock-ups can be used for other applications, the ultimate purpose of the construction is to check the maintainability. The expenses of these mock-ups led ITP to research an alternative using haptics.

\textbf{Figure 1: Maintenance operation on an aircraft-engine (Photograph Courtesy of Rolls Royce)}

ITP is the exclusive supplier of low-pressure turbines for Rolls-Royce engines of greater than 35,000lbs of thrust - primarily the Trent engine family. It is also the Spanish participant in the EJ200 engine for the Typhoon Eurofighter, and earlier this year became a 13.6\% shareholder in the TP400 engine programme for the A400M European military transport aircraft.

Dressings and Maintainability design areas have always aspired to do away with -partially or totally- the physical mock-up, at least during the development phase. During production, the first production engine serves as a physical mock-up.

The main aim of this project is thus to develop a haptic device that can be used as a tool to predict the maintainability of an aircraft engine. One of the main advantages of this development would be that mock-ups were no longer needed for this purpose, leading to important cost savings in the development of a new engine.
2. Description of the system

REVIMA is a haptic system developed to check the maintainability of aircraft engines. The system has been created from scratch by CEIT Applied Mechanical Department. This is a multidisciplinary development that includes, amongst others, the following disciplines: mechanical design, control theory, computer graphics, computational geometry and human-machine interaction.

The research involved in the project concerns two main areas: mechanical design and software development. Both of them deal with important challenges since system maintenance simulation needs to be very close to reality.

One of the main targets of the mechanical design was that the workspace of the device should match that of an aircraft engine. At the same time, any haptic device had to have low inertia. Both requirements have been achieved by combining mechanical design with significant sensible use of a force sensor. The need of large workspace was established by ITP to perform ergonomic studies. This design is explained in section 3.

![Figure 2: Photo of the CEIT LH1fAM in a virtual maintainability operation on a CAD aircraft engine model](image)

In turn, software development has involved the integration of a fast control loop that reflects force to the operator, the evaluation of collisions, and the visualization of the scene. The two last tasks are especially difficult because of the enormous size of the model (more than 2 million triangles). Section 4 describes this integration.

3. Haptic interface

The Large Haptic Interface for Aeronautic Maintainability (LH1fAM) which has been developed, is an example of nonportable force-feedback hardware. The most prevalent forms of force feedback interfaces in use today, are desk-grounded masters [2]. The system that this paper presents is floor-grounded due to the large workspace needed for the maintainability application. In fact, the basic workspace of the haptic interface occupies a cylindrical sector, which corresponds to a wide work area of a virtual 3D aircraft engine full-scale mock-up.

The dimensions of the basic cylindrical work-space are: internal radius, 242 mm; external radius, 772 mm; depth 1500mm; angle, 120°.

The system provides force feedback in three translational degrees of freedom while three additional orientations are measured, but not actuated, by a special wrist. The 6 DOF are obtained as follows:

The kinematic configuration of the three translational degrees of freedom is PRR, consisting of one prismatic and two revolute joints. A variant of a parallelogram mechanism is used, mounted on a commercial linear motion-rolling guide to obtain the largest displacement (about 1.5 metres).

A Roll-Pitch-Roll wrist provides the three orientations. These are measured by high-resolution encoders (2048 cpr). A classic design of the RPR wrist has been compacted to obtain a robust and light (less than 140gr) device to measure the orientation of the virtual tool.

The end-effector is cylindrical-shaped and can be held like a pen (for increased dexterity) or like a handle (for increased power). It is designed to be interchangeable between different shapes to reproduce several ways of holding operation tools.

![Figure 3: Main parts of the haptic interface.](image)
DC brushed motors with encoders transmit torques to the linkages through pre-tensioned cable reductions. To obtain the linear motion of the prismatic joint, a special cable transmission has been developed and tested, providing high performance.

The maximum providing continuous force capability of the device is about 16 N, while the limit of the peak force is about 70 N. The nominal resolution is 0.02 mm at the end effector.

An interesting design feature of the LHiFAM is that its workspace can be relocated: to reproduce different maintainability operations and check different situations from an ergonomic point of view, the basic cylindrical sector can be reconfigured as shown in Figure 4. The linear-motion-guide is supported by two columns, which allow the system to be placed at different heights, depending on the required maintainability task.

