# Human-Centred Design Processes in Virtual Environments: Methodologies and Real-Life Case Studies


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## Half-Day Course
## Siggraph 2002
## San Antonio

SAN ANTONIO
SIGGRAPH
2002

# Course Description

**Human-Centred Processes in Virtual Environments: Methodologies and Real-Life Case Studies.**


**Course Organizer**
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Virtual Reality, or "interactive 3D", has gained significant recent support in the design of processes, complex systems, or in rapid prototyping, communication and training all of which demand *real-time interaction* on the part of the human operator. Human factors initiatives in the late 1990s, including those designed to promulgate international interactive media standards (eg. ISO 13407), are now helping VR/i3D developers and system integrators to avoid the historical pitfalls of "technology for technology's sake" and to deliver affordable technologies that *empower* human users in a wide range of industrial and commercial applications. Based on 2 modules, the first dealing with guidelines, standards and analytical techniques for human-centred design, the second drawing upon experiences of putting these techniques into practice in real-world VR applications, the course aims to provide attendees with a foundation from which they can build appropriate processes into their own organizations' practices.

# Prerequisites

Attendees require no prior experience in the field of human factors/ergonomics. Those with some experience of introducing VR into real-world applications, or those considering or assessing VR technologies for their own organization will benefit from the information provided.

# General Topic List

- Virtual Reality(VR)/Virtual Environments(VR)/Interactive 3D ("*i3D*")
- The Pitfalls of "Technology Push"
- Human Factors (HF) Issues – "Remember the User"
- Human-Centred Design Standards – MoD/DoD/NASA and International Sources (ISO 13407)
- VR/HF Methodologies and "Best Practices"
- US & UK Evidence in Support of Human-Centred Design
- US & UK Case Studies:
    - Surgery
    - Aero and Space
    - Defense
    - Automotive
    - Engineering
    - Ceramics
    - Education
- The need for Future Research & Development:
    - Human Performance Metrics
    - Spatial/Temporal Situational Awareness
    - Collective Training
    - Transfer of Training …

# Syllabus

## *Module 1 – Human-Centred Design Processes and Techniques*

| Topic | Presenter(s) | Timeline |
|---|---|---|
| Introduction & Scope: What is Human-Centred Design? | RJS and KC | Start to +10 minutes |
| The Importance of Human-Centred Design In VR and Interactive 3D Graphics | RJS | +11 to +20 minutes |
| Human Factors Standards and Processes Within NASA | KC | +21 to + 35 minutes |
| Emerging International Standards (ie. ISO 13407 - *Human-Centred Design Guidelines for Interactive Systems*) | RJS | +35 to + 50 minutes |
| Information Sources Supporting ISO 13407 – NASA | KC | +51 to + 70 minutes |
| Information Sources Supporting ISO 13407 – Other (aerospace, defence, etc.) | RJS | +71 to + 80 minutes |
| Human Factors Guidelines and Methodologies Specific to Interactive 3D Graphics | RJS | +81 to + 95 minutes |
| Discussion/Questions/Requests for Follow-Up Material | KC and RJS | +96 to + 105 minutes |

## *Module 2 – Human-Centred Activities in Real-World Applications*

| Topic | Presenter | Timeline |
|---|---|---|
| Introduction & Scope | RJS and KC | Start to +10 minutes |
| Recent NASA Experiences | KC | +11 to … |
| Lessons Learned and Research Opportunities | KC | … +50 minutes |
| Recent UK Experiences in Surgery, Automotive, Ceramics, Aerospace and Defense | RJS | +51 to … |
| Lessons Learned and US-UK Research Opportunities | RJS | … +95 minutes |
| Discussion/Questions/Requests for Follow-Up Material | KC and RJS | +96 to + 105 minutes |

# INTRODUCTION

**"Virtual Reality refers to a suite of technologies that support intuitive, real-time human interaction with computerised databases..."**

(Based on definition by Stone, 1996)

Absent from this definition are what many still believe – erroneously – are the two most important features of VR: computer graphics and *immersion*. Indeed, references to these terms occur regularly on Web sites dealing with the possible role of VR in Synthetic Environment-Based Acquisition. The term immersion (or "inclusion") is used to describe the situation where users are supposed to experience a strong sense of *presence* in a virtual world, having either donned a head-mounted, stereoscopic display and/or special forms of instrumented clothing, or having been presented with special projection display systems that envelope their visual field of view. Despite the hype and promises of the late 1980s and early 1990s, technologies delivering a full sense of presence within a virtual environment have not yet been delivered to the VR community. Indeed, as will be mentioned later, having conducted a thorough human factors analysis of the tasks being considered for simulation, it is often the case that achieving immersion is totally unnecessary. The additional omission of the term "computer graphics" or computer generated imagery (CGI) from the definition is also intentional, as CGI emphasises the *visual* nature of the databases with which the human operator may be interacting and ignores other forms of sensory display or relevant media.

The four key issues in this definition are:

(1) **Suite of technologies**. To use a phrase from the business IT community, VR is a **convergence** of technologies including telerobotics, multimedia, computer-aided design (CAD), process simulation, CGI, animation and, of course, human factors and ergonomics. Other component technologies include LAN/WAN networking, digital humans, AI, GIS and so on.

(2) **Intuitive interaction**. The term "intuitive" reflects an ambition of the i3D/VR community in that it has always striven to provide users with a transparent interface that makes navigation within, and interaction with virtual environments as "natural" as possible, thereby avoiding lengthy and costly training in specific computing skills.

(3) **Real-time**. This – the most important feature of VR – relates to the importance of developing local and networked technologies that allow users the freedom to explore and interact with virtual objects and environments without incurring disruptive time delays between their actions (eg. head or hand movement, or any data input device) and the result of those actions (and the actions of others) within the virtual environment.

(4) **Databases**. The significance of VR lies not in the nature of the sensory experience *per se*. (with vision typically providing the dominant channel), but in the structure and behaviour of the data underpinning the real-time experience. At one extreme, an example of an underpinning dataset might be the basic product data or electronic documents associated with a single engineering object. Moving to another level of complexity, the dataset might relate to objects or processes that are impossible to visualise in reality (eg. molecular structures and rigid body or fluid dynamics). At another extreme, software qualities and "intelligence" might be endowed to objects in a virtual environment database, which, together with their geometric and behavioural relationship with other objects, permit an approximation to the nature of their real-life counterparts.

# Why a Course on Human-Centred Design?

Over the past decade, the commercial and industrial Virtual Environment (VE) or Virtual Reality (VR) developer community has experienced many problems as a result of the outrageous claims of the early proponents of "immersive" technologies and the dominance of graphics supercomputer companies. Today, the very fact that a commercial, off-the-shelf personal computer, equipped with a low-cost graphics accelerator can out-perform some of its supercomputer "competitors" – at a fraction of the cost it takes to *maintain* those competitors – has rekindled interest in those commercial and industrial organisations who were once potential adopters of VR for competitive advantage. Today, Virtual Reality, or "interactive 3D" (*i3D*), is gaining stronger support than ever before within organisations involved in the design of processes, equipment and systems, and in rapid prototyping, communication and training.

The successful adoption of VR technologies into organisations, be it for commercial gain, for streamlining operational procedures, or even basic education is not just a case of trying to impress potential users with the capabilities of an exciting technology. Understanding the needs and characteristics of the individual user and his or her organisation is essential to the future development of VR as a stable form of information technology. It is all-too-easy (even for qualified human factors specialists) to fall into the trap of striving for visual and technological excellence at the expense of usability and meaningful content (something many academic VR Centres are doing quite well at the moment), not to mention losing sight of the needs of the user organisation. For example:

> "...many developers (especially in the human factors field) believe that one effect brought about by the existence of advanced [VR] hardware and software technologies has been a reduction in the application of scientific rigour to the design of human-system interfaces. Suddenly, reasonably user-friendly software tools have become readily available which have, in some cases, permitted the designers of information displays to "go to town" in their design approach. The result? "3D works of art" - visually impressive interface formats - but of questionable usability. The drive for visual impact appears to have over-shadowed the crucial issue of

> concentrating on the underpinning human factors issues surrounding the need for sophisticated 3D display formats...".
>
> Stone (1997)

Also, gone (fortunately) are the days when the Virtual Reality salesperson would make such blatant claims as "buy our head-mounted display and all your interface problems will vanish". The quest for the ultimate immersive experience continues unabated, although it is likely that the sensation of total presence within a computer-generated virtual world is still many years, if not a decade or two away. In the meantime it is necessary to suppress the temptation simply to procure the latest and most exciting technologies and concentrate instead on analysing what it is the end user actually requires and the tasks he or she performs. To do this, one must turn to the field of human factors, or ergonomics, for a wealth of experience in task analysis.

Task analysis is a process by which one can formally describe the interactions between a human operator and his/her real *or* virtual working environment (including special-purpose tools or instruments), at a level appropriate to a pre-defined end goal (typically the evaluation of an existing system or the definition of the functional and ergonomic features of a new system). An excellent definition of task analysis was put forward by Bradley of axsWave Software, Inc., based on two IBM documents compiled by Terrio & Vreeland (1980) and Snyder (1991):

> *A task analysis is an ordered sequence of tasks and subtasks, which identifies the performer or user; the action, activities or operations; the environment; the starting state; the goal state; the requirements to complete a task such as hardware, software or information.*

Without a properly executed task analysis, one runs the risk of specifying or designing a VR (or any computer-based training or multimedia) system that fails to record or measure those elements of human skill one was targeting in the first place. One also jeopardises the future integrity of any experimental programme that sets out to validate one's training and assessment concept, not to mention the transfer of training from the virtual to the real.

There is no one "magical" formula for executing a task analysis. The type of analysis employed depends on the human factors specialist involved, whether or not the task exists in reality, the goal of the analysis (eg. are the results required for new system design or training procedures) and any constraints imposed by the analysis environment. It is the author's belief (based on many years of practice) that a task analysis should form an early and central component of any project that involves a major human-centred component. VR projects are no exception.

One important recent development in this respect is the publication of an international standard, ISO 13407 (1999) – *Human-Centred Design Guidelines for Interactive Systems*. This standard specifies 4 general principles of human-centred design and 4 further principles of human-centred design activities, namely:

### *Principles of Human–Centred Design*

**(a)** Ensure active involvement of users and a clear understanding of user and task requirements (including context of use and how users might work with any future system evolving from the project – if at all),
**(b)** Allocate functions between users and technology (recognising that today's technology, rather than de-skilling users, can actually extend their capabilities into new applications and skill domains),
**(c)** Ensure iteration of design solutions (by involving users at as many stages of the design and implementation process as is reasonable practical),
**(d)** Ensure the design is the result of a multidisciplinary input (again this emphasises the importance of user feedback, but also stresses the need for input from such disciplines as marketing, ergonomics, software engineering, technical authors, etc, etc).

### *Human–Centred Design Activities*

**(a)** Understand and specify the context of use (including the characteristics of the intended users; the tasks the users perform, or *are* to perform; the environment in which users use, or *are* to use the system; relevant characteristics of the physical environment),
**(b)** Specify user and organisational requirements (in the context of the present project, this includes aspects of team working, health and safety issues, user reporting structures and responsibilities),
**(c)** Produce design solutions (with multidisciplinary team and user involvement),
**(d)** Evaluate designs against requirements (a continuous process throughout the design cycle).

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# Virtual Reality in the Real World: A Personal Reflection on 12 Years of Human-Centred Endeavour

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**Abstract**

Over the past decade, the Virtual Environment (VE) or Virtual Reality (VR) community has experienced many problems as a result of the outrageous claims of the early proponents of "immersive" technologies and the short-lived dominance of graphics supercomputer companies. Today, the very fact that a commercial, off-the-shelf personal computer, equipped with a very low-cost graphics accelerator, can out-perform some of its supercomputer "competitors" – at a fraction of the cost it takes to *maintain* such equipment – has rekindled interest in those commercial and industrial organisations who were once potential adopters of VR for competitive advantage. This paper is a personal reflection on some of the industrial successes of the past few years or so of VR/VE developments and a constructive critique on present academic and commercial research and development trends.

**Key Words**: Virtual Reality, VR, VE, Human-Centred Design, Task Analysis, Ergonomics, Human Factors.

## 1. Introduction

No more than 4 years ago one could have been forgiven for looking at the Virtual Reality (VR) or Virtual Environments (VE) community, shaking one's head and wondering what had happened to an industry once full of enthusiasm and promise. "A world where your dreams come true…", one was led to believe, delivered by what was described as "…the most important communication medium since television". We were also expected to accept the *de facto* status of head-mounted displays and the notion that "immersion" within computer-generated worlds had become the ultimate in human interface technology for applications as diverse as the training of surgeons or dismounted infantry to the playing of games on domestic PCs or video consoles. Surveys conducted in the UK and the US during this time (eg. CyberEdge 1998, 1999, 2000, 2001; Cydata, 1998, 2000) made reference to – and *still* make reference to – annual markets worth hundreds of millions of dollars, with major expenditure on VR technologies being planned and put in place by many large corporations in such markets as petrochemical, defence, aerospace and automotive. However, for companies at the "sharp end" of trading in VR – those providing simulation and system integration services – this level of investment has still yet to be seen, no matter what their size.

Having said that, this personal reflection has not been written in order to celebrate the passing of VR – quite the opposite, in fact. It provides a snapshot of some of the experiences, results and problems from the world of VR that have helped to evolve the community out of its naïve "technology-push" state of 4-5 years ago to become an industry capable of responding today to significant market pull and, of greatest importance the needs and requirements of today's and tomorrow's IT users. It is only possible to scratch the surface of today's developments in a paper of this size. However, the interested reader can gain a much greater insight into many of the issues contained herein by obtaining a copy of the forthcoming *Virtual Environments Handbook*, due for publication by Lawrence Erlbaum Associates, Inc. in the Spring of 2002 (Stanney, 2002).

Today, Virtual Reality, or "interactive 3D" (*i3D*), is gaining stronger support than ever before within organisations involved in the design of processes, equipment and systems, and in rapid prototyping and training. However, this process is still taking somewhat longer than most would like. Part of the problem is that there is still a concerning lack of awareness as to what VR is and how accessible it has become, despite major awareness initiatives on the part of a number of influential individuals and bodies, such as the UK's Department of Trade & Industry, whose VR Initiative was carried out between 1996 and 1999. Another problem lies in the fact that the *i3D* community is still suffering from the trivialisation legacy of the early arcade forms of immersive VR. Finally, and this is particularly the case for defence-based organisations, when one tries to categorise VR using the IT or computer-based training guidelines distributed by these organisations, their definitions of VR are often restrictive and erroneous. That is, assuming that VR, as a form of technology-based training, is mentioned at all.

Rather than focus on the technology underpinning VR (as this has been well covered elsewhere), this paper asks the question: what are the key issues surrounding the successful implementation of a VR or *i3D* system, with reference to real commercial applications?

## 2. Human-Centred Design

Gone (fortunately) are the days when the Virtual Reality salesperson would make such blatant claims as "buy our head-mounted display and all your interface problems will vanish". The quest for the ultimate immersive experience continues unabated, although it is likely that the sensation of total presence within a computer-generated virtual world is still many years, if not decades away. In the meantime it is necessary to suppress the temptation simply to procure the latest and most exciting technologies and concentrate instead on analysing what it is the end user actually requires and the tasks he or she performs.

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One important recent development in this respect is the publication of an international standard, ISO 13407 (1999) – *Human-Centred Design Guidelines for Interactive Systems*. This standard specifies 4 general principles of human-centred design and 4 further principles of human-centred design activities, namely:

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**(c)** Produce design solutions (with multidisciplinary team and user involvement),
**(d)** Evaluate designs against requirements (a continuous process throughout the design cycle).

One good example of the success that can be achieved by adopting this human-centred design (HCD) approach is the minimally invasive ("keyhole") surgery simulator MIST (www.mentice.com), the subject of a well-documented range of clinical and applied psychological studies since the late 1990s (McCloy & Stone, 2001; Stone, 2001a). Here, detailed task analyses of surgical procedures led to the development *not* of a high-fidelity simulation of a virtual human body (requiring a highly expensive graphics supercomputer), but of a simplified psychomotor skills trainer, hosted on a commercial off-the-shelf (COTS) PC, capable of generating objective student performance records (Fig. 1).

A related human-centred issue in the field of VR and *i3D* is that of the level of fidelity – an issue that seems to be preoccupying the minds of many potential VR adopters involved with technology-based training at the present time. By adopting an HC approach to simulation design, projects such as MIST demonstrate that one can actually solve the problem of what level of fidelity is necessary to deliver meaningful training content, thereby promoting the transfer of training or skills from the virtual environment to the real-world setting.

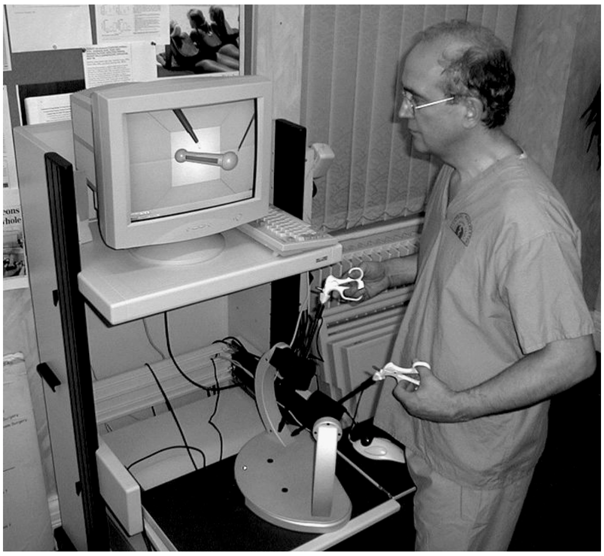

Fig. 1 Minimally Invasive Surgical Trainer, MIST

Another more recent example of the importance of an HCD approach is the TNA scoping project carried out by the author for the NATO Submarine Rescue System (NSRS) Project Definition Study, under subcontract to the Study Prime, W.S. Atkins. Having defined the personnel, equipment and tasks for 3 candidate systems under consideration (manned submersible, remotely operated vehicle or a hybrid system), the HCD methodology led the author to conclude that over 80% of the tasks expected of the NSRS team did **not** warrant *i3D* or any other form of high-tech training.

As the NSRS hardware will probably be available for training throughout a given year (ie. at times when it is not required for deployment on exercise or actual submarine rescue), investment in high-tech training simulators would not, in this case, deliver a cost-effective solution. Where *i3D will* deliver training content of relevance to the end users of NSRS is in the form of a real-time submersible navigation/piloting simulator (Fig. 2), capable of varying such mission-critical, "what-if" parameters as ocean bed turbidity, current strength and direction, submersible propulsion reliability, power failures, surface ship dynamic position-keeping problems, distressed submarine resting angle, artificial lighting sources and so on.

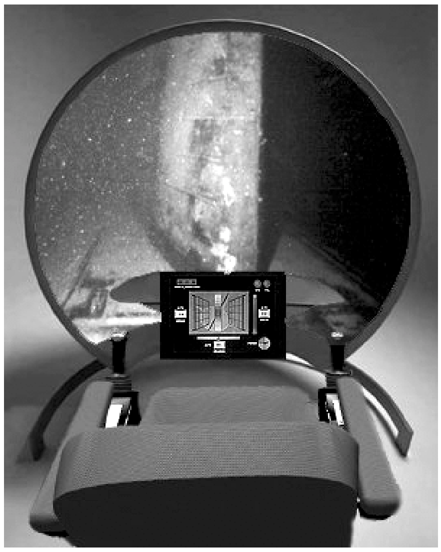

Fig. 2 NSRS System VR Training Concept

## 3. Appropriate Interface Technology

The author's experience of adopting a human-centred approach to *i3D* applications, coupled with the findings of recent market surveys indicate that, of all the various technologies available for displaying and interacting with virtual environments, the ubiquitous keyboard and mouse are still top of the data input league, accompanied by the standard workstation or desktop PC screen for data display. This is testament to the fact that, despite the impressive nature – the "wow factor" – of Reality Centres, CAVEs, back-projected workbenches, head-mounted displays (HMDs), and so on, the majority of *i3D* applications outside of the academic laboratories simply do not actually warrant (and, indeed cannot afford) expenditure on these high-end facilities. Single-screen (wall-size) projection facilities, sometimes using passive stereo (twin polarised projectors) or active stereo (single projector field-sequential LCD glasses) come a reasonable second place to desktop VR. Some of the new high-luminance data projectors are finding favour with those conducting design and project reviews for virtual prototypes on a 1:1 scale with the human observers. HMDs, in conjunction with spatially tracked hand controllers or "wands" (as opposed to instrumented gloves – the "technology of choice" in the late '80s and early '90s) are making a slow comeback, but only in applications where they are used in tandem with other physical components existing in the real world, as will be discussed under "augmented reality" below. One technology that appears to be maturing quite rapidly is haptic (force/touch) feedback, with products such as Sensable Corporation's *PHANToM* feedback device (www.sensable.com) delivering impressive results in areas as diverse as ceramic design, undercarriage maintenance for the A380 and mine clearance training for the French Army.

For example, British companies such as Wedgwood and Royal Doulton, famous international, historical names in the production of quality crockery and figurines, have turned to VR in an attempt to embrace technology within their labour-intensive industries. Ceramics companies and groups, such as the Hothouse in Stoke-On-Trent, are experimenting with new haptics techniques and achieving some quite stunning results (Fig. 3).

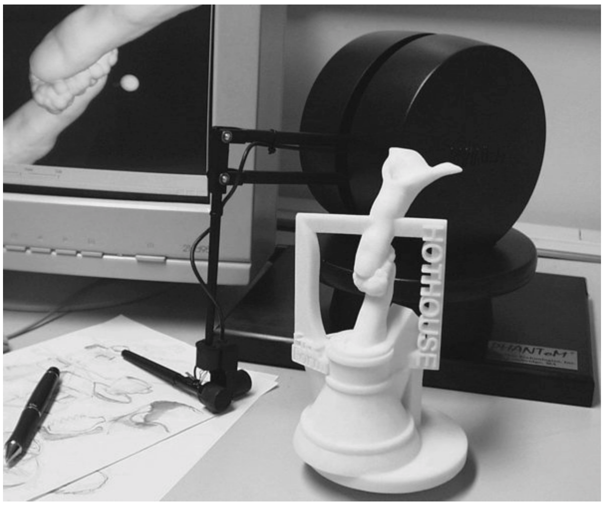


Fig. 3 Virtual and Real Sculptures Created Using the *PHANToM* Haptic Feedback Device

The importance of experiments like these, however, lies not so much in the results but in the people who actually *produce* the results. Talented sculptors – people with incredible manual skills but *no* background in computer technology whatsoever – have, given access to the *PHANToM* and *Freeform* "digital clay" products, started to produce ornate sculptures *within 3-4 days*! Then, using local industrial resources, they have used 3D printing and stereolithography facilities to convert these virtual prototypes into physical examples and high-end VR to display them in virtual showrooms and domestic settings of very high visual fidelity.

Another project is supported under the European Union's Framework V Initiative and is called *IERAPSI*, an Integrated Environment for Rehearsal and Planning of Surgical Interventions. Continuing on the human-centred theme described earlier, an early *IERAPSI* work package related to the analysis of surgical procedures (again based on ISO 13407), specifically focusing on surgical activities underpinning mastoidectomy, cochlear implantation and acoustic neuroma resection (Stone, 2000). The surgical procedures definition and task analyses were conducted in collaboration with the ENT department of Manchester's Royal Infirmary. These exercises resulted in the selection of the *PHANToM* Desktop/1.5A for haptic and vibratory stimuli when simulating the use of pneumatic drill (through cortex and petrous bone) and a second *PHANToM* device for irrigation and suction (Fig. 4).

Fig. 4 The IERAPSI Temporal Bone Training Simulator Workstation

## 4. VE Content

An HCD approach to simulation design will take account not only of the qualities of the target user population and the tasks expected of them, it will also help to optimise the price-performance envelope of the host computing platform. For example, research conducted for the UK's Flag Officer Submarines (FOSM) between 1997 and 1998 considered a number of techniques for delivering virtual SSN and SSBN submarines to naval ratings undertaking basic Submarine Qualification (Dry) (SMQD) training. FOSM, together with other branches of the RN submarine training organisation were targeted by commercial organisations offering quite different solutions to developing a virtual boat trainer, from photogrammetry-derived CAD to custom-built *i3D* models, and from basic PowerPoint or HTML "walkthrough" presentations to digital panoramas (eg.

using Apple's *QuickTime VR*, MGI's *Photovista* and others).

An HCD approach to defining the information actually required by a novice submariner and how it should be delivered (depending on whether the task involved spatial awareness, systems tracing, compartment familiarisation, safety equipment location and operation, etc.) revealed that these content generation techniques could not deliver meaningful training when considered in isolation. What was required was an integrated approach to using simplified *i3D* hull, deck and compartment models, enhanced where necessary by detailed systems representations (high-pressure air, hydraulics, electrics, etc.) extracted from CAD databases (Fig. 5). High visual fidelity can be provided on a selected compartment-by-compartment basis using panoramic techniques, enhanced using individual 3D models of valves, controls and line replaceable units. This solution also guaranteed that the complete SMQ(D) simulation could be hosted on a COTS Windows NT PC as opposed to a dedicated VR computer costing 10 to 15 times the price. These concepts will now be applied to the development of the SMQ(D) element of the new *Astute* Class SSN submarine.

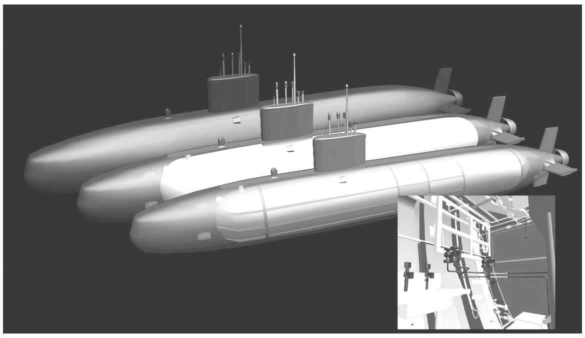

Fig. 5 Spatial Navigation Database for Submarine Qualification Training Derived from CAD

## 5. Augmented Reality

Although based on anecdotal experience at the moment, there is a body of evidence suggesting that the fidelity and "believability" of *i3D* or VR simulators can be enhanced using a variation of what is known as *Augmented Reality* (AR). Throughout research circles Augmented Reality is used to describe situations where users, typically confronted with very complex *real* scenes (patients undergoing surgical interventions, petrochemical plant interiors, etc.), exploit modified immersive VR technologies – semi-transparent head-mounted displays with integrated miniature cameras, for example – in order to superimpose task-relevant virtual data onto the real scene. In fact, this form of AR is still in its infancy and relies highly on the accurate registration of the position and orientation of the user's head to guarantee a match between the virtual and the real (Stedmon & Stone, 2001).

However, there is another, and more mature variant of AR, where elements of the *real* world are used to enhance the (sometimes limited) fidelity of the virtual world. At its most basic level, this demands that students exposed to pure VR training, as in the case of Virtual Presence's Avionics Training Facility for the *Tornado* Maintenance School at RAF Marham, for instance, should (for health and safety reasons at the very least) be exposed to a continuum of actual physical components, such as line replaceable units of various sizes and weights (Stone 2001b; Stedmon & Stone, 2001; Fig. 6).

The choice of appropriate peripheral interface device also falls within this basic level, with the device chosen supporting some degree of familiarity between the user and his or her "tools of the trade", as was found with the sculptors when using the *PHANToM* haptic feedback system, described earlier.

Fig. 6 RAF F3 Tornado VR Avionics Trainer Database

Taking this one step further, however, is there merit in using basic physical mock-ups of actual systems in conjunction with VR? On a simple level, the French Army mine detection system mentioned briefly earlier is based on a COTS haptic feedback system modified to support a standard ground probing stylus. As another example, the mobile excavator company FERMEC uses a cut-down version of a real backhoe digger cab seat, complete with joysticks, to augment the experience of their immersive virtual prototypes during design reviews and introductory training. Many of the automobile companies use seating bucks in combination with immersive VR to evaluate the ergonomic and aesthetic aspects of proposed car interiors. By realistically constraining the user's posture and providing them with interior surfaces that double as a form of tactile cue or "reach delimiter", the visual VR experience becomes much more convincing than if the user had been provided *only* with a visual VR experience delivered via an HMD.

In the naval training sector, a good example of real equipment augmenting the synthetic experience is the Close-Range Weapons Simulators commissioned by the RN's Naval Recruitment & Training Agency (NRTA) for HMS Collingwood in the south of England. Here, 20/30mm weapons aimer and director students don head-mounted displays and are presented with a synthetic environment, creating the effect of being located on the port side of a generic Royal Navy vessel. The aimer's task, under conditions of variable sea state, precipitation, fog and time-of-day, is to engage surface and airborne threats under the instructions of a Weapons Director Visual (WDV). The VR headsets used – Kaiser *ProView* XL-50s – do not fully enclose the eye orbits of the students, as would other headsets. Instead, their design affords students some peripheral vision in both azimuth and elevation. As well as the VR environment, students interact with *real* weapons hardware, made available when the original shore-based training facility near Plymouth closed down earlier in 2001. In the case of the 20mm GAM BO weapon, the aimer is normally strapped into the shoulder rests, thereby helping to maintain a fixed relationship between the eyes and gun sight (Fig. 7).

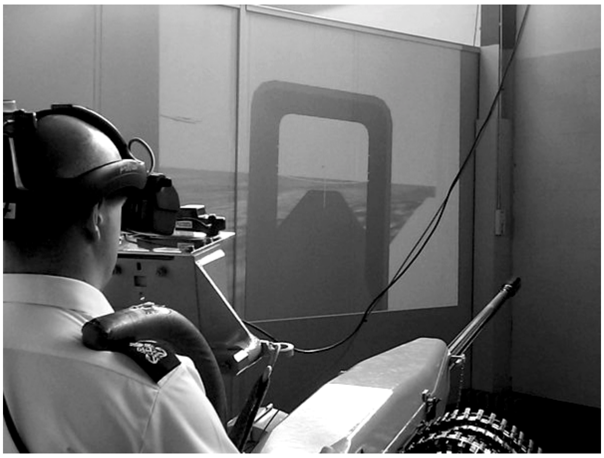

Fig. 7 Royal Navy Semi-Immersive 20mm Close-Range Weapon Trainer

As the sight is not present on the RN's simulation facility weapon, both the gun and the aimer's head have to be tracked in order to preserve this visual relationship. Also, as aimer looks around, other parts of the virtual ship come into view, including a virtual Weapons Director Visual supervising activities from a raised Gunner Director's Platform (GDP).

In a similar vein, the WDV (also equipped with a headset) can look down from a physical mock-up of the GDP (Fig. 8) and view the virtual aimer strapped into the virtual gun. The Kaiser HMD design enables the aimer to view parts of the real weapon peripherally, including the firing mechanism and gun locks.

Fig. 8 WDV With HMD on Platform Above Weapons Aimer

This further avoids any problems of disorientation that might be evident with a headset that enveloped the eyes completely. Similarly, in the MSI 30mm gun example, where the aimer actually sits at a small weapon control panel, the VR headset affords visual access to the real panel, as well as displaying it in the virtual reproduction of the weapon. Real visual access is achieved by glancing down (eye movement only), whilst the virtual panel comes into view when the aimer's head rotates downwards.

## 6. Assessment and Evaluation

One of the important features that should be considered by the sponsors of virtual training systems is an ability for their commissioned software to perform human performance data recording with some degree of early analysis and evaluation. In the case of those simulators designed according to human-centred principles, the definition of key performance parameters and the integration of software modules to collate relevant data for post-session analysis (and **not** just playback for debrief purposes) is reasonably straightforward. The MIST example described earlier is one good example of this concept and has been used by the author's company to develop *FrameSET*, a self-contained modular software architecture that can be adapted to future training systems, both stand-alone and networked, to provide a complete pedagogical service, from simulation parameter set-up to data collection and analysis (over the Internet if required; Fig. 9). Another example can be found in an ROV simulator developed by Imetrix Inc of Cataumet, US. *ROV-Mentor* collects and presents data on performance objectives that were developed from extensive task analyses and studies of expert submersible pilots.

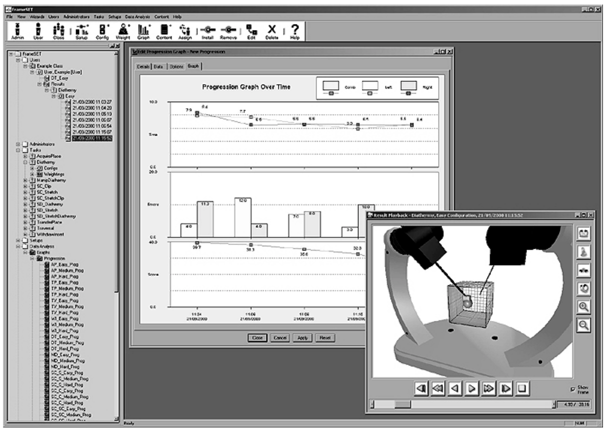

Fig. 9 *FrameSET* Screenshot Example During Replay of Surgical Student's Task Performance

Unfortunately, however, this is an area that warrants much more attention than can be given by commercial VR companies and offers an exciting opportunity to the academic community to research and develop usable, pragmatic tools that enable defence training organisations to evaluate their VR simulators, generating objective measures of situational awareness, transfer of training, information recall, and so on.

It is a regrettable fact that many of the world's so-called academic centres of VR "excellence" have, to date, been preoccupied with possessing and announcing the biggest and best equipped VR facility. This has meant that quality research ideas and programmes, focused on the needs of the wider VR user community, have not been forthcoming. There are a handful of notable exceptions to this rule, but surely it is now time for the industrial and defence communities to demand much closer involvement with – and supervision of – university-based VR teams to make sure that their efforts take full account of what is happening in the real world of *i3D* and simulation.

## 7. VR Software, Standardisation and Reusability

Within various government ministries at the present time (industry, trade, defence, etc.), there is much talk of the importance of centralising digital resources in order to promote standardisation across their particular community in everything from *e-learning*, distributed simulation, 3D computer-generated models and simulation code to Smart Procurement and Continuous Acquisition and Life-Cycle Support (CALS). Focusing on the VR community, one of the major problems faced in trying to accelerate such a standardisation across the defence industry is the fact that, over the past 12 years, there have been so many different approaches to 3D graphical modelling, Computer-Aided Design (CAD) data conversion, VR database management, real-time rendering and distributed simulation. Some historically well-known VR companies have ceased to exist simply because of a change in emphasis by larger suppliers of their core real-time software system.

Returning to the issue of fidelity, it is always interesting to witness the behaviour of domestic computer games software users and how, from a psychological standpoint, they manage to achieve *full immersion* in their endeavours without the use of sophisticated HMDs or video projection facilities such as CAVEs. Today, every computer-owning parent will be able to recall many instances in which an addictive first-person "shoot-'em-up" game has induced "tunnel vision" and focused auditory attention in the young computer specialists of tomorrow! Titles such as *Project IGI*, *Delta Force*, *Operation Flashpoint*, *Soldier of Fortune*, and e-Sim's acclaimed *Steel Beasts* tank simulator spring to mind in this respect – all of which, quite frankly, put some of today's expensive *i3D* simulations to shame in terms of visual quality and combat effects.

But even before these graphically detailed covert operations and mercenary publications burst onto the scene, many will remember *Battlezone* – a wire frame tank game published in 1983 for the Atari, or *The Colony* – a space survival game created in 1988 for the Apple Macintosh by David Smith (also the founder of Virtus Corporation in 1990 and accredited with developing the first VRML Internet tool kit in 1995). Then there was the revolutionary *Wolfenstein* (1992, soon to be relaunched as *Return to Castle Wolfenstein*), *Doom*, *Quake*, *Hexen*, *Heretic*, *Unreal* and *Half Life*… the list goes on. The graphics may appear crude and simple. But as long as the user's attention is captured and he or she is required to maintain a spatial and temporal awareness of the 3D situation in order to survive within the scenario, and as long as the simulation responds meaningfully in real time, a training simulator can be designed to deliver valid, reliable and believable content to highly motivated students of all ages and skills.

Virtual or synthetic environments delivered using games software must no longer be thought of as a trivial or unprofessional solution to the needs of *i3D* or VR developers. Evidence suggests that computer games actually improve logical thinking, strategic planning, observation skills, problem solving and many other cognitive and psychomotor skills. Some companies are now even supplying simulators for nuclear control room activities, chemical plant maintenance and offshore platform evacuation training, based on, for example, Epic Games' *Unreal* engine (www.epicgames.com/unrealenginenews.html). Epic's latest *Unreal* engine, codenamed *Warfare*, has been used by researchers in Gifu, Japan and the US to develop a brand new action/strategy game called *Devastation* (due for launch in 2002) and was the underpinning technology for an impressive synthetic data fusion demonstrator based on a dynamic climatic model of Snowshoe Mountain in West Virginia (Thrane Refsland, 2001). The Snowshoe demonstration uses satellite data, environmental sensors and real-time GIS data to render large-scale, virtual environments that foster virtual life and natural behavioural conditions (Fig. 10).

Fig. 10 Virtual Snowshoe Dynamic Climate Demonstrator (courtesy Scot Thrane Refsland)

Only now are VR developers following the practices of games developers in exploiting emerging graphics acceleration hardware and adopting, for example, industry-standard, cross-platform applications programming interface (API) standards such as OpenGL. Also, the archiving of synthetic 3D models in robust formats such as VRML (Virtual Reality Modelling Language) finds favour with many VR developers, reducing the size of models built using such packages as 3DS Max to a level compatible with Internet sharing and review.

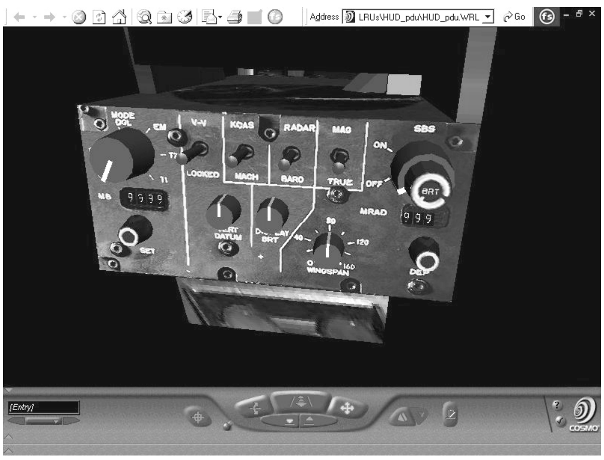


Fig. 11 Part of the RAF F3 Tornado Head-Up Display Archived as VRML (.wrl) and Viewed Via *Cosmo Player*)

The line replaceable units developed for the RAF's Avionics Trainer, mentioned earlier, were all archived in VRML and were therefore capable (subject to classification) of being e-mailed to the prime contractor and end users for visual QA approval using a free down-loadable 3D browser (*Cosmo Player* – Fig. 11 – or *Cortona*). As for operating systems, the jury still seems to be out on the issue of NT or future Windows releases *vs*. the Unix family (including Linux).

All being said, the evolving *real* commercial interest in VR for training and design is producing a number of software applications which, suitably managed, could bring major benefits and cost reductions to future training contracts by reusing real-time code and 3D models. For example, in the case of developing a VR helicopter search-and-rescue training system (a project started in October of 2001; Fig. 12), the re-use of the virtual ocean, time-of-day and weather simulation modules developed for the Royal Navy's gunnery trainer, described earlier, is saving considerable project time and money.