This is possible, without decreasing its dynamic properties, thanks to the special characteristic that the mechanism presents. The centre of gravity coincides with the pivotal point over the linear-guide for any position of the mechanism. To obtain this counterbalanced system, the DC motors are specially arranged on the parallelogram structure, which is also built using advanced structural materials.

4. System Architecture

The software of REVIMA is based on C++ and OpenGL Graphical Library. It has been developed using Microsoft Visual C++ and Microsoft Windows 2000 OS. This has represented a challenge because Windows 2000 is not a real time OS but it has advantages of cost, easy support and management, and software development tools.

The system runs in 2 PCs. One (control PC) is in charge of executing the control loop to command the LHiFAM. The other (simulation PC) runs the main module, the Graphical User Interface (GUI), the collision solver and the graphics engine. Both PCs are interconnected through an Ethernet LAN network using the UDP network protocol. This type of architecture is also used in [3] and [4].

The computer that controls the haptic interface is a 233 MHz Pentium II CPU. A dual processor (two 866 MHz Pentium III Xeons with an Intense3D Wildcat 4210) runs the simulation. Collision detection is executed in one dedicated processor of the simulation PC.

The scheme of the system architecture is presented in Figure 5.

![Figure 5: System Architecture](image-url)
independent modules encapsulated in DLLs to improve their development and support.

The software modules mentioned earlier are described below.

4.1 Simulation PC modules

The main module synchronizes several events: the GUI, the 3D scene visualization, collision detection and the reception of messages from the Control PC. This is achieved using a standard defined interface.

The visual engine needs to exceed 20 frames per second to achieve the application’s requirements and obtain a good interaction with the user. This module uses several culling techniques and graphical database optimizations.

This module receives periodically, at a frequency of 1 kHz, the user position from the control PC. Since this frequency is higher than the visual module’s rate, only the last position received is taken into account.

Due to the high frequency of the control loop, collision detection should have as fast a rate as possible. Efficiency has been preferred to saving memory. Therefore, algorithms have been chosen on the basis of spatial partitioning by means of voxels [5]. These algorithms use large amount of memory but are very fast (the access to the voxels is direct as against the search system of some hierarchical methods). In addition, the Boeing Company has experience in projects employing this kind of massive virtual environment [6].

For maintainability and accessibility, faithful reproduction/representation of the contact is critical. This module obtains good results because the structure stored reaches the triangle level, i.e. the maximum level accordi

![Figure 6: Graphical representation of the collision information](image)

Another essential part of the collision module is the computation of the necessary information to obtain the most realistic force possible throughout the LHFAM. All the computational effort is expended in the collision module and only minimal information for the control loop is sent off minimizing the network traffic.

This computational cost arises from calculating a direction or contact normal and a penetration. With these values, the LHFAM can obtain a direction and magnitude for the feedback force.

Figure 6 shows a visual example of this computation.

Besides these two values, the simulation PC sends the user-position, employed to calculate the penetration, through the network to the control PC. This value is necessary for the algorithm of the control PC.

4.2 Communications

There are several reasons to choose the architecture of two PC’s connected by Ethernet. The most obvious relates to efficiency. To control the LHFAM, a control frequency of about 1 kHz is proposed. Since an application of this kind needs to run with real-time priority, it can have problems if other modules are running in the same machine at the same time.

Other reasons include:

- Reuse of the haptic in any application using the defined standard protocol.
- Disposition of a control PC to connect different devices to the application REVIMA.

As previously mentioned, the two PC’s communicate by UDP. The disadvantage of this protocol compared with TCP is the lack of reliability of the messages received. In this kind of real time application this isn’t a disadvantage because the loss of a packet is unusual in a point-to-point connection via Ethernet. The sender has a much higher frequency than the receiver, which takes the last packet, received.

These messages are normally exchanged across the network. The system also has a second communication “control” channel, which it used for very specific control messages. This channel uses the TCP protocol because reliability is required rather than speed. Examples of this kind of message include: the remote execution of the control loop from the simulation PC, messages to take and release different pieces of assembly, notification from the control PC to the simulation PC of problems with the LHFAM as the excessive heat of the motors, etc.