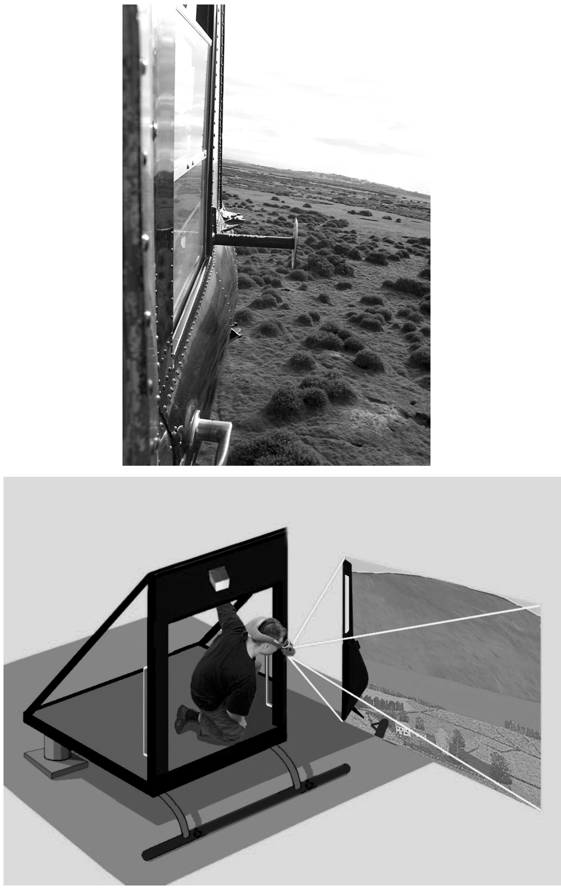

Fig. 12 RAF Voice Marshalling VR Training Concept (Upper Image Shows Actual View from Griffin Helicopter)

Returning to submarine training, it has been recommended that the future developers of virtual environments for the *Astute* class submarine and, if accepted, the new NATO Submarine Rescue System (NSRS) take full advantage of *i3D* efforts being expended in both areas. Then trainee submariners would be able to rehearse emergency evacuation from their virtual *Astute* SSN into a virtual NSRS system, as well as the NSRS pilot gaining experience in mating with that class of vessel. These are just simple examples that scratch the surface of a truly integrated digital service for future industries – from defence to aerospace, from heavy engineering to education.

## 8. Conclusions

Overall, recent developments in VR or *i3D* have been very encouraging indeed (Stone 2001b). Examples of the potential contribution virtual or synthetic environments occur with increasing regularity in texts inviting companies to pre-qualify for a particular study or development project, even with the impact of falling budgets in certain sectors. Potential industrial or commercial VR users need no longer be shackled by over-priced, high-end/high annual maintenance computer architectures and display peripherals. They can now rest assured that a major proportion of the design or training applications in which they are interested can be delivered using COTS PC hardware with sub-$600 graphics cards. Content development costs are on a par with Computer-Based Training (CBT) offerings and, in the majority of cases, are significantly cheaper, with minimal resources necessary for through-life support – annual maintenance and technology refresh, for instance.

Eight years ago, the author wrote a paper entitled "Virtual Reality Comes of Age". With hindsight, that title was wildly off the mark and optimistic. Today, however, the foundations are in place to help VR "come of age" and, with some reality-focused effort on the part of the academic community, VR is set to deliver quality defence training and simulation facilities for many decades to come.

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# Contents

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# Document control

| Document details | |
|---|---|
| Report title | Report on 3D representations for tactical displays |
| Author | Professor R.J. Stone |
| Project | Advanced military interfaces |
| Contract | CHS0/5002S |
| Deliverable | Deliverable 1 |
| Client | Centre for Human Sciences, DERA |
| Location of master | Gregory Harland Ltd in GHL Technical Library |

| Change history | | |
|---|---|---|
| Date | Version | Details |
| 3 Feb 97 | 0.1 | Draft for Review & Approval |
| | 1.0 | Initial release |
| 31 Feb 91 | 2.0 | Final release |

| Authorisation (for release versions) | |
|---|---|
| Signature | |
| Name | Dik Gregory |

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# 1 Introduction

### Study context

1.1 This report constitutes the final deliverable under contract reference CHS0/5002S, performed through Gregory Harland Ltd under the Authority of the Secretary of State for Defence (represented by the DERA Centre for Human Sciences, Portsdown West).

1.2 Operations rooms are information-intense environments. Current communications and defence operations have lead to increased information loads while reducing the time available for information processing and tactical decision-making. As the information increases and response time decreases there is a need to re-examine the nature of the information and its relationship to the display medium of choice being used. Further, the following question has to be posed: is it possible to augment the data processing capabilities of the end users of such displays, by using novel forms of data representation, thereby exploiting their natural information processing systems (such as navigation and depth perception)?

### Novel representations of information

1.3 Despite recent reported corporate failures in the Virtual Reality (VR) community, international developments in methods for displaying and interacting with novel representations of information continue unabated. Indeed, the author [1], defining VR as:

*"...a suite of technologies which permit intuitive interaction with real-time, three-dimensional databases",*

goes on to say:

*"VR is not about one single group of technologies. If there is one real contribution VR has made to the international R&D community that is worthy of mention, then that must be that it has stimulated the emergence of an impressive range of new and, in many cases, reasonably cheap human-computer interface technologies. Many of these may never end up as de facto peripherals in turn-key VR systems. Nevertheless, their potential for solving other, more conventional ergonomic and interface issues is immense".*

1.4 At the present time the "impressive range" of data display and data input peripherals is very much on the increase. New products appear almost on a weekly basis, as can be witnessed in recent review issues of *VR News*. A good number of these products - particularly those concerned with tactile and force (haptic) feedback, multi-function/degrees-of-freedom data input, neural signal recognition and the generation of synthetic aromas (a key research area funded in the States by the Advanced Research Project Agency, ARPA) - are, however, currently in a form that can only be described as pre-product prototypes. Their "maturation" into robust usable products (as has happened with, for instance, 3D sound) very much depends on the post-purchase integration and testing efforts of research and development or VR user organisations across the world.

1.5 A similar criticism can be levelled at so-called "advanced" graphics software. Many packages are quite ill suited to solving all the interface design problems one may encounter. Fortunately, this situation is also changing by the month and, whilst a good number of software products will come and go, there appears to be a core of systems which are now gearing up to compete for the title of de facto industry standard.

1.6 One "sub-suite" of technologies which has matured considerably over the course of the past 2-3 years can be classified under the very broad heading of 3D visualisation systems. New display devices emerging at a considerable rate - from head-mounted displays to all-enclosing (and expensive) CAVEs, from "immersive workbenches" using field sequential liquid crystal "shutter" glasses to individual high-resolution 2D/3D kiosk-like units. The same emergence rate applies to the software packages necessary to calibrate and drive such devices. 3D visualisation is, then, the most mature of a suite of evolving technologies, and has been specifically considered in this report.

**The study focus questions**

1.7 At the project start-up meeting held at Portsdown on 11 December, 1996, CHS indicated its intention to accelerate a programme of research aimed at addressing advanced and novel representations of naval command and control data, specifically in the air warfare arena. Particular emphasis was placed on the "conversion" of existing two-dimensional (PPD) data into 3D representations and whether or not validated methodologies for so doing existed. Less emphasis was placed on other novel form of data representation, but it was acknowledged that the development of software toolkits, new forms of interaction devices (data input peripherals) and specialised display techniques (eg. 3D projection, volumetric imaging, possibly immersion, 3D sound, and so on) within the Virtual Environments (VE) field could have a rôle to play in delivering workable solutions.

1.8 The meeting resulted in the following focus questions being put forward:

- Why should the CHS Advanced Naval Interface Programme consider 3D data display?
- What does 3D offer over and above conventional 2D data display (eg. as currently used for tactical plan position displays - track/threat/IFF/response data, etc.)?
- Is there any (preferably experimental or field) evidence to support a "move" by the military from 2D to 3D data display, given the nature of the naval platform operations room environment (not to mention the sceptical Royal Navy seniors)? What are the potential pitfalls of moving to a 3D representation?
- If so, are there any accepted or emerging human factors *principles* for effective 3D data design (data display software, as opposed to hardware and peripherals)? It is important that any principles that are identified are fully backed up by robust cognitive and perceptual theories/models or experimental paradigms.
- What distinguishes "good" or "bad" human performance with regard to evaluating a given 3D display item? Do any valid performance metrics exist?

### Study objectives

1.9 Following a review of the evidence supporting the development of 3D information displays, together with an analysis of the current (rather disappointing) situation regarding appropriate methodologies, the document outlines, in broad terms, one possible technique for assessing and translating information held on 2D tactical displays, or existing in conceptual form (ie. not yet implemented), into 3D tactical real-time information environments.

1.10 The report also makes a series of recommendations on the way forward with respect to this methodology.

### The case for 3D/virtual displays

1.11 Human beings evolved to perceive in a three-dimensional way simply because their natural “habitat” is three-dimensional. In the early evolution of tactical display systems the technology was simply not available to reproduce a 3D information environment capable of the performance requirements of an operations room environment. The real-time 3D model of an engagement or a defence situation was recreated or fused from symbolic information representation on 2D plan position display (PPD) screens by the mental models of senior officers in charge. As can be appreciated from earlier comments, the technology to externalise these “internal visualisations” is now well established, albeit unproven in real service or combat settings.

1.12 For certain information formats, 2D representation may provide the optimum solution, but in situations where there a number of co-evolving (spatially and temporally), linked and independent variables - as is the case with the "new" military information environment - they may not.

1.13 Unfortunately, the true importance of, and benefits to be gained from the use of 3D in the display of information to human users has never been proven beyond doubt. In the academic and technical literature published since the late 1970s, there have been regular "surges" of interest in 3D and stereo, occurring almost sinusoidally on a 2-yearly basis. Initial studies of 3D and true stereoscopic displays (ie. those which exploit the binocular vision, or stereoptic/stereopsis characteristics of the human viewer) concentrated on video systems, relaying information from teleoperated vehicles stationed at remote and hazardous worksites, (eg. within nuclear hot cells or subsea). A range of prototypes was constructed, but a good number of these failed to gain full operator acceptance and, therefore, never attained operational status. In 1988, the author [2] put forward a simple reason for such failures:

*"This trend will probably continue until researchers realise the importance of an **integrated** perceptual-motor approach to designing MMIs for remotely operated systems, rather than assuming that technologies such as stereoscopic viewing will, in isolation, bring significant performance benefits".*

1.14 It has only been of recent years (1994 to the present) where technology has developed to a level where it has become possible to access adequate hardware and software (at least from a controlled laboratory standpoint) in order to experiment with synthetic or "virtual" representations of environments, be they hazardous worksites, training/ design prototypes or military theatres of campaign. It should be pointed out that a good number of these environments have not been designed to work with binocular displays - VR headsets, BOOMs (Binocular Omni-Orientable Monitors), LCD glasses and the like. The lack of concrete evidence for implementing stereo, the fact that many stereoscopic imaging devices do not adequately support true 3D viewing (due to poor image quality and content, and restrictive field-of-view displays) and the computer rendering penalty one has to incur when "drawing" left- and right-eye views - an image refresh rate reduction of up to 50% - have forced system designers to consider more conventional interface technologies for the delivery of pseudo-3D ("2½D") data, including standard desktop systems and various forms of projection displays.

1.15 Even taking these comments on board, many developers (especially in the human factors field) believe that one effect brought about by the existence of advanced hardware and software technologies has been a reduction in the application of scientific rigour to the design of human-system interfaces. Suddenly, reasonably user-friendly software tools have become readily available which have, in some cases, permitted the designers of information displays to "go to town" in their design approach. The result? "3D works of art" - visually impressive interface formats - but of questionable usability. The drive for visual impact appears to have over-shadowed the crucial issue of concentrating on the underpinning human factors issues surrounding the need for sophisticated 3D display formats. Evidence for this conclusion is, currently, more than apparent in the field of virtual telecommunications network display design (spearheaded by the likes of British Telecom; see also some of the "works of art" in Young [3]).

1.16 Despite this trend, a handful of recent projects have considered the importance and effect of introducing 3D into information displays. Ware & Franck [4, 5], for example, conducted experimental studies that demonstrated an improvement in the understanding of abstract information net by a factor of 1.6 when 3D was employed, and up to a factor of 3 when head coupling was employed. They suggest that motion parallax cues are of greater importance than stereopsis in revealing structural information. Koike [6] showed how the introduction of visual 3D frameworks can dramatically reduce users' cognitive loading when forming mental correlations between multiple window environments (previously displayed in 2D). Their applications were based on electrical power control room and remote manipulator scenarios. Crosby & Nordbotten [7] went on to demonstrate that their "...Results...suggest that the graphic style [of models employing embedded symbology, separated symbology or list structures] affects the ease with which they are read and understood".

1.17 The Koike work is an important development with regard to the present application area, as one element of concern with introducing 3D display material into a command and control context is the extent to which physically disparate 3D displays in the operations room might compromise the performance of Principal Warfare Officers and others who need to fuse multiple sources of information (eg. air, surface, subsea threat, ECM, etc.) mentally into one global image. Of relevance here is the work of Ellis et al. [21], referred to later in this document, who, reporting on further fundamental aspects of 3D display design, review the egocentric (body-centred) and exocentric (detached viewpoint) information display issue. Disparate 3D displays, some presented egocentrically with respect to the user, some exocentrically with respect to, say, a fixed geographical point , will most certainly confuse the individual attempting to form a complete mental picture of the theatre of campaign and could lead to potentially fatal errors.

1.18 Also of importance to the present study, Wickens et al. [8] showed that 3D displays using monocular cues produced shorter response times than 2D displays. They also claim that it is possible to transform information from a 2D display into a 3D representation. However, Hollands et al. [9] provided experimental evidence to suggest that 2D displays generally elicited better trend and difference estimation performance than 3D displays.

1.19 It appears that information displayed in 3D can, as far as the user's performance is concerned, be supported or confounded by the integration of other, essentially monocular or dynamic cues. Foe example, Ware & Franck [4] discovered that motion cues in information display are more significant than stereo cues, irrespective of the type of motion.

- o Wickens et al. [10] and Merwin et al. [11] further demonstrated that colour coding did nothing to help users' understanding of 3D displays. Sound appears to play a reasonably important rôle in enhancing situational awareness, reducing loading on visually dominated sensory systems (eg. Venolia [12]), with 3D audio improving target location and identification (Perrott et al. [13]). 3D audio appears to act in a similar fashion to abrupt visual onsets, but with an attention-capturing capability at much longer distances (Strybel et al. [14]). In a general study of audio feedback in conjunction with virtual displays, McKinley et al. [15] found, using both subjective and objective measures, a positive effect of sound on 3D localisation.

1.21 These studies, then, are but a small selection of empirical investigations which have been carried out in the broad domain of 3D visualisation. Some have considered true stereopsis, others have addressed the notion of pseudo-3D - the representation of strong monocular cues on conventional CRT and projection displays. Apart from one specific public domain summary publication by Wickens et al. [16], with some reference to 3D in the likes of Boff & Lincoln [17] and Farrell & Booth [18], there has been no serious attempt to collate a series of usable guidelines for the implementation of 3D visualisation systems.

# 2 Study methodology

### Study description

2.1 In order to generate the information contained within this and subsequent reports, a number of international information databases were trawled using the following supporting introductory statement:

*ÒTopic: Theoretical and experimentally validated human factors principles for designing the content of three-dimensional displays, with a primary focus on naval and aerospace command and control domains.*

*Background: The sender has been commissioned by the UK Government, as part of an Advanced Interface Programme to carry out as comprehensive review as possible (in the short timescale involved) of the possible future use of three-dimensional visualisation techniques in command and control scenarios.*

*The aim of this work is, at some time in early January 1997, to be able to take an appropriate mission study, decompose the mission events into specific task components and then, assuming they exist, apply any principles to "evolving" a 3D representation of the command and control data - effectively "transforming" the data from its 2D source. Later (Spring, 1997), it is planned to produce a simulation of the proposed 3D data display scenario for experimental comparison with its former 2D source.*

2.2 Versions of the focus questions, as listed earlier, were provided, according to the database being trawled.

### Databases

2.3 The main search was carried out using the Crew Systems Ergonomics Research Information Analysis Center (Wright Patterson AFB), where direct access is available to the following databases reviewed:

1. Defense Technical Information Center (DTIC)
2. DTIC Work Unit Information Summaries
3. NASA Recon
4. Ei Compendex Plus
5. INSPEC
6. National Technical Information Service
7. Dissertation Abstracts Online
8. PsycINFO
9. SciSearch
10. Energy SciTec
11. Jane's Defence & Aerospace

2.4 The CSERIAC Search and Summary yielded over 150 pages of abstracted information. It is recommended that CHS attempts to obtain a number of those papers (referenced in Appendix 1[1]) considered to be of greatest relevance to the focus questions listed earlier, before embarking on a programme of 2D-3D transformation and experimental validation. As might have been predicted, the Search and Summary contained a good proportion of articles which can be best described as containing “review and conjecture” material - from listings of new technological approaches to 3D display hardware, from discussions on the possible merits of using 3D for air traffic control to the rôle of 3D in map displays, aircraft taxiing cues and cockpit design. Some of the early papers - 1973/7 and the like - were ignored in the reading of the Search and Summary, as they typically refer to technological shortcomings which have since been eradicated, courtesy of developments in display technologies and developmental/run-time software.

2.5 In addition, as extensive a review of Internet and World Wide Web sources as time permitted was undertaken, including sites at NASA (Ames, Goddard, JPL and others), HITLab (Washington State), Orbit Interaction (developers of InfoSpace), and pages which contained information of relevance in the distributed interactive simulation (DIS) and synthetic warfare arena, including the US Air Force Institute of Technology’s Graduate School of Engineering (Wright Patterson). Where appropriate, academic contacts of the author were approached with the aim of assessing current relevant developments, especially in the UK.

[1] The complete Search & Summary has been supplied as a separate document to this report. The reader will notice that the CSERIAC researcher has provided his own list of recommended references. However, the list given under Appendix 1 represents a more specific reference listing of relevance to (or appearing to contain relevant references to) the focus questions.

# 3 Database search results

### Results overview

3.1 Currently there are no fixed formulae or established, readily available methodologies for transferring information between a traditional 2D representation and a 3D information environment.

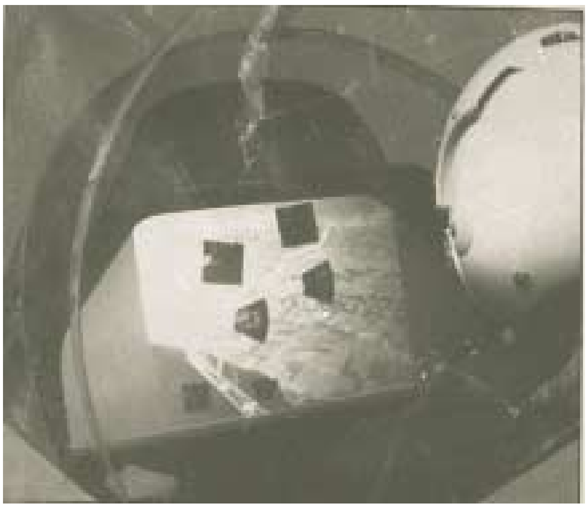
3.2 For certain quantifiable parameters, mathematical translation is relatively easy (eg. a 2D scalar variable can be represented as a single-value 3D surface). Yet there is not necessarily a perceptual benefit in simply changing the mathematical representation. Key questions emerge, as follows:

- What are the rules for representing task-oriented information effectively and productively?
- What are the benefits of such representation?
- How does one implement, document and archive this in a formally grounded, human factors manner?

3.3 There is an emerging body of research that can help provide a methodological approach to tackling this problem. Building on research in the areas of scientific visualisation, ecological perception and information design, a suite of techniques can be embodied together to form a translation framework aiding in the effective presentation of data. The remainder of this document outlines this body of work, related technical examples and concludes with an outline method for developing such a framework.

### Background Research

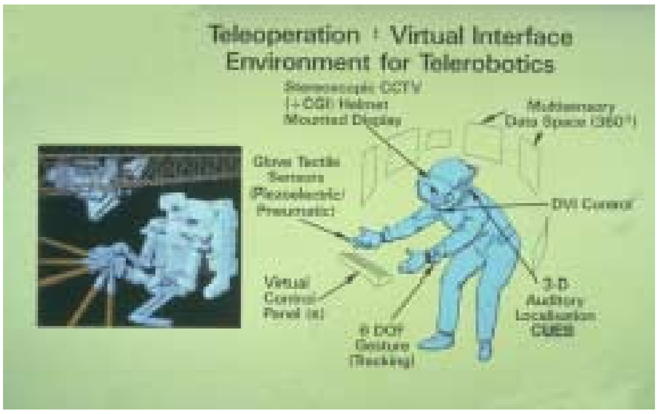
**Figure 3.1: The "Big Picture" Display - A Fore-Runner to the *Supercockpit* Programme**



3.4 Early work in virtual environment based tactical and navigational displays used widely varying information representation and interaction techniques with some success. These efforts include the USAF's *Supercockpit* programme [19] (see Figure 3.1), NASA's Virtual Environment Workstation (VIEW) Project [20] and MIT's Architecture Machine group (now part of MIT's Media Lab). From the outset, the Supercockpit project examined the use of a 3D in the representation of a computer-synthesised theatre of engagement, using real-time information cues to pilots in combat situations. Further human factors work has since been undertaken at Washington State's HITLab by Tom Furness, the individual most associated with the Supercockpit's origins. Some of HITLab's recent offerings were highlighted in the literature search, but very little of substance was in evidence.

### NASA

**Figure 3.2: NASA VIEW Telepresence Concept**




3.5 One of the first Virtual Reality video sequences to be released by the NASA Ames VIEW (Virtual Environment Workstation) Team showed the flight performance of a virtual astronaut, controlling a virtual representation of himself or, in another example, the NASA Flight Telerobotic Servicer (FTS) as it was deployed around a model of Space Station Freedom (see Figure 3.2).

3.6 Despite the use of primitive wire frame graphics in the early version of VIEW, the NASA demonstration incorporated many excellent examples of features designed by human factors experts - features which, sadly, are rarely evident in demonstrations today (the quest for photorealism seems to have over-ridden the sensible design of virtual environments). The trainee (immersed) astronaut's navigation and telepresence performance was enhanced by the provision of visual and auditory cues, including a lower-resolution reference ("God's Eye View") cube ("Navcube") containing the Space Station itself and the current position of the astronaut/FTS. By uttering the word "Locate", the system plotted a vector line between Freedom and a virtual representation of the Hubble Space Telescope, thereby providing the immersed astronaut with enough information to locate himself (ie. the position of the FTS) relative to the Station and his next target. Further examples of how to build an effective virtual world included use of auditory signals to cue FTS robot arm performance limits and collision detection, limited use of simple tactile feedback and the careful formatting of information windows, displayed within and around the immersed astronaut/FTS trainee's visual field of view on receipt of a spoken request (as shown in Figure 3.2).

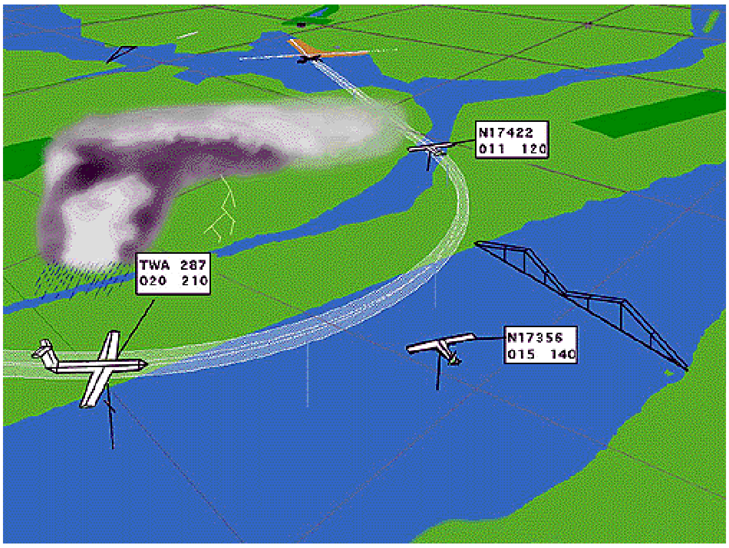
3.7 Many of the background experiences to the early NASA work can be found in a subsequent book entitled *Pictorial Communication in Virtual and Real Environments* [21] and in recent publications relating to the Advanced Display and Manipulative Interface for Air Traffic Management (ATM) project, funded by the Terminal Area Productivity (TAP) Program out of NASA Headquarters [22]. The goals of the project include:

- Development and evaluation of perspective-format displays of air traffic (eg. Figure 3.3) for improved situation awareness and reduced workload of air traffic controllers under anticipated traffic environments of the future;
- Development of interactive path planning techniques for optimising traffic flow.

3.8 Amongst the project objectives are:

- Design, develop, test and evaluate advanced 3D geometrical techniques for presenting aircraft position, spacing, flight path, conflicts, and weather systems;
- Evaluate manual and automated viewing parameter manipulations;
- Design, develop, test and evaluate manipulative interfaces for route specification and modification due to perturbations in the normal procedures due to weather, runway or gate closures;
- Make use of computational techniques to simulate future consequences of route modifications using predictors based on flight plans, runway assignments, and aircraft situation.

**Figure 3.3: An Example of NASA's Perspective Virtual ATM Display (**Poor Quality .GIF Original From Web Site)




**MIT**

3.9 MIT's Architecture Machine Group under the supervision of Negroponte [23] developed a system known informally as "Put That There". Developed by Prof. Richard Bolt, the system examined the use of multi-modal interaction - 2D visual representation, 3D tracking using a Polhemus 3Space sensor and speech input. The participant chose an action ("PUT") then an object (initially a block - later a ship) by vocal selection (using the

"THAT" in conjunction with positional pointing - inferred from the Polhemus tracker) and then a new position (designated by new spatial co-ordinates inferred from the tracker and the vocal command "THERE"). A derivative of "Put That There" was later used by the US Navy as a representation for naval war games allowing a more natural interaction with a 2D display.

**The Synthetic BattleBridge**

3.10 The *Synthetic BattleBridge* (SBB) is an evolving Virtual Environment development tool and facility, primarily (but not exclusively) geared towards immersive VR, developed by the US Air Force's Institute of Technology at Wright Patterson AFB. The SBB research programme is focused on the development of VR displays interfaces that assist the military user to monitor, assess and analyse complex activities in real time. The Institute is conducting the SBB development programme in line with emerging distributed interactive simulation (DIS) protocols, thereby ensuring the portability of their results to other military users. Lt. Col. Martin Stytz, principal investigator of the SBB Programme, has pointed out [24] that while there have been other attempts to generate immersive VR systems for the visualisation of battlespaces (and the orientation of the viewer therein), most combine 2D plan views of the theatre of campaign with a capability for simple navigation within the 3D virtual reconstruction.

3.11 Central to the SBB concept (at least from a human factors perspective) is the notion of *Sentinels*. Sentinels are described as "user assistance tools", driven by an expert system which consists of around 50 basic rules, and are considered to assist the SBB user in assimilating the masses of information which could well feed a battlespace display system. The researchers [25, 26] claim that, by mimicking human reasoning, sentinels are an invaluable aid to enhancing a VR user's situational awareness.

3.12 Some of the features of the SBB are, in some respects, similar to earlier *Supercockpit* work and include the capability to display *locators* (simple geometric forms which highlight areas of activity, often colour coded to denote IFF results), *trails* (visual cues to the motion of the locators over time), *grids* (temporarily-displayed or user-demanded visual inserts to the main display showing larger areas of the theatre of campaign). Locators are endowed with level of detail features, ensuring that multiple locators in the distance (displayed as simple geometries) do not clutter a display, whilst closer locators are displayed as geometric reconstructions of the vehicles they represent. The SBB (Version 2) can also display time-of-day effects, the Sun, Moon, and low-orbit/low-altitude spacecraft, as well as traditional ground vehicles and aircraft. A parallel Institute development programme, the *Missile Endgame Visualisation* project, aims to develop a graphical simulation package that shows the interaction of a missile, its fusing cones, and target during the fraction of a second of the missile/target encounter.

3.13 Even with these features (see Figure 3.4), it is not long before a particular display can become extremely cluttered. Sentinels, then, can be stationed at user-designated portions of the battlespace and will proceed to analyse the activity therein (Figure 3.5). A second display (Figure 3.6) then summarises the activity for each "watchspace" covered by the sentinel, and a priority "at-a-glance" bar chart links activity level with each area.

**Figure 3.4: Typical SBB Display Example (**Poor Quality .GIF Original From Web Site). The centre of the illustration shows an elongated aircraft profile (rear elevation). The "rugby ball"-shaped objects are "locators" (blue for friend, red for foe). Trails can be seen across the image. All $C^3$ activities are shown relative to the aircraft, which is over-flying an airstrip

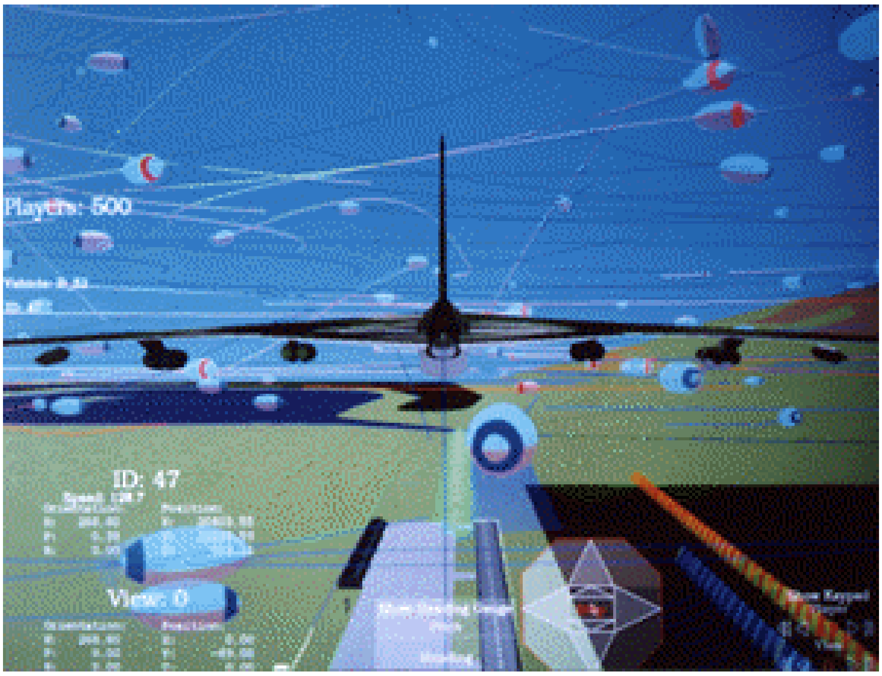



**Figure 3.5: SBB Sentinel Locations** (Poor Quality .GIF Original From Web Site). This illustration shows 6 cylindrical Sentinels (the Sentinel just left of centre confirms the cylindrical profile), each denoting an area of military activity or strategic importance

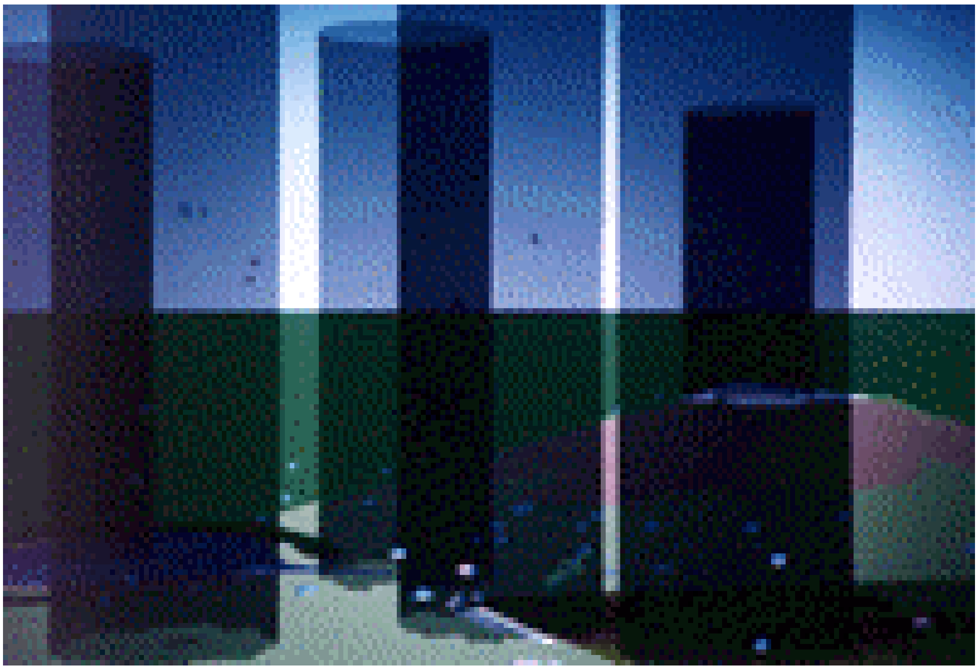
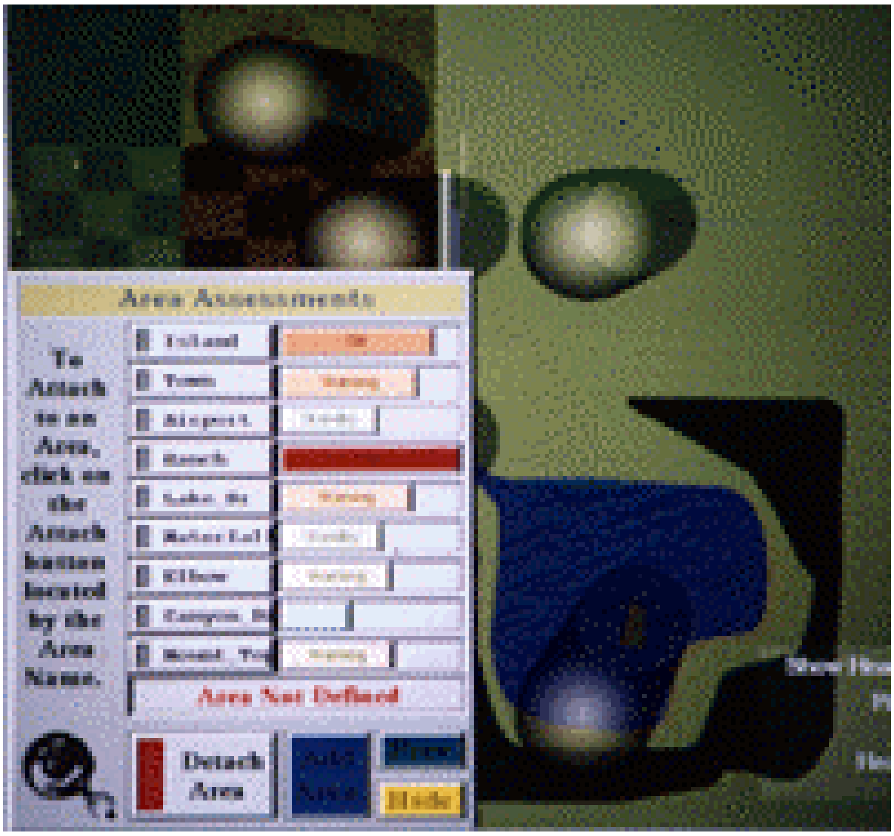


**Figure 3.6: Sentinel Activity Summary (Area of Interest) Display** (Poor Quality .GIF Original From Web Site). Here the Sentinels are shown in plan view, represented by a hemisphere with shadowing. The interactive window on the left of the display invites the user to "attach" to an area within the display (Sentinel or other). Bar charts with colour coding provide an "at-a-glance" summary of area activity. Increased detail is made available following "attachment" to an area of interest.




3.14 As mentioned above, the main physical interface for interaction and navigation through the SBB is immersive VR, although other papers (eg. [24]) indicate the use of standard cathode ray tubes and BOOM systems. Transparent controls and a capability for expansion into Direct Voice Input is also built into the SBB.

3.15 The Air Force Institute has also been investigating the notion of an *Information Pod*, a virtual “capsule” which surrounds the immersed user and, so it is claimed, obviates the need to employ other familiar interaction metaphors, such as the desktop or ship’s bridge. In many respects, the Pod idea is similar to that originally put forward by the NASA VIEW Team, during their telepresence work in the early-to-mid 1980s.

3.16 The Pod user makes gross movements and can reorientate himself in the virtual environment by moving the Pod, and fine adjustments in his viewpoint are accomplished by head movement. Within the Pod, the user is surrounded by 2D panels in 3D space, with each panel devoted to a specific set of tasks. Each panel can contain subpanels, with each subpanel in turn containing controls and displays that are associatively grouped into the subpanel. The Institute claims that, as well as with immersive equipment, the Pod can be used with CRTs (presumably banks of CRTs, rather than single units), although there is no information on how interaction occurs in the case of a non-immersive implementation.

**InfoSpace**

**Figure 3.7: The *InfoSpace* Home Page**


3.17 Developed by Leftwich Design and Orbit Interaction, *InfoSpace* is a system which combines a three-dimensional visual interface with a three-dimensional virtual environment in order to create a new mode of data organisation and human/ information interaction. In many respects, some of the concepts put forward in *InfoSpace* are similar to those under the Synthetic BattleBridge. However, there is some evidence in Leftwich's writing to suggest that the underlying concepts to *InfoSpace* are more formalised than the US Air Force counterpart.

3.18 *InfoSpace* is a multi-dimensional information and data format that can serve as a three-dimensional virtual environment for the creation, manipulation, and access of many forms of storable data, including text, audio, two-dimensional graphics, video and multimedia. These data forms can be static, animated or user-interactive, depending on the type and purpose of the information and application. Jim Leftwich, the principal investigator, says:

*"It is accurate to term this a new level and not a completely new form [of information interaction] because none of the previous forms of communication and information interaction need be abandoned, but rather can be incorporated within this new interlinked, three-dimensionally organising superstructure".*

He goes on to claim (becoming somewhat metaphysical):

*"Such a method of organising and manipulating information may well have an equally important impact upon human thought, communication, learning and the interpretation of information, since it will allow the three-dimensional visualisation of informational relationships in ways heretofore impossible or impractical. This gives rise to the possibility of utilising spatial memory and other psycho-physiological means to absorb, process, and synthesise information. Just as an individual organises, relates to, and*

*interprets his or her physical environment in ways far more complex than can be represented on paper or similarly with the two-dimensional metaphors of the desktop utilised in many of today's visual interfaces, InfoSpace creates an informational environment in which these higher orders of interaction can take place. InfoSpace is an attempt to harness these higher orders of interaction and apply them in an informational universe that parallels our physical environment dimensionally, yet goes far beyond it in terms of its potential for simulation, manipulation and interaction by way of its virtual nature".*

o *InfoSpace* consists of a variety of components, each linked in such a way that, it is claimed, will enable the user to interrogate and manipulate data in a highly intuitive fashion. Such interaction takes place in *space*, which is described as the three-dimensional "canvas", viewed (typically) using a head-mounted display and interacted with using instrumented gloves, spatial hand controllers ("wands"), each of which permits object grasping or the control of a three-dimensional cursor.