4.3 Control PC

The control loop, located in the control PC, has a sampling period of 1 kHz. According to the studies of Shimoga [7] the majority of authors choose one sample frequency of either 500 Hz or 1 kHz.

This control module acquires the position of the robot manipulator and sends that information to the simulation PC.
The collision forces are calculated according to the actual user-position, the last collision information received (note that the collision solver runs at a slower frequency) and the contact model in use. Figure 7 shows the parameters received from the simulation PC: the contact normal \( \mathbf{n} \), the penetration \( x \) and the tool position \( \mathbf{p} \).

\[ \text{Figure 7: Collision information} \]

The contact model used in REVIMA is a simple spring [8]. The collision force is directly proportional to the penetration of the virtual tool in the environment. The stiffness, \( K \) of the model is selected experimentally to be as high as possible, whilst maintaining stability. This stiffness is quite low (1 kN/m) because the workspace of the device is very large. Joint stiffness (in Nm/rad) is divided by the square of the arm length at the end-point (in N/m). A different model that includes virtual damping and that permits higher stiffness is currently being studied.

A friction model following based on that described by Salisbury et al. [9] is also implemented in REVIMA.

Since the control loop runs faster than the collision module, several strategies must be implemented in order to avoid brusque changes of the contact force. There are three problems that should be taken into account.

The first one is the delay that exists in the collision information. When a collision message arrives in the control PC, its information is only true for a previous position of the user, not the actual. Knowing the position of the user where that information is true, \( \mathbf{p}_{\text{collision}} \), and assuming that the contact normal, \( \mathbf{n}_{\text{new}} \), has no change, the variation of the collision penetration, \( \Delta x_{\text{delay}} \), can be estimated by projecting the difference between actual and collision positions on the contact normal. This variation is added to the received collision penetration, \( x_{\text{collision}} \), to estimate the actual penetration that must be taken into account, \( x_{\text{new}} \).

\[ \text{Figure 8: Processing the collision information} \]

The second problem is what to do if there is no new collision information in a control iteration. This arises if the collision module is slower than the control loop. In this case, the contact normal is maintained and the penetration is modified by projecting the difference between actual and previous positions on the contact normal. This is represented in Figure 9.

\[ \text{Figure 9: Incrementing the penetration without collision information} \]

The last problem is how to solve the great changes in normal direction and penetration, which can appear every time that new collision information is received. Mark et al. [4] developed a method that calculates \( n \) intermediate penetrations, i.e., intermediate planes along normal direction in their algorithm- in order to reconstitute a smoother force along the \( n \) following sampling periods. In REVIMA a similar intermediate iteration is used, but also \( n \) intermediate normal directions are calculated, as is represented in Figure 10.

\[ \text{Figure 10: Intermediate normal directions} \]

The combination of the strategies described in this section permits sufficiently stiff and smooth touch
simulation even in the presence of several contact points or great changes in the contact surface.

Another important factor that concerns the control loop is the fact that a motor is used in order to aid the user in his/her movement. The result of this strategy is a decrease in the apparent inertia that the user feels.

To achieve this decrease, the force exerted by the user is measured and filtered. The control loop restores a force $K_f$ times greater, so the apparent inertia is decreased $1+K_f$ times. In REVIMA a reduction of 6 times the apparent inertia of the system has been implemented.

5. Conclusions

The main conclusion of this work is that haptics can be directly applied to the industry and that these systems may lead to important cost savings.

The system has shown that it is possible to have a device with a workspace as large as an aircraft engine with low apparent inertia. This matching of workspaces and the ability to relocate its spatial position are especially useful in performing ergonomic studies.

Another interesting characteristic of this system is that CAD models used in design phase are also useful for simulation studies without preprocessing.

The employed architecture of two different control loops (a slow one for collision detection and a fast one for force restitution) has proven to be a good approach to treat the problem of managing large CAD models in real time.

There are two completely developed systems that are being used and validated by ITP.

Future research includes the development of software and hardware for a haptic device with 6 actuated degrees of freedom.

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7. References


2892