3.20 The principal unit of data or information within *space* is the *block*, in effect a three-dimensionally projected cube, representing any possible form of data or group of related data. Blocks may be displayed together in various ways within an organising *matrix*. Figure 3.7 gives a rough idea of the space/block/matrix idea. Use is made of related concepts, such as *submatrices*, *supermatrices*, *superblocks*, and the like, but the concept of *InfoSpace* as a collection information *systems* remains the same - a 3D interface which can be interrogated to different depths of detail, calling up information links and navigational support cues (floating directories as and "system up-trace panels") when necessary. Keen to move away from 2D interaction metaphors (such as the clipboard idea for temporary file storage on PCs), even file transfer is achieved using a familiar 3D metaphor - the *briefcase*!

3.21 The problem with the *InfoSpace* idea, as it currently exists, is that the associated publications are littered with terms such as "will", or "may", or "could". Some of the pictorial material contains the legend "this illustration was created by…". One might, then, be forgiven for concluding that *InfoSpace* does not actually exist. Even if it does, actual applications seem to be very thin on the ground and validation trials appear to be non-existent.

# 4 Can the goodness of virtual displays be measured? Human Factors Issues

4.1 All of the systems described in Section 3 have been more or less successful within their (lab-based) briefs, but the representation schematics used were as a result of trial and error. Indeed this fact led to the director of the Supercockpit programme later writing:

*"How should the "goodness" of the virtual display designs be measured, including the accompanying perceptual, cognitive and motor control resources which are expended to accomplish specific tasks?" Furness [27]*

4.2 Ten years later, researchers in the VR and "synthetic environments" arenas are approaching a point where it is just becoming possible to answer Furness's questions, although there is still a long way to go. It is fair, perhaps, to say that three of the main stumbling blocks have been (a) the reticence of many VR researchers to even attempt to design a multi-variate experiment where the control of a number of the variables is practically impossible, (b) the absence of a generic methodology to assist researchers to overcome the problems in (a), and (c) the absence of reliable and, importantly, validated human performance assessment measures.

4.3 Keller & Keller [28], whilst working under contract to the US Department of Energy at the Lawrence Livermore National Laboratory, recognised a similar set of problems for the field of Scientific Visualisation, which they define as:

*"…the graphic representation and supporting techniques which facilitate visual communication of knowledge".*

4.4 However, Keller & Keller have since established a methodological approach which can be summarised in basic terms as follows:

1. Conduct analyses of the data to be represented, when it is to be displayed, to whom it is to be displayed and in what form;
2. Make the data both system and application domain independent;
3. Remove the constraints of dimensional representation;
4. Define the visualisation goals and consider the representation schema most appropriate: traditional data representation (bar charts, dials, etc.), contextual cues (motion blur, parallax, etc.) and phenomena representation;
5. Implement the visualisation.

4.5 If one is considering extending this approach into the experimental domain (which is considered of crucial importance if one is to move away from the "works of art" scenario discussed under 1.15), then, in the opinion of the author, two further steps should be added to this list:

6. Conduct initial rapid visualisation assessment trials, exposing potential users to the implementation and assessing such issues as acceptance, feature recall, situational recall, and so on. This could be done using simple print-outs of specimen visualisations (eg. screen format examples) or using tachistoscopic presentation;

7. Once refined on the basis of results from 7, conduct a more rigid experimental programme, comparing performances between original 2D formats and new 3D visualisations, using appropriate assessment methods (eg. reaction time, task completion time, error recording, recall, situational awareness assessment techniques).

4.6 Keller and Keller's work is not aimed specifically at the field of virtual environments but lends itself readily to information representation within a virtual environment. Stages 1-3 abstract the information away from its field and traditional representation forms. This is important since the traditional ways of representing information may not necessarily be the best. Stage 4 equates to the crux of the problem as described by Furness earlier.

4.7 In order to define the visualisation goal, Keller & Keller provide a broad classificatory system that allows the main goal and sub-goals of the visual representation to be broken down, as depicted in Table 4.1.

4.8 Keller & Keller propose that the broad classification aids in the choosing of appropriate representations. Each category and sub-category are supported by examples which help in the application representation. Other sources of information such as Tufte's texts, "The Visual Display of Quantitative Information" and "Envisioning Information" [29, 30] can be used to extend the examples. Implementation of the system is summarised in Table 4.2.

**Table 4.1: Classification of visual representation goals**

| Main Category | Sub-Category |
|---|---|
| Comparison | Images, positions, datasets and subsets, etc. |
| Distinguishing | Importance, objects, activities, range of value, etc. |
| Indicators | Direction, orientation, direction of flow, rate of change, etc. |
| Relationships | Concepts [value and direction, position and shape, etc.] |
| Location | Position, relation to axis, objects, maps. |
| Value Representation | Numeric value of data. |
| Revealing Hidden Objects | Highlighting, visibility, enhancement, etc. |

**Table 4.2: Example Implementations of Keller & Keller's visual representation approach**

| Step | | Comment |
|---|---|---|
| 1 | Examine the data to be presented | In the case of existing tactical display material, analyse what information is represented and what information is inferred (or intended to be inferred) by the end user. |
| 2 | Classify the information in a platform and application domain independent manner | For example, structured English, Schlaer-Mellor diagram, Entity Relationship Diagram, etc. |
| 3 | Define the visualisation goal | For example, what does the displayed material need to do? (identification of an object's position and/or course, and/or speed) |
| 4 | Using Keller & Keller's classificatory index or Wehrend's modified version (see below), attempt to exploit a number of proven examples in the field of Scientific Visualisation | How each representation evokes its perceptual response can be traced back through current human factors oriented research (see Human Factors basis for using Keller & Keller's method, below). |
| 5 | Implement the representation | Implementation of graphical effects are well documented (eg. Ellis et al. [21], Earnshaw [31], Earnshaw et al. [32], Foley et al. [33], Tufte [29, 30], Stokes et al. [34], etc.). It should be noted that Virtual Environment representations have their own unique requirements and these have to borne in mind when physically implementing the development of 3D tactical displays. Furthermore, the design of these displays and environmental representations should be conducted based upon Kaur et al.'s usability guidelines [35]. |
| 6 | Iteratively refined through testing with the end user | The aim here should be to increase the efficacy between the end user's mental model and performance with the system. |
| 7 | Test the 3D information. Environment should be tested in parallel with its 2D equivalents | Once this is successful the next stage is commissioning with efficacy to information load and performance monitoring though out its lifetime. |

4.9 Keller and Keller explicitly do not deal in implementation technologies. One important drawback of their approach is that they do not address specific *interaction* issues - displaying data is but one component of providing an advanced operator interface, as emphasised earlier by the author [1]. Neither do they address the techniques required to support the suggested visualisation methods. Each example only indicates the class of computing platform deemed necessary to implement a given application, from PC/Apple Mac-based equipment through Silicon Graphics workstations, to supercomputers plus workstations costing well in excess of $1,000,000. The considerations for real-time 3D representations should be noted when implementation issues are considered, though, again, these techniques are well established and increasingly easy to access.

4.10 The problem with this approach is that the categorisation of the visual goal and its suggested exemplar support is very generalised and not underpinned by either known or emergent human factors or applied psychological principles.

**"Formalised Exemplar Searching"**

4.11 Stephen Wehrend, in appendices to the Keller & Keller book [28], tackles the first part of this problem, which attempts to provide formal generic descriptions which are peculiar to the application under consideration. Wehrend formalises the definition of the visualisation goal and provides a refined classification structure which uses this formal definition to better identify appropriate examples. Using a fixed length vocabulary of defined terminology, the user is encouraged to formulate a classification for their goal in terms of representation, category and action. These are then used to indicate appropriate examples through Wehrend's refined category index. The examples used by Wehrend are the same as those used by Keller and Keller, although requirements can be more closely pinpointed. Trotter and Webb [36] have produced a computerised version of Wehrend's index and applied it as part of a Rapid Application Development (RAD) toolset for the development of construction industry 3D interface applications for the construction industry.

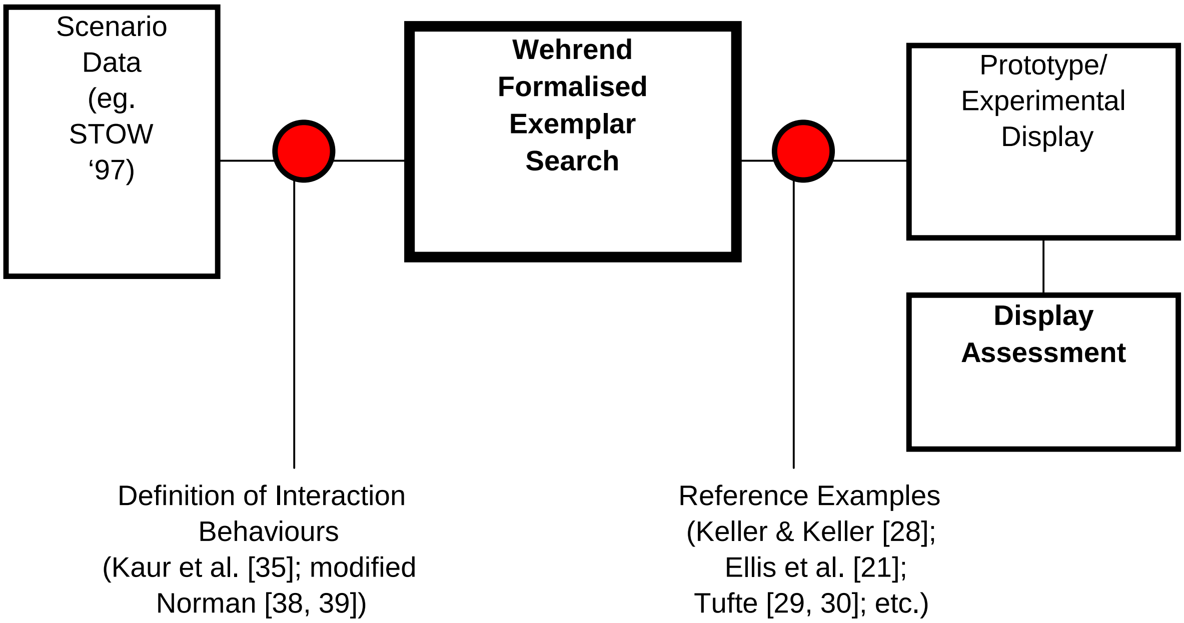
**Human Factors Basis for Using Keller & Keller's Method**

4.12 In the representation formats suggested by Keller and Keller and subsequently Wehrend [28] and Trotter & Webb [36], the contextual cues have equivalent definitions in terms of providing perceptual context for task-orientated or goal-orientated representation as those found in the work of both Gibson [37] and Norman [38, 39]. Gibson provides the concepts for both environmental affordance and object affordance (ie. how structural information - size and shape invariance - defines the visual world), which subsequently formed the basis of the ecological school of psychology. The concept of affordance relates an object's appearance to its utility. Norman extends Gibson's concept of affordance and relates it to the concepts of mental models, object and interface utility and usability. Further Kaur et al. [35] are currently using Norman's concept of mental models and interaction cycles as a basis for their work on developing a methodological design guidance for usability in virtual environments. Norman developed a simple 6-stage model of goal-driven interaction with the world, involving perceiving the state of the world, interpreting the perception, evaluating the interpretations, generating an intention to act, planning a sequence of actions and executing the main action sequence. Kaur et al.'s approach refines this model to take account more of exploratory and reactive behaviours, particularly those initiated by the system and not the VR user.

4.13 The definition of a visualisation goal and its relation to the formation of a mental model allows iterative user testing to be performed. This would allow the chosen representation used in a 3D form of a tactical display to be checked against both performance and mental model fit of the intended user. Kaur et al.'s [35] work should, providing the initial (1997) user trials are successful, eliminate many of the initial usability problems - those remaining will be application-specific. Iterative user testing based on establishing increased efficacy should go some way to produce effective tactical displays.

4.14 The above discussion actually provides a first-level framework on which to build R&D programmes to develop and assess the introduction of 3D into information displays. This framework is illustrated in Figure 4.1.

**Figure 4.1: A Research Framework for analysing, classifying and generating prototype 3D display formats**




4.15 The only component of the model illustrated in Figure 4.1 left "untreated" is that concerned with the crux of Furness's original question regarding the measurement of the "goodness" of a virtual display: how should user performance with novel displays be assessed?

**Human Factors/Performance Assessments**

4.16 As mentioned above, the availability of reliable and validated methods of human performance assessment when experimenting with novel forms of display is problematic. The whole area of performance assessment in the domain of advanced 3D/virtual environment displays requires further in-depth study. However, a number of possibilities exist, some of which have only recently been applied to assessments of performance in virtual environments, and to users' well-being during and immediately after immersive VR experiences. These include:

1. Verbal Protocol Analysis (administration of pre-test questionnaire to establish user's domain knowledge, then elicitation of an ongoing explanation of behaviours during each experimental session).

2. Standard performance measures, such as reaction time, task completion time, error records and event/ display structure recall. Reaction time to system-initiated events will be of importance in supporting Kaur et al.'s [35] refined version of Norman's concept of mental models and interaction cycles [38, 39], as discussed in 4.12.

3. Measures of users' cognitive styles (eg. using Embedded Figures Test) and mental rotation capabilities (eg. using the Shepard & Metzler 3D Rotation Test [40]) and analysis of quantified performance results for correlations. Parker & Harm [41] proposed that an individual's mental rotation capabilities are important for the reduction of motion

sickness and for the fostering of competent performance (navigation and interaction) in and with virtual environments.

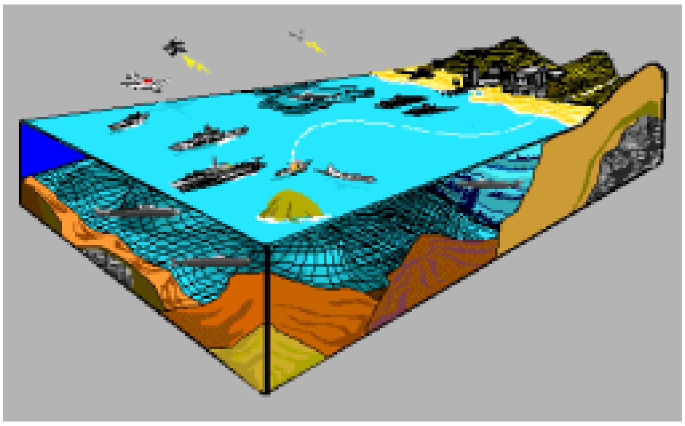
4. Measures of Situational Awareness. Of particular interest here is a situational awareness technique known as SAGAT, developed by Northrop in the States [42]. SAGAT has been applied to measure flight crew awareness of the status of a particular mission, and of the aircraft being flown. Its modification for use with virtual environments or 3D display-based interfaces is currently unknown.

5. Measures of user workload. Typically this is undertaken using subjective measures, such as the NASA TLX. The TLX is a multi-dimensional rating procedure which provides an overall workload score based on an average of ratings of six subscales: Mental Demands, Physical Demands, Temporal Demands, Own Performance, Effort and Frustration. The TLX, originally developed during a 3-year research effort at NASA Ames, has been used to good effect in many advanced technology human factors projects (with analysis of individual ratings consistently supporting the findings and observations of the Experimenters). To enhance administration of the index during experimental trials, the TLX has been produced in a form suitable for running on conventional desktop or laptop PCs.

6. Physiological workload recording methods (such as EEG recording and the correlation of the P300 event with mental "resource" allocation) should not be ruled out, at least from a laboratory perspective. Work elsewhere has shown that the frequency spectrum of EEG records reflects some 6-7 psychological or behavioural states, including "high cognitive (moderate amplitude theta wave) activity", "alert (high frequency, very low amplitude) activity", "quiet contemplative (high amplitude alpha wave) activity", and "drowsy (very high amplitude, intermittent spindle wave) activity". Physiological monitoring equipment is becoming readily available, at affordable prices, although (in the author's opinion), unintrusive systems for specific EEG waveform recording are unlikely to exist in a mature state for at least another 12 months.

# 5 First attempt, using CHS case study material

**Figure 5.1: Simplified Perspective Display Illustration** (Poor Quality .GIF Original From DoD Web Site)



5.1 For the purposes of this section, Appendix F of the Gregory-Harland Report, reference GHL/CHS/5002/3/Deliverables/Soar/v1.0, has been used (Air Defence Scenario for UK STOW 97). Whilst a full display design has not been attempted, it is hoped that some of the principles, based on the above discussions, will be understood - there will, at this early stage, undoubtedly be some omissions. For example, a formal methodological treatment of each of the events listed in STOW 97, using the emerging guidelines from Kaur at al.'s work has not been attempted, due to constraints of time. The following examples should, therefore, be treated as a “first-pass” nature only. As has been mentioned earlier, an iterative approach is in order, and further work is necessary to refine the approach.

5.2 It is imperative that CHS obtains a copy of (at least) the Keller & Keller book [28] to understand the significance of the formalised terms used. However, the list provided below gives some idea of the meaning of the formalised terminology used in Table 5.1 (Table 5.2 takes the terminology one step further by quoting possible display format types as catalogued in the body of the Keller & Keller reference). Inevitably, with a first attempt of this nature, there will some overlap in the terms actually selected from Wehrend's listing. However, a future iterative approach (as repeatedly recommended herein) will undoubtedly overcome some of the definition problems encountered during this first pass.

- **Spatially Extended Region or Object (SERO):** this refers (in the present context) to a surface or space (ie. military area, general geography) in which features can be measured using both absolute and relative descriptions. A SERO format might take the form of a geographical area **[A]** or, in the case of representing the air, surface and subsea threat, a set of differently coded volumes **[B]**. To avoid cluttered visual displays, smaller SEROs might be represented in a form similar to the Synthetic BattleBridge "Sentinels" described earlier in this report.

- **Locate SERO:** the term location here refers to the determination of a specific position. "Locate" is typically linked with a SERO, so as to convey such features as boundaries (eg. safe/hostile corridors), range/threat grid markers, and "own" position **[C]**.
- **Categorise SERO:** categorising a SERO defines how a military area might be subdivided, thereby representing areas of (for example) known military activity, NBC residue (no-go) areas, concentration of small force elements, and the like.
- **Identify SERO:** this is the finest level of detail one should be presented with which (at a glance) identifies the key components of a military area. In a similar fashion to that described under SERO, this might take the form of a global area populated with Sentinel-like representations, each coded to indicate levels of activity or the degree to which their contents are supported by reliable intelligence.
- **Associate Position:** association is the process by which two or more objects or attributes in the display are linked (eg. own vessel and incoming aircraft **[D]**; own vessel and other support forces).
- **Categorise Nominal:** several "nominals" might exist in a given display - safe and hostile corridors might be one example. As with the categorisation of a SERO, these objects need to be endowed with a format which indicates their current status (eg. inactive/active; friendly/hostile).
- **Distinguish Shape:** an object or event of interest (real or abstract) which needs to be outline or surface coded such that it is different or distinct from surrounding display components (eg. aircraft or aircraft group **[E]**).
- **Distinguish Position:** the coding of the relative/absolute location and vector of the shape referred to above such that it is different or distinct from surrounding display components **[F]**.
- **Identify Direction:** the highlighting of motion between two points, coded according to accepted conventions (eg. compass points, relative direction, up/down/left/right indicators, and so on **[G]**).
- **Identify Position:** the highlighting of an object of immediate interest, using appropriate coding techniques.
- **Identify Scalar:** the highlighting of a quantity that is completely specified by one number on an appropriate scale (eg. intensity).
- Distinguish Nominal: the highlighting of a change in the status of a categorised nominal (see above).
- Correlate Scalar and Nominal: display a direct (possible causal) connection between two or more objects (eg. missile and time-to-impact).

5.3 Some of these features have been illustrated in Figure 5.1 which shows a conceptual perspective display format developed by the author. The bold letters in square parentheses (following certain features in 5.2 above) correspond to a graphical components keyed in Figure 5.1.

**Figure 5.1: Conceptual Perspective Display Illustration, suggesting some graphical representations of the features listed under 5.2. Textual references, essentially equating to those shown in Figure 3.3, have been omitted, to preserve some clarity on the limited size of an A4 page.**

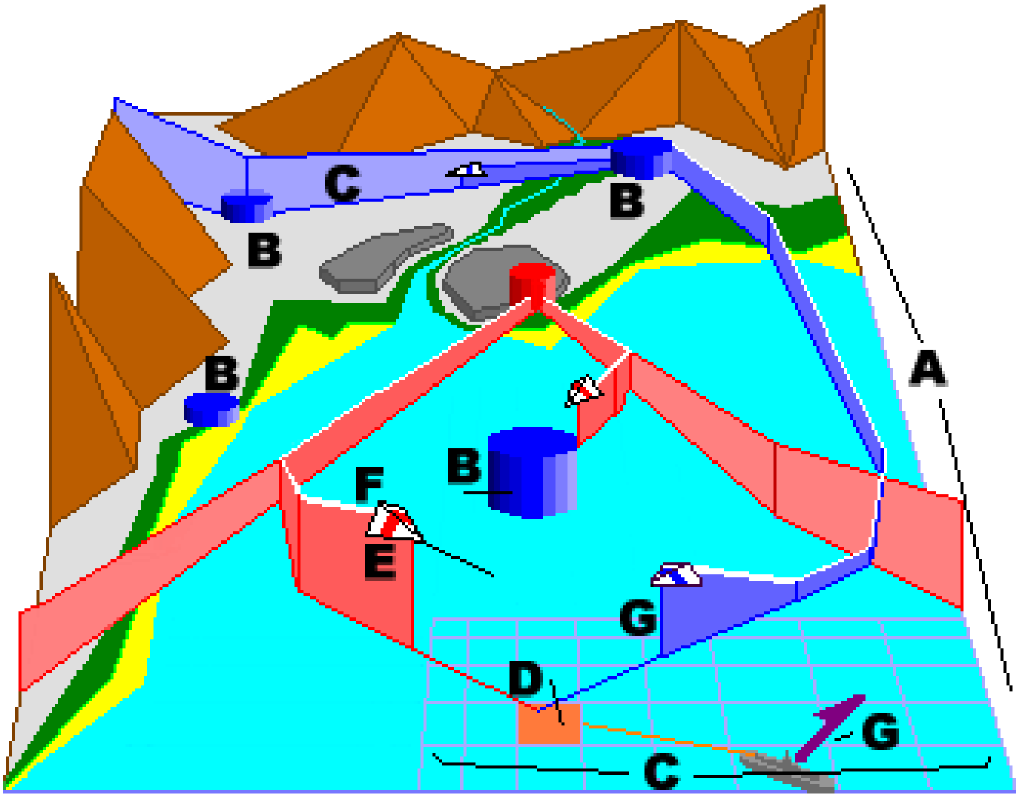

A
B
B
B
B
C
C
D
E
F
G
G

**Table 5.1: A Sequence of Events (as listed in the STOW 97 Air Defence Scenario), Classified Using the Formalised Visualisation Terminology put Forward by Wehrend in Keller & Keller [28]**

| Elapsed time | Event | Formalised Classification |
|---|---|---|
| TTW | General Monitoring/Status | Spatially Extended Region or Object (SERO); Locate SERO; Categorise SERO; Identify SERO; Associate Position; Categorise Nominal |
| +00 | Lynx detection of FBP 090$^o$ | Distinguish shape, position; Identify direction, position and scalar; Associate SERO, nominal, scalar; Correlate scalar and nominal. |
| +5 | Big Bulge Radar 020$^o$ | Identify position, direction and scalar; Distinguish nominal; Associate SERO, nominal and scalar; Locate SERO |
| +7 | Big Bulge Radar Cessation | Associate Nominal and Scalar |
| +8 | 020$^o$ Aircraft Detection 180nm | Identify position, direction, scalar; Distinguish nominal; Associate SERO, nominal and scalar; Locate SERO; Correlate scalar and nominal. |
| +11 | Big Bulge 018$^o$ | Identify Position, Direction, Scalar; Distinguish Nominal; Associate SERO, Nominal and Scalar; Locate SERO |
| +14 | Big Bulge and Link Track 018$^o$ | Identify Position, Direction, Scalar; Distinguish Nominal; Associate SERO, Nominal and Scalar; Locate SERO |
| +15 | 2 Unknown Aircraft 320$^o$ 60nm | Identify Position, Direction, Scalar; Distinguish Nominal; Associate SERO, Nominal and Scalar; Locate SERO; Correlate Scalar and Nominal |
| +18 | HIFIX Detection 320$^o$ | Identify Position, Direction, Scalar; Distinguish Nominal; Associate SERO, Nominal, Scalar; Locate SERO |
| +20 | HIFIX Cessation | Associate Nominal and Scalar |
| +22 | 2-Flogger Over-Flight | Distinguish Nominal, Direction and Structure; Cluster Position; Identify Direction and Shape; Rank Position; Correlate and Nominal Scalar |
| +25 | PUFFBALL Detection 040$^o$ | Identify Position, Direction, Scalar; Distinguish Nominal; Associate SERO, Nominal, Scalar; Locate SERO |
| ⇒ 5 minutes elapsed time ⇐ | | |
| +30 | 2 Unknown Aircraft 040$^o$ 60nm | Identify Position, Direction, Scalar; Distinguish Nominal; Associate SERO, Nominal and Scalar; Locate SERO; Correlate Scalar and Nominal |
| +31 | Heavy ECM, Centre Spoke 040$^o$ | Identify Position, Direction, Scalar; Distinguish Nominal; Associate SERO, Nominal, Scalar; Locate SERO |
| ⇒ 12 minutes elapsed time ⇐ | | |
| +43 | Multiple AS6 Radar 040$^o$ | Identify Position, Direction, Scalar; Distinguish Nominal; Associate SERO, Nominal, Scalar; Locate SERO |
| +44 | AS6 Launch - Active/ARM, T42 Target | Distinguish Nominal, Shape, Direction and Scalar; Correlate Scalars, Nominal and Direction; Categorise SERO |
| +45 | ECM Cessation | Associate Nominal and Scalar |
| +45 | 2 Unknown Aircraft 138$^o$ 125nm | Identify Position, Direction, Scalar; Distinguish Nominal; Associate SERO, Nominal and Scalar; Locate SERO; Correlate Scalar and Nominal |
| +48 | AGARVE Radar Detection 140$^o$ | Identify Position, Direction, Scalar; Distinguish Nominal; Associate SERO, Nominal, Scalar; Locate SERO |
| +49 | AS6 Missiles at T42 | Distinguish Nominal; Compare Nominal; Distinguish Scalars |
| +51 | 2 Aircraft, Fast, 141$^o$ 85nm | Identify Position, Direction, Scalar; Distinguish Nominal; Associate SERO, Nominal and Scalar; Locate SERO; Correlate Scalar and Nominal |
| ⇒ 4 minutes elapsed time ⇐ | | |
| +55 | Super Etendard (+ Exocet) 60nm | Distinguish Nominal, Shape, Direction and Scalar; Correlate Scalars, Nominal and Direction; Categorise SERO; Locate SERO |
| +59 | 075$^o$ FPB Launches 2 SSMs 540kts | Distinguish Nominal, Shape, Direction and Scalar; Correlate Scalars, Nominal and Direction; Categorise SERO |

| | | |
|---|---|---|
| +59.5 | 2 Further SSMs Launched | Distinguish Nominal, Shape, Direction and Scalar; Correlate Scalars, Nominal and Direction; Categorise SERO |
| +62 | Exocets Reach Ship | Distinguish Nominal; Compare Nominal; Distinguish Scalars |
| +64 | First SSM Pair Reaches Ship | Distinguish Nominal; Compare Nominal; Distinguish Scalars |
| +64.5 | Second SSM Pair Reaches Ship | Distinguish Nominal; Compare Nominal; Distinguish Scalars |
| +66 | Smoke Observed, Hill $330^{o}$ 20nm (Exocet Launch) | Distinguish Nominal, Shape, Direction and Scalar; Correlate Scalars, Nominal and Direction; Categorise SERO; Locate SERO |
| +68 | Shore-Launched Exocets Reach Ship | Distinguish Nominal; Compare Nominal; Distinguish Scalars. Distinguish Nominal |
| +70 | 2 Unknown Aircraft $110^{o}$ | Identify Position, Direction, Scalar; Distinguish Nominal; Associate SERO, Nominal and Scalar; Locate SERO; Correlate Scalar and Nominal |
| +70.5 | Associated HIFIX | Detection Identify Position, Direction, Scalar; Distinguish Nominal; Associate SERO, Nominal, Scalar; Locate SERO; Correlate Scalars and Direction |
| +71 | 4 Unknown Aircraft $170^{o}$ | Identify Position, Direction, Scalar; Distinguish Nominal; Associate SERO, Nominal and Scalar; Locate SERO; Correlate Scalar and Nominal |
| +71.5 | Associated HIFIX Detection | Identify Position, Direction, Scalar; Distinguish Nominal; Associate SERO, Nominal, Scalar; Locate SERO; Correlate Scalars and Direction. |
| ⇒ 10.5 minutes elapsed time ⇐ | | |
| +82 | 2 Flogger Attack (Iron Bombs) | Distinguish Nominal, Direction and Structure; Cluster Position; Identify Direction and Shape; Rank Position; Correlate Scalar and Nominal; Distinguish Scalars |
| +83 | 4 Flogger Attack (Iron Bombs) | Distinguish Nominal, Direction and Structure; Cluster Position; Identify Direction and Shape; Rank Position; Correlate Scalar and Nominal; Distinguish Scalars |

5.4 Taking this one step further, the cross-referencing of some of the above formalised terms to Keller & Keller's Graphical Implementation Examples (in the main body of the book's text) and other sources (eg. Synthetic BattleBridge) produces the broad recommendations given in Table 5.2, below (listed for a few of the above events only).

**Table 5.2 Possible broad display format options for representing formal visualisation terminology used in Table 5.1**

| Formal term (examples) | Graphical options (see also Figure 5.1) |
|---|---|
| SERO | 2D/3D Coastline Schematic; Area Grid (low contrast). |
| Locate SERO | Stylised/Superimposed Images; Grid and Lining Effects |
| Categorise SERO | Coloured Regions; White Regions for Tactical Importance (also SBB-like *Sentinel* effects?) |
| Identify SERO | Coloured/Photorealistic Images; Exaggerated Heights; Stylised 3D Objects; Wire Frame Surrounds |
| Associate SERO | Inset/Magnify/Overlay Images |
| Associate SERO and Nominal | Exaggerated Heights |
| Associate SERO and Scalar | Stylised Images and Linked Plots |
| Associate Position | Broken/Solid Lines + Object (time history, as with NASA ATC - see Figure 3.3) |
| Identify Position | 3D Wire Frame; Extended Broken Lines (NASA); Particle Trace |
| Identify Direction | Use of Arrows/Triangles; ÒComet TailÓ/Tunnel Effects |
| Associate Nominal and Scalar | Colour Coding; Object Representation (object- value). |
| Correlate Scalar and Nominal | Coloured ÒRibbonsÓ + Translucent Objects (object/airspeed correlation). |

# 6 Conclusions

To return to the original focus questions listed under 1.8:

- Why should the CHS Advanced Naval Interface Programme consider 3D data display? The evidence for or against the adoption of 3D displays is still contradictory, although most of the "blame" for negative comments fall on the designers of the original displays who pay scant attention to the human factors aspects of their work. Even in the absence of formal guidelines, the author believes that carefully implemented 3D displays will bring associated performance benefits, as is being experienced in (for instance) the engineering community of users of VR today.
- What does 3D offer over and above conventional 2D data display? 3D offers a more intuitive interface from the point of view of situational awareness and navigational strategies. There is evidence that relates the use of 3D to improved recall and information uptake, although much of this evidence has been generated using quite simplistic experimental comparisons between textual and basic graphical data representations.
- Is there any (preferably experimental or field) evidence to support a "move" by the military from 2D to 3D data display? What are the potential pitfalls of moving to a 3D representation? Quite simple, no. Whilst there are a number of programmes under way which demonstrate a military focus to the use of 3D displays, very few (if any) have been tested in a field setting or even within a naval vessel simulator environment.
- Are there any accepted or emerging human factors *principles* for effective 3D data display formats? The present report has attempted to integrate the work of a number of researchers to overcome the problem that, apart from one or two very broad references, there is little of any immediate practical use. Even those researchers involved in developing visually quite impressive command and control display concepts have been unable to answer this question.
- What distinguishes "good" or "bad" human performance with regard to evaluating a given 3D display item? Do any valid performance metrics exist? It is possible to define a list of variables that could - suitably validated - define good or bad performance. These include recall, reaction time, integrity of situational awareness, and so on. Whilst a number of qualitative and quantitative measures of human performance exist, it is a fact that most will have to be refined for use in the present context, and evaluated using rigid experimental techniques.

Two statements in a paper by GHL at the recent CHS Interaction Workshop (Military Scenarios and Battle Narratives) are pertinent:

** In the past, theoretical analysis or modelling has often followed technological development. To what extent might new ways of thinking be able to reverse this pattern?*

** How easy would it be to "scale up" an academically insightful proof of concept for an approach to deal with a real application?*

In answer to the first question, it is apparent that technological development has already reached a stage where it is possible to develop all manner of sophisticated information displays. A number of establishments, as has been seen in this report, are already quite some way down the path of showing this to be the case. However, unless the authors have been extremely lax in their reporting, their literature indicates that very little human factors “thought” has gone into the design of the display material. Rather, they appear to have evolved into examples based on trial-and-error practices or just "works of art", and their implementation has been made all-too-easy with the power of current-generation graphics workstations and software toolkits.

As far as the second question is concerned, academic contributions to the development of advanced graphical interfaces (especially in the UK) are almost non-existent. As pointed out in the recent report by the author [1] to the Department of Trade & Industry:

> *“it is generally felt by the commercial VR community that it is unlikely that results and deliverables of real industrial significance will emerge from UK universities engaged in EPSRC funding within the next 24 to 36 months”.*

In short, and unlike previous texts designed to provide well-underpinned guidance for the designers of contemporary human-computer interfaces (eg. Smith & Mosier [43]) there is as yet no “academically insightful proof of concept” to which one can turn. Certainly, when one reads various texts on the use of VR and related techniques in human-system interface design, there are many examples of why 3D information display should be adopted (relating optimal performance with information to optimal performance in a 3D physical world), but these examples are typically anecdotal in nature and all too often reflect the desire of the author(s) to “brainwash” readers into believing 3D is important. Until a proper formal approach to 3D information display design is conducted, experimentally validated (using reasonably robust measures of human performance) and published with explicit cost-performance benefits over and above more conventional display techniques, the human factors community will have to put up with the existence of very disparate sources of information and adopt whatever happens to best (or most credible) practice on a case-by-case basis.

Having attempted to follow some of the guidelines extracted” from one such source - Keller & Keller [28] - it has become increasingly obvious in the short period over which this study has been conducted that basic information of relevance to the developers of $C^3I$ and tactical displays simply does not exist. Certainly there are pockets of useful information here and there (see recommended texts in the following section), but the overall picture as far as principles are concerned is disappointing.

The Keller & Keller/Wehrend approach has, however, been useful in that the procedure helps to focus the mind by breaking down events into a formal structure and linking the components of that structure to established graphical principles (albeit with a bias to the domain of Scientific Visualisation). Problems arise when one needs guidance of relevance to the military domain.

In the absence of formalised, published guidelines, then, one has to turn to current or recent initiatives for “inspiration”. The most impressive of those reviewed during the study are those under way at Wright Patterson AFB and NASA. The work at NASA Ames [22], relating to the investigation of perspective displays for Air Traffic Control, is particularly noteworthy, as the author has held the work of Steve Ellis in high esteem for many years. Ellis’s human factors pedigree is second to none. If the work undertaken by NASA could be used to refine the display concepts so vividly developed under the Synthetic BattleBridge project of WPAFB, backed up with sound experimental trials (using some of the usability assessment criteria being developed by (in particular) Kaur et al. [35] and at University College London), then one might be able to see the beginnings of a strong 3D display standardisation programme. Indeed, even from the “first-pass” analysis of the STOW 97 scenario, it has become evident that there is some commonality between the formalised terms used in Keller & Keller, the graphical representations to which they cross-refer and the concepts put forward in the SBB programme.

# 7 Recommendations

It is highly recommended that CHS obtains copies of the texts highlighted (thus: ♣ in the Reference Section of this report). Whilst there are no fixed implementation guidelines, the recommended texts do contain elements of interest which will enable a more thorough 2D-3D data transformation process to take place.

It is also recommended that CHS makes direct contact with the Synthetic BattleBridge team at Wright Patterson (contact: Stytz - mstytz@afit.af.mil). Following an initial contact by the author, Stytz has offered to travel to the UK and present his work to CHS. Whilst the present study has not been able to identify any formal principles underlying the evolution of the SBB, nor have any evaluation reports been discovered, it would be worth opening a dialogue with the US. At the very least this will serve to demonstrate the UK's interest in maintaining some degree of commonality, particularly in the DIS arena. Indeed, any tactical information display development programme undertaken as a result of this report or other initiatives within CHS should bear DIS developments world-wide strongly in mind. As with similar developments elsewhere within DERA (eg. Chertsey), benefits have accrued in ensuring some degree of commonality between UK and US programmes, especially under the DIS umbrella.

Contact should also be made with Kaur and her colleagues (also Alistair Sutcliffe at the Centre for HCI Design, School of Informatics, City University, Northampton Square, London, EC1V 0HB) and with Lisa Miller (Ergonomics & HCI Unit at University College London, Bedford Way, London, WC1H 0AB). Ideas for performance metrics, probably based on such techniques as Spatial Memory, Cued Recall, Structural Reasoning not to mention the use and relevance of pre-administered cognitive style and spatial rotation tests (etc.) will also be forthcoming in contacts made with these individuals. This contact can be assisted by the author, if required, who is currently involved in supporting both researchers.

The formalised methodology attempted above should be continued with the aim of generating at least a basic structure for selecting graphical implementations. In the absence of more in-depth information, the STOW 97 exercise should continue to provide the basic scenario. It is the opinion of the author that, even by taking a structured approach to developing formats for STOW 97, the result will more likely than not yield an exemplar 3D display concept similar to that put forward by the SBB team.

Once a range of 3D display formats have been agreed, it becomes a straightforward matter to model them, using (for instance) MEDIT, in order to produce a library of 3D tactical display components. This would happen prior to incorporation into a first-level demonstration (eg. based on Performer, or some other run-time operating system). Screen grabs of the resultant images can be obtained, using snapshot, and used for simple experimental glimpse tests - obtaining viewers' feedback on what they remember following presentation for a few seconds, or what the overall image conveys to them.

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***UNCLASSIFIED TITLE***: Effects Of System Delay On Aviator-Related Performance.
***PERSONAL AUTHORS***: Best, P. S.; Schopper, Aaron W.
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***CORPORATE AUTHOR***: Foreign Technology Div Wright-Patterson AFB Oh
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***PERSONAL AUTHORS***: Bross, Paul; Dausmann, Guenther
***REPORT DATE***: Apr 23, 1991

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***CORPORATE AUTHOR***: Computer Sciences Corp Moorestown Nj Defense Systems Div
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***PERSONAL AUTHORS***: Hedden, Geoffrey M.
***REPORT DATE***: Mar 21, 1988

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***CORPORATE AUTHOR***: Massachusetts Inst Of Tech Cambridge Artificial Intelligence Lab
***UNCLASSIFIED TITLE***: How Are Three-Dimensional Objects Represented In The Brain?
***PERSONAL AUTHORS***: Buelthoff, Heinrich H.; Edelman, Shimon Y.; Tarr, Michael J.
***REPORT DATE***: Apr 18, 1994

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***AUTHORS***: A/Barfield, Woodrow; B/Lim, Rafael; C/Rosenberg, Craig ***PAA***: C/(Washington, University, Seattle)
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***AUTHORS***: A/Steiner, Bruce A.; B/Dotson, Diane A. ***PAA***: B/(Lockheed Aeronautical Systems Co., Burbank, CA)
***CIO***: United States-- ***In***: Human Factors Society, Annual Meeting, 34th, Orlando, FL, Oct. 8-12, 1990, Proceedings. Vol. 1 (A92-11126 01-54). Santa Monica, CA, Human Factors Society, 1990, p. 36-40.

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***AUTHORS***: A/Mazur, Kim M.; B/Reising, John M. ***PAA***: B/(USAF, Cockpit Integration Directorate, Wright-Patterson AFB, OH)
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***AUTHORS***: A/Parrish, Russell V.; B/Busquets, Anthony M.; C/Williams, Steven P. ***PAA***: C/(NASA, Langley Research Center, Hampton, VA)
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***AUTHORS***: A/Previc, Fred H.

***CORP***: School of Aerospace Medicine, Brooks AFB, TX. ***CSS***: (Crew Technology Div. )

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***AUTHORS***: A/Schor, Clifton

***CORP***: California Univ., Berkeley, CA. ***CSS***: (School of Optometry.)

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***AUTHORS***: A/Kaiser, Mary Kister; B/Proffitt, Dennis R. ***PAA***: B/(Virginia Univ., Charlottesville.)

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# The Opportunities for Virtual Reality & Simulation in the Training and Assessment of Technical Surgical Skills[1]

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## Abstract

The prohibitive costs and technological difficulties of implementing surgical simulators based on comprehensive virtual humans using dynamic visual, tactile, auditory and even olfactory data have prompted a number of computer-based training (CBT) proponents to carry out a radical rethink of their methodological approaches. One example of such a rethink, MIST (Minimally Invasive Surgical Trainer), evolved from a comprehensive in-theatre task analysis, based on sound ergonomics principles, to ensure that the final product actually measures what its original development team intended it to measure. MIST is a British PC-based "keyhole" surgical trainer which uses commercial Virtual Reality (VR) and database software to foster and document trainees' acquisition of minimally invasive surgery skills, thereby enhancing skills assessment during initial training and career revalidation points. This paper puts MIST developments into the context of world-wide developments in VR generally (hardware, software and surgical applications) and addresses some of the key issues to bear in mind when considering CBT as a solution to medical training and assessment.

## Introduction

Over the past 2 years and, after an incubation period lasting some 6-7 years, the field of endeavour popularly referred to as *Virtual Reality* (VR) has experienced something of a revival. A revival that has taken the form of a number of important developments which have helped VR to become an accessible, usable and justifiable member of the computer-based training (CBT) fraternity for many applications, particularly in the arena of medical and surgical training.

But what exactly has changed? It is impossible to catalogue all recent developments in an article as short as this. However, from a general perspective, VR, in its attempt to promote intuitive, real-time interaction with three-dimensional databases [1], has evolved from a purely (and quite limited) visual interactive experience to become a mature toolkit

[1] Paper presented in Proceedings of *Surgical Competence: Challenges of Assessment in Training and Practice*; Royal College of Surgeons and Smith & Nephew Conference, London, 2 November, 1999.

for which there are, today, **real** applications and evidence of **real** financial, training and assessment benefits. Preoccupation with the once-ubiquitous head-mounted display (HMD) and so-called *immersive* VR has diminished, for the time being, at least. Desktop implementations (using standard computer screens), together with conventional or stereoscopic image projection systems have become popular of recent years. "Higher-end" visualisation techniques, such as the CAVE (small rooms defined by large video projection walls) and dome-based or "wrap-around" imaging systems are highly impressive. However, in the medical world, they tend to be restricted to wealthy foundation or governmental research laboratories and tend not to be focused on real-world cost-effective applications.

The most important change has been the arrival of low-cost, industry-standard multimedia computers and high-performance graphics hardware. Coupled with this, the spread of VR modelling and run-time software (eg. DirectX, OpenGL, VRML, panoramic digital imaging tools, even some PC games engines), together with low-cost and free resources from the Web, is beginning to make VR much more accessible to the non-specialist user or developer than was the case just 2 years ago.

## VR and the Medical Community

During the late 1980s, many visionaries – notably at the University of North Carolina and within the Department of Defense in the US – were developing the notion of the surgeon or consultant of the future, equipped with a head-mounted display and rehearsing procedures in VR, from detailed inspections of an unborn foetus, through to the accurate targeting of energy in radiation therapy, even socket fit testing in total joint replacement. For many years, the US led the field in medical VR, and some of the early conferences and exhibitions delivered many promises about how technology would revolutionise surgery in the new Millennium. Many of those promises would, even today, be hard-pushed to reach reality before 2050, let alone 2000. Nevertheless, in 1995, one of the leading practical advocates of Virtual Environments in the US, Colonel Richard Satava, attempted to categorise achievable applications of VR in medical and surgical domains [2]. He saw developments in the fields of surgical intervention and planning, medical therapy, preventative medicine, medical training and skill enhancement, database visualisation and much more. Satava's original work, sponsored by the Advanced Research Projects Agency, ARPA, focused on large-scale robotic or *telepresence* surgery systems, using VR technologies to recreate the sense of presence for a distant surgeon when operating on, say, a battlefield casualty. However, other research efforts began to emerge across the States (and Europe) using VR in a classic simulator mode to rehearse or plan delicate operations (eg. total joint replacement or in certain ophthalmic operations). It was then shown that one could actually use the successful virtual procedures to back up in situ performance (ie. through the projection of 3D graphics onto the operative site – "augmented reality").

Other programmes saw the future not as *either* robot *or* surgeon, but as a combination of the two with the automated component of the operating theatre augmenting the skill of the surgeon, having been thoroughly pre-programmed in a pre-operative virtual world [3]. Augmented reality took a step further when, as early as 1993, a magnetic resonance image (MRI) had been taken of a patient and overlaid onto a real-time video image of the head [4].

During the late 1980s and early 1990s, the application of VR and associated technologies to the field of medicine and surgery steadily increased, with pioneering (if, at that time, somewhat optimistic companies) such as High Techsplanations (HT Medical) and Cinémed becoming responsible for fuelling the obsession with "making surgical simulation real" [5]. However, very recent conferences and exhibitions suggest a plateau may have been reached, with some of the front-running concepts undergoing a period of consolidation through clinical validation. Tried and tested products, available at prices that are affordable to the greater majority of surgical teaching institutions, are still somewhat elusive. Nevertheless, the key uses of VR remain as Satava predicted, with many projects receiving academic grant support or national and continental funding (as one finds in Europe, with the Framework V Initiative, for example). Developments in technology continue to deliver more and more robust hardware and software and the surgical community gradually becomes more and more involved (albeit at a snail's pace in the UK, it sometimes seems, with collaboration between currently fragmented groups still desperately needed to avoid wasteful reproduction of effort).

A paper such as this cannot hope to cover all historical and contemporary aspects of VR and medicine/surgery under a single cover. However the interested reader can obtain a more in-depth appreciation by accessing the Web pages provided at the end of the text [6, 7] and by selectively reading papers in the excellent publications of Westwood *et al*. [8, 9].

**"Technology Push"**

Despite the coming of the PC/Windows era, bringing with it the capability of delivering highly interactive virtual medical environments (attractive to resource-limited surgical teaching bodies), the international academic research community (in the main) still shows a bias towards sophisticated anatomical and physiological simulations of the human body, hosted on graphics supercomputers. From the digital reconstruction of microtomed bodies of executed convicts (eg. the Visible Human Project [10]) to speculative deformable models of various organs and vascular systems (eg. Forschungszentrum Karlsruhe [11] and University of California Berkeley's VESTA project - Virtual Environments for Surgical Training and Augmentation [12]), the quest to deliver comprehensive "virtual humans" using dynamic visual, tactile, auditory and even olfactory modes of interaction looks set to continue into the foreseeable future. The problem is, who in the real surgical world can afford to procure, operate and maintain such systems? More to the point, do they really offer trainee and consultant surgeons a career-enhancing advantage?

One can partly attribute the failure to deliver practical and affordable training and assessment systems based on VR to a lack of technological appreciation and experience on the part of individual surgical specialists or administrators within the research organisations concerned. In the recent past, a good number of institutions have purchased VR equipment, often on the basis of what looks to be an attractive discount, or with promises of free technical support. However it has soon been discovered that owning a VR system is not as straightforward as it might seem, for at least two reasons:

(1) The development of bespoke, high fidelity libraries of correctly behaving virtual anatomical and physiological datasets is extremely complex. Such libraries do not exist as ready-to-use, off-the-shelf products and the in-house resources required to produce such datasets can be enormous.
(2) As will be discussed later, many VR technologies have not yet developed to a level where they can be used to provide meaningful and experimentally reliable data on surgical performance. A wrist-mounted electromagnetic tracking system may, if correctly set up, provide reasonable data on the spatial motion of the wrist, but will not provide an overall metric of arm-wrist-hand-digit dexterity.

The poor uptake also stems from an equally poor understanding – sometimes on the part of the original simulation developers – of the medical needs and ergonomic requirements of the surgical users and trainees. Furthermore, it is all to often easy to forget that most medical organisations simply cannot justify the excessive initial costs of so-called graphics "supercomputers" – not to mention crippling annual maintenance charges, depreciation and, in today's rapidly changing IT world, rapid technological redundancy.

## VR Peripheral Technologies

If there is one real contribution VR has made to the international R&D community that is worthy of mention, then that must be that it has stimulated the emergence of an impressive range of new and, in many cases, reasonably cheap computer interface technologies. Many of these "peripherals" – devices operated or worn by the human user in order to input data into the computer – never end up as *de facto* components of turn-key VR systems. They tend to appear instead as repackaged "high-tech" solutions to long-standing problems in the assessment of human-computer interfaces, or as attempts to quantify certain features of psychomotor skill.

For example, in the mid-1990s, the company Ingersoll-Rand adapted a commercially available VR hand exoskeletal device called the Dextrous Hand Master (developed by the US company Exos Inc.) by endowing the physical structure of the multi-link device with resistive ink force sensors. The *Ergo Quantifier*, as it was known, was designed primarily for evaluating the effects of equipment design on the performance of the human hand, but was advertised as a keyboard ergonomics analysis tool to assess the potential risk of repetitive strain injury based on individual typing styles. Although the *Ergo Quantifier* was delivered as a PC-based solution with its own suite of software, it faded into oblivion quite rapidly. It is likely that the product's demise was caused by technical and reliability problems with the DHM system (which was one of the *better* peripheral VR devices at the time), coupled with the dexterity restrictions it imposed upon its wearers (thereby introducing artefacts into keystroke analyses).

This is but one example which stresses caution when considering the use of technology – VR or otherwise – for assessing human skill. Today, it is possible to purchase a wide range of devices – multi-axis controllers, instrumented gloves, haptic feedback joysticks, electromagnetic trackers, physiological monitoring units for "biocontrol" (eg. low-cost EEG, EMG, EOG), "wearable computers" with monocular and binocular headsets, and so on. Each class of device has its own merits and limitations, with the latter rarely being made explicit on marketing or technical support material. However, there is one important fact to bear in mind:

**VR peripheral technologies are *not* precision scientific instruments**.

Nevertheless, in the right hands, the potential for using these imprecise products to solve certain conventional ergonomic and interface issues is considerable.

## What can VR Deliver Besides Sensory Experiences?

It is not just the peripheral technologies from VR markets which, when in the right hands, can contribute to the assessment of human performance. The very object-oriented nature of many current VR run-time and data management packages make them ideal application programming environments for recording – even replaying – the user's performance when navigating and interacting within a virtual environment. Consequently, recent efforts by a small number of international institutions and companies have focused on adding value to their simulations by endowing otherwise "dumb" virtual environments and objects with an ability to record user-induced motions, handling times, collisions (both intentional and erroneous), and so on. One example of such a system will be described later. But what, returning to the topic of surgical assessment, should VR systems actually record?

Darzi *et al*. claim that "finding objective criteria for judging good surgical technique is difficult" [13]. In fact, the problem is much more acute than this and one should, perhaps, replace the word 'good' with 'any'. However, from an assessment standpoint, specialists from the ergonomics community will contest the claim that it is difficult to find objective criteria in the assessment of all skill-based activities. Indeed, the disciplines of ergonomics and applied psychology have, for the latter half of the 20$^{th}$ Century, made significant advances in developing techniques for the analysis of tasks characterised by specialist decision-making and psychomotor behaviours [14]. Some of the techniques, for measuring such features as mental workload or mental resource, cognitive performance, perceptual-motor skills and situational awareness have been subjected to quite stringent validation, when integrated within appropriate experimental designs and régimes [15, 16, 17, 18, 19]. However, a good many still rely on quite antiquated products and, when exposed to users in a contemporary setting, require considerable subjective effort on the part of the administrator during the interpretation of results.

Virtual Reality, coupled with a competently programmed database management system, offers the means by which subjectivity in performance assessment can be significantly reduced, even removed altogether. However, this statement is only true if the VR system, or the peripheral technology used, is selected and implemented so that **it measures what the researcher intended it to measure**. This is typically referred to as the *ecological validity* of an instrument or experimental design. It is generally agreed that the term *competency* refers to an individual's knowledge, skills or abilities (sometimes called "KSAs") performed to an acceptable standard when observed or recorded in the individual's place of work. **It should – stress *should* – make little or no difference if that place of work is real or virtual**.

### What is Being Measured? The Importance of an Ergonomics Task Analysis

> "Attention comes first, learning after attention is focused. And learning is primarily action..." (Dewey *et al*., in Bricken [20]).

> "The most important principle of classroom activity design is that the students' actions determine what will be learned..." (Walker, in Bricken [20]).

The most important three words in these quotes are **attention**, **action** and **learning**. By its very nature, Virtual Reality is an attention-grabbing medium with the anecdotal *intrinsic motivational* qualities such a feature commands (ie. learning or information retention are improved and subsequent performance in the real world equivalent is enhanced). Increasingly, the VR community is providing good examples, with objective measures, of *transfer of training* – improved performance (eg. faster learning rates and fewer errors) in the real world following training in the virtual world equivalent. This is a key issue for the medical community and one that will accelerate the uptake of VR once valid and reliable results from the growing installed base of experimental simulator prototypes are published in reputable journals.

However, to achieve this, one has, once again, to turn to the ergonomics and applied psychology community, not just for guidance in the appropriate design of experimental programmes [15, 16, 17] but for guidance in the structured analysis of real-world surgical tasks. Additionally, one needs to be able to use the results of such an analysis to specify the abstraction of the real-world task elements into their VR counterparts.

An excellent definition of task analysis was put forward by Bradley of axsWave Software, Inc., based on two IBM documents compiled by Terrio & Vreeland [21] and Snyder [22]. A task analysis is an ordered sequence of tasks and subtasks, which identifies the performer or user; the action, activities or operations; the environment; the starting state; the goal state; the requirements to complete a task such as hardware, software or information.

Without a properly executed task analysis, one runs the risk of specifying or designing a VR (or any CBT or multimedia) system that fails to record or measure those elements of human skill one was targeting in the first place. One also jeopardises the future integrity of any experimental programme that sets out to validate one's training and assessment concept, not to mention the transfer of training from the virtual to the real.

## An Example – MIST (Minimally Invasive Surgical Trainer)

During the second half of 1994 and early in 1995, numerous articles appeared in the British Press and on mainstream TV news programmes which cast serious doubt on the future of "keyhole" surgery, specifically those practices in support of laparoscopic cholecystectomy. The fact that patients had died or had been left in considerable pain, sometimes as a result of surgeon error, led to serious calls for action, especially with regard to improving the training and assessment of surgeons "graduating" from conventional, open surgery, onto these more remote techniques. In the UK, unlike the US or some countries within continental Europe, live animal-based training is prohibited. As a result, primary laparoscopic experience is typically fostered through the remote handling of sweets or candy, grapes, raw chicken tissue, plastic tubing, foam-mounted balloons or synthetic body models with replaceable (and, thus, quite costly) organs. This situation, coupled with increasing UK regulatory and certification pressures (the pressures are still evident today), meant that in 1994 the provision of a simulator – with some form of basic, yet integrated means of assessment – was seen as instrumental to the development of specific surgical skills.

Established in the Spring of 1994, the North of England Wolfson Centre for Minimally Invasive Therapy commenced operations under grant support from the UK Wolfson Foundation and the British Government's Department of Health. Today, as in 1994, the Manchester Centre revolves around a collaborative arrangement between Virtual Presence and Manchester Royal Infirmary (MRI). The collaborators were, over a 2-year period, tasked with evaluating VR and related technologies, possibly progressing to a stage whereby a prototype British laparoscopic cholecystectomy simulator could be developed to a state where clinical and human factors evaluations could take place [23].

## User Requirements: In-Theatre Task Analyses

The first stage of the Wolfson Centre project involved a number of short in-theatre observation and recording sessions (assisted by specialists at the Manchester Royal Infirmary), using video and digital endoscopy. The aim of these task analyses, which were based on similar exercises carried out by the author, albeit in the applications fields of subsea robotics and the food industry [24, 25], was to obtain a clear understanding of the performance and ergonomic features of the surgeon's task and workplace, addressing such issues as how dexterity and psychomotor skills are affected by:

- Workspace layout,
- Proximity of surgical team (ie. how the surgeon's performance is constrained by the physical presence of colleagues and their associated equipment),

- Surgeon's posture (including the need to change and hold postures for certain activities; such as diathermy, the short-term impact of upper torso fatigue),
- Individual working styles,
- Patient condition,
- Surgical progress, contingency measures (ie. deviations from the "norm" brought about by sudden changes in patient's state or even surgical errors).

However, another part of the in-theatre exercise involved the evaluation of a number of different forms of media for image capture (and subsequent digitising for the anticipated anatomical texture mapping exercises). In other words, the decision to "make surgical simulation real" [5] had already been taken. In addition, MRI surgeons provided practical demonstrations of current training practice as well as strictly supervised "hands-on" experience, in order to appreciate the physical properties of human anatomy, such as form, mass, compliance and the extent of movement of the laparoscopic instruments. These exercises, together with lengthy briefing sessions from practising and trainee surgeons, produced a number of conclusions which were very much examples of "technology push", as criticised earlier. Concerns about how to avoid the use of head-mounted displays but still deliver a 3D image to the surgeon's eyes (eg. via autostereoscopic systems) was but one example of this preoccupation with VR technology. Other areas of recommendation addressed the problems of modelling the deformation of complex virtual tissues and fluid behaviours, or the design of sophisticated haptic interface devices.

Unfortunately, these recommendations served to drive the Wolfson Centre research programme forward for at least 12 out of the allocated 24 months. This is not to criticise the work that was actually done, the results of which actually resulted in impressive prototype British systems long before the emergence of their American or Japanese counterparts [23]. However, what was unfortunate was that the *real* ergonomic findings of the in-theatre task analyses had been ignored, resulting in a research programme which, had there not been a radical rethink, would have delivered a simulator which could neither be used nor afforded by most medical teaching institutions.

**MIST**

The specific result of taking a step back and revisiting the earlier task analyses with a more unbiased approach was the identification of an urgent need to develop a low-cost, PC-based laparoscopic cholecystectomy simulator. What the task analyses had actually produced was a structured decomposition of a range of minimally invasive tasks which could be defined in the form of "human performance primitives". It was found that each primitive could be implemented reasonably easily within a proprietary VR software package and each could be endowed with "academic credibility", particularly from the domains of applied/experimental psychology and human factors (eg. Boff & Lincoln [26]).

The end product of these further analyses was **MIST**, a surgical psychomotor **skills** trainer, based on a commercially-available instrumented laparoscopic interface, connected to an industry standard PC. Movements from the laparoscopic interface tools (recently redesigned by Virtual Presence and Immersion Corporation) are translated into

3D computer graphics which accurately track and represent the movements of those tools within a virtual "operating" volume. Within this volume, simple geometric shapes are generated and subsequently manipulated using the interface tools. The graphics have been intentionally kept simple in order that high frame rates may be maintained on relatively low cost equipment and to preserve the validity and reliability of the simulations when used in applied experimental research.

**MIST** features 5 general modes of operation: tutorial, training, examination, analysis and configuration. Closer analysis of the video records generated during the earlier in-theatre observation sessions, together with iterative review sessions involving consultant surgeons and senior registrars, subsequently drove the specification of 6 basic task modules for **MIST,** including combinations of instrument approach, target acquisition, target manipulation and placement, transfer between instruments, target contact with optional diathermy, and controlled instrument withdrawal/replacement.

These tasks, described in more detail below, can be configured for varying degrees of difficulty and the configurations saved to a library for reuse. Specific task configurations can be assigned to individual students. In the examination mode the supervisor can select the tasks and repetitions and is able to order and save to a specific file for that trainee. Progress can be assessed with optional performance playback of the training session or examination. Data analyses permit quantification of overall task performance (accuracy and errors, plus sub-task time, time to completion and motion efficiency are logged during the tasks) and right/left hand performances. The data are accessible in forms suitable for statistical analysis and significance testing.

## The MIST Task Set

The main interface to **MIST** is quite simple. As well as the task setup, calibration and help/text sections, the majority of the display is occupied by the interactive graphics window. In essence, this takes the form of a wire-frame box which describes the effective operating volume in which target stimuli appear, are acquired and can be manipulated by virtual representations of the laparoscopic instruments.

For all tasks, a **MIST** training session starts when the subject manipulates the instruments to "touch" a simple start box located in the centre of the operating volume. Once objects have been acquired, successful and erroneous acquisitions are colour coded appropriately (and recorded).

### *Task 1: Simple Object Acquisition and Placement*

Task 1 tests the subject's ability to acquire an object with either hand and move it to a new 3D location within the virtual operating volume. The task has relevance to such operative activities as clip placement, tissue removal and gall stone recovery. The system generates a spherical target object at a random position within the operating volume. The subject moves the instrument tip to acquire the sphere. Once acquired, a small wire-frame box appears at a random position within the operating volume and the subject is required to position the sphere within the box. The task is repeated for a set number of repetitions.

### *Task 2: Between-Instrument Transfer*

Task 2 relates to a fundamental surgical requirement - the transfer of an object from one instrument to another. The task has relevance (for example) to the fundus of the gallbladder being passed between two grasping forceps before being retracted. A more advanced skill application would be passing a needle between two needle holders during suturing. The system generates a spherical target object at a random position within the operating volume. The subject moves the instrument tip to acquire the sphere. Once acquired, the subject is required to pass the sphere to the other instrument. Intersections with the sphere and parts of the instrument other than the tool tips result in deductions to the accuracy score. On successful transfer, a wire-frame box appears at a random position within the operating volume and the subject is required to position the sphere within the box. The task is repeated for a set number of repetitions.

### *Task 3: Target Traversal*

Task 3 focuses on sequential instrument-to-instrument transfer - the “walking” of instruments along vessels or structures to reach their extremities (eg. the neck of the gallbladder, as seen at the start of a laparoscopic cholecystectomy). This task in effect combines the skills of Task 1 with Task 2. The system generates a cylindrical target object at a random position within the operating volume. The cylinder is subdivided into a number of segments. The subject is required to grasp the top segment with either instrument, followed by the next segment along the cylinder with the remaining instrument. The procedure is repeated in a step-by-step fashion, alternating between instruments until all segments have been acquired. The task is repeated for a set number of repetitions.

### *Task 4: Tool Withdrawal and Insertion*

Changing from one instrument type to another and being able to reinsert the new instrument quickly and accurately is a key skill in laparoscopic surgery. In Task 4, the system generates a spherical target object at a random position within the operating volume. The subject moves the instrument tip to acquire the sphere. Once acquired, the remaining instrument is brought into contact with the sphere. After contact has been made, it is then withdrawn completely from the operating volume. The same instrument is then reintroduced to make contact with the sphere. Unintentional collisions with the sphere and other instrument result in deductions to the accuracy score. The task is repeated for a set number of repetitions.

### *Task 5: Diathermy Procedures*

Task 5 focuses on the accurate application of diathermy to specific bleeding points in the gallbladder bed. The task requires accurate 3-D location with activation of the diathermy instrument only when appropriate contact has been achieved. The system generates a spherical target object at a random position within the operating volume. In this case, the surface of the sphere possesses 3 small cubes, which have to be accurately acquired with the appropriate instrument. Once acquisition of a cube has occurred, the application of diathermy is simulated via the depression of a foot pedal. The cube gradually changes colour to reflect the amount of heating applied and vanishes when diathermy has been "completed". All three cubes have to be removed. The task is repeated by switching the hands holding the grasping and diathermy instruments.

### *Task 6: Object Manipulation and Diathermy*

The final task of the original **MIST** trainer combines the skills acquired in Tasks 4 and 5 and focuses on object acquisition, manipulation and diathermy, within a restrictive volume. An in-theatre example might be accurate instrument replacement of dissecting forceps with a diathermy hook to control precisely a bleeding point on the gallbladder. As before, the system generates a spherical target object at a random position within the operating volume. The subject moves the appropriate instrument tip to acquire the sphere. The remaining instrument is then withdrawn completely from the operating volume. This triggers the system to "endow" the sphere with a pre-set number of small cubes. The previously withdrawn instrument is then reintroduced into the operating volume and the subject is tasked to apply diathermy to the cubes, only this time the position of the sphere has to be maintained within a small bounding box as well. The task is complete when the set number of cubes have been removed from the sphere. Any unintentional collisions with the sphere and other instrument result in deductions to the accuracy score. The task is repeated by switching the hands holding the grasping and diathermy instruments.

## Conclusions

Subsequent worldwide testing by clinicians and applied psychologists alike have yielded a battery of objective results, one example outcome being that the MIST system now forms a mandatory component of basic and advanced medical courses at the European Surgical Institute near Hamburg, covering a wide range of techniques, from cholecystectomy to thoracic surgery. The results include such features as improvements in surgical movement efficiency (actual/ideal instrument path lengths, past-pointing errors and sub-movement corrections) and error reduction when MIST trainees are compared to control groups (eg. Taffinder *et al*. [27, 28, 29]). MIST task sensitivity to sleep deprivation has also been shown [30], as have improvements in multiple incision performance, reduction of the *Fulcrum Effect* (perceived instrument reversal) and increased use of both hands in endoscopic tasks have been reported (Gallagher [31]). In general, it can be stated that experimental results based on MIST tasks demonstrate statistically clear performance differences between novice, junior and experienced laparoscopic cholecystectomy surgeons (Gallagher *et al*. [32]).

Of course, MIST is not the only VR-based surgical assessment tool on the market at the present time, although it has been subjected to a more in-depth experimental treatment than many of its contemporaries (NB. around 5 papers delivered during the training session of the September 1999 Annual Scientific Meeting of the Society for Minimally Invasive Therapy were actually based on the MIST system [33]). Companies such as HT Medical are still forging ahead with their own marketable developments. However, MIST is one of the very few systems that has benefited from an initial (if somewhat protracted) human factors analysis. Such an analysis has resulted in a very focused simulation development which not only offers trainers and assessors a structured and validated means of appraising the performance of those in their care, but also allows for future modular expansion, independent of technological developments in the quest for the comprehensive "virtual body". The philosophy underpinning MIST also offers researchers and developers in other domains – operating theatre designers, ergonomics, medical devices and instrument design, for example – a means by which their concepts can be tested by consultant surgeons, thereby minimising the time to market.

As developments in the medical and surgical fields become more and more advanced – in direct intervention/surgery assistance robotics, interactive bespoke patient imaging techniques and microtechnology, to mention but 3 – the need for these modular skills simulators will become apparent.

Virtual Reality and associated technologies offer enormous potential in the field of early surgical training and in the assessment of perceptual-motor competency/skills at revalidation points of a surgeon's career; this is clear. However, the key to the successful adoption of VR lies not with the hardware and software developers *per se*., but with a clear user-centred implementation [34], making sure the technology satisfies the **real** training and assessment needs of the surgical fraternity of the future.

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# IERAPSI

***Integrated Environment for the Rehearsal and Planning of Surgical Interventions***

## A Human-Centred Definition of Surgical Procedures

**Work Package 2, Deliverable D2 (Part 1)**

**Revision 1.1**

**Contract No.: IST-1999-12175**

**Prepared by: Prof. Robert J. Stone**
**MUSE Virtual Presence**

**Date: July, 2000**

**Ref.: IERAPSI/VP/RJS/TR/000504/1**

# Executive Summary

This Interim Report has been prepared in fulfilment of Deliverable D2 (Part 1) required for completion of Work Package 2 (part T2.1) of the EU Framework V Project ***IERAPSI***, an Integrated Environment for Rehearsal and Planning of Surgical Interventions. Deliverable D2 (Part 1) relates to the **human-centred definition of surgical procedures**, specifically focusing on surgical activities underpinning mastoidectomy, cochlear implantation and acoustic neuroma resection.

Following a review and critique of similar studies carried out elsewhere, a context specific task analysis is described, based on the guidelines laid out in ISO 13407 (Human-Centred Design Guidelines for Interactive Systems) and on the following sources of data:

- "off-line" investigation, through document reviews, informal interviews and personal experience with existing training techniques (cadaveric temporal bone, CD-ROM training and synthetic temporal bone dissections),
- in-theatre observation and verbalisation of and from practising surgeons,
- first-level review of video records of operations.

With the support of the staff of the ENT unit, the Department of Otolaryngology, Head & Neck Surgery and the theatre personnel at Manchester's Royal Infirmary and the Institute of Laryngology and Otology (ILO), University College London, the author was permitted to observe and, where possible, video record surgeon performance and close-in drilling activities (backed by additional important video contributions from the University of Pisa). Five theatre sessions were analysed in detail, each lasting an average of 6 hours:

- Infantile Cochlear Implant,
- Middle Fossa Acoustic Neuroma,
- Translabyrinthine Acoustic Neuroma (2 examples)
- Stapedectomy "Follow-Up" and Ossicle Prosthesis at ILO (*combined approach*)

The results of the task analysis are discussed in the context of 2 classes of IERAPSI system, a virtual **surgical planning** environment and a virtual **training** environment.

With regard to **planning**, whilst IERAPSI concentrates on the development of software modules to support the processing of radiological data, the way in which surgeons actually use the data must be considered early and refined by consultation with users as the concepts emerge. Initial human interface proposals are put forward which describe two systems:

- An off-line (pre-operative) system based around a multi-user real-time 3D display and appropriate interactive 6-dof controls. Amongst the key anatomical features to be highlighted are the facial nerve (and any other key neuronal features), the jugular bulb and sigmoid sinus, blood vessels of secondary importance, the semi-circular canals and close proximity of brain tissue.
- An on-line (intra-operative), scaled-down version of the multi-user system, ergonomically located to provide maximum benefit to the surgeon with possible

interaction via speech recognition. THIS SUGGESTION IS, IN FACT, OUTSIDE THE SCOPE OF THE CURRENT IERAPSI PROJECT BUT MAY BE WORTH CONSIDERING FOR FUTURE PRODUCT EXTENSIONS.

The **training** environment is designed to simulate those aspects of the surgeon's task that are characterised by special procedures and operative skills. The report considers key human interface features, including stereoscopic *vs.* conventional display, haptic feedback, fidelity and coding techniques for initial bone exposure, drilling/burring effects, use of other virtual instruments and materials, and error/performance recording. Careful consideration must be given to the display-control stereotypes expected by temporal bone surgeons and those delivered by the final training interface. Otherwise, a fixed display (or display frame) moveable image solution might foster negative transfer of training from the virtual to the real.

Finally, although not a requirement of the IERAPSI project, it was decided to analyse the available data to a slightly deeper level, to see if, like another surgical skills product (Virtual Presence's MIST laparoscopic cholecystectomy trainer), the surgeon's skills could be decomposed to abstract task elements. As the very nature of temporal bone tasks demands the use of some form of haptic feedback, at least in the simulation of drilling activities, an abstract content task simulator cannot expect to provide all training for future ENT surgeons. Nevertheless, a number of common task elements/surgical behaviours were used to develop an initial proposal for such a simulator:

- "deep" drill positioning,
- sensitive structure visual avoidance,
- thin bone "hooking",
- bone structure contour following,
- simple linear tracking,
- deep drilling under conditions of partial visual obscuration of the smallest of burrs,

## Acknowledgements

The IERAPSI Project (an Integrated Environment for the Rehearsal and Planning of Surgical Interventions) is a collaboration between the University of Manchester, CRS4, the University of Dresden, University College London, the University of Pisa, Virtual Presence Ltd., Genias Benelux b.v. and CS-SI. The project is managed by the University of Manchester and is funded by the European Community under the IST Project IST-1999-12175. The author would like to acknowledge the contributions from members of Manchester Royal Infirmary's Department of Otolaryngology, Head & Neck Surgery, and of the Department of Surgery and North of England Wolfson Centre for Minimally Invasive Therapy:

**Prof. Richard Ramsden**, Professor of Otolaryngology, Manchester Royal Infirmary (MRI)
**Prof. Anthony Taylor,** Head of Department, Institute of Laryngology and Otology (ILO), University College London
**Mr Ghassan Alusi**, Lecturer, ILO

**Prof. Stefano Sellari-Franceschini** and **Dr Emanuale Neri**, Divisions of Otolaryngology and Diagnostic & Interventional Radiology (respectively) University of Pisa

**Mr Rory F McCloy**, Clinical Director, North of England Wolfson Centre for Minimally Invasive Therapy (also Head, University Department of Surgery, MRI)

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**Dr Simon Hargreaves**, Specialist Registrar (ENT), MRI

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**Theatre staff**, **nurses** and **secretaries** of the relevant departments within the MRI and ILO

# Contents

# 1 Introduction

This Interim Report has been prepared in fulfilment of Deliverable D2 (Part 1) required for completion of Work Package 2 (part T2.1) of the EU Framework V Project ***IERAPSI***, an Integrated Environment for Rehearsal and Planning of Surgical Interventions. Deliverable D2 (Part 1) relates to the **human-centred definition of surgical procedures**, specifically focusing on surgical activities underpinning mastoidectomy, cochlear implantation and acoustic neuroma resection. The deliverable therefore forms an important input to subsequent project discussions on issues of relevance to the design and evaluation of human-centred components of the *IERAPSI* system and of temporal bone operations generally. The report is structured as follows. Following a brief review of the importance and nature of human factors task analyses (in the context of emerging international standards), a short section addressing the contribution of other related studies in the temporal bone arena is presented. The main section of the report, Section 2, describes the actual analysis sessions undertaken, from "hands-on" cadaveric training within the Temporal Bone Laboratory of Manchester's Royal Infirmary (MRI; Department of Otolaryngology, Head & Neck Surgery), through experience with commercial training products (multimedia and physical models), to the generation of *in situ* observational records (at the MRI and Institute of Laryngology and Otology, University College, London), including video (with contributions from the University of Pisa), surgeon verbalisations and interviews. The relevance of these findings to future IERAPSI work packages and other opportunities (eg. abstract content task trainers) are also presented.

## 1.1 Task Analysis

A task analysis is a process by which one can formally describe the interactions between a human operator and his/her working environment (including special-purpose tools or instruments), at a level appropriate to a pre-defined end goal (typically the evaluation of an existing system or the definition of the functional and ergonomic features of a new system). An excellent definition of task analysis was put forward by Bradley of axsWave Software, Inc., based on two IBM documents compiled by Terrio & Vreeland (1980) and Snyder (1991):

> *A task analysis is an ordered sequence of tasks and subtasks, which identifies the performer or user; the action, activities or operations; the environment; the starting state; the goal state; the requirements to complete a task such as hardware, software or information.*

Without a properly executed task analysis, one runs the risk of specifying or designing a VR (or any computer-based training or multimedia) system that fails to record or measure those elements of human skill one was targeting in the first place. One also jeopardises the future integrity of any experimental programme that sets out to validate one's training and assessment concept, not to mention the transfer of training from the virtual to the real.

There is no one "magical" formula for executing a task analysis. The type of analysis employed depends on the human factors specialist involved, whether or not the task exists in reality, the goal of the analysis (eg. are the results required for new system design or training procedures) and any constraints imposed by the analysis environment (see also Section 2.2). The task analysis should form an early and central component of any project that involves a major human-centred component. Indeed, recognition of this has recently been formalised by the publication of International Standard ISO 13407, *Human-Centred Design Processes for Interactive Systems* (ISO, 1999). ISO 13407 specifies 4 general principles of human-centred design and 4 further principles of human-centred design activities, namely:

## Principles of Human–Centred Design

**(a)** Ensure active involvement of users and a clear understanding of user and task requirements (including context of use and how users might work with any future system evolving from the project – if at all),
**(b)** Allocate functions between users and technology (recognising that today's technology, rather than de-skilling users, can actually extend their capabilities into new applications and skill domains),
**(c)** Ensure iteration of design solutions (by involving users at as many stages of the design and implementation process as is reasonable practical),
**(d)** Ensure the design is the result of a multidisciplinary input (again this emphasises the importance of user feedback, but also stresses the need for input from such disciplines as marketing, ergonomics, software engineering, technical authors, etc, etc).

## Human–Centred Design Activities

**(a)** Understand and specify the context of use (including the characteristics of the intended users; the tasks the users perform, or *are* to perform; the environment in which users use, or *are* to use the system; relevant characteristics of the physical environment),
**(b)** Specify user and organisational requirements (in the context of the present project, this includes aspects of team working, health and safety issues, user reporting structures and responsibilities),
**(c)** Produce design solutions (with multidisciplinary team and user involvement),
**(d)** Evaluate designs against requirements (a continuous process throughout the design cycle).

The present report concentrates primarily on **Principle (a)** and **Activities (a)** and **(b)**. A context-specific task analysis, such as that reported here, will achieve many of the requirements listed under these principles and activities and should prove of considerable value to focusing efforts in the second part of WP2, namely the definition of target system functionality. Here decisions taken will affect how well the human's capabilities and limitations are taken into account when the overall human element is integrated into the proposals for the final system design, operational procedures and training régimes.

However, this report does not mark the end of the task analysis process. As with the rôle of design in the ISO 13407 treatment of a human-centred system (**Principle (c)**), task analysis is also an **iterative** process. Once the initial exercise has provided an input into early system design processes, it will be necessary to perform the analysis again in order to ensure that the recommendations do not produce any unforeseen human performance artefacts or safety-critical consequences. As a project progresses and the design concepts for system, equipment and procedures become more concrete, task analyses can be used to guide requirements for personnel and training, and to support quality accreditation, in any case where an exploitable product may arise.

There are many techniques for carrying out a task analysis. Some involve observational and/or interview techniques (often backed up with video and/or audio records). Others can employ quite sophisticated computer-based solutions, from mixed media data recording (video, keystrokes, physiological parameters, voice, etc.) to simulations based on human performance parameters and cognitive models. Some of the more popular methods are charted in Table 1.

The methodology chosen for the present study was based on a combination of a subset of those listed in Table 1 and previously used to good effect in the analysis of remotely operated submersible missions (Stone, 1984), offshore diving supervision tasks (Stone, 1991), the food processing industry (Stone, 1994), laparoscopic cholecystectomy tasks (Stone, 1999a) and, more recently, the integration of haptic feedback technologies in a virtual mannequin aerospace maintenance training demonstrator (Stone (1999b)). Due to the short time available for the present analysis sessions (and the need to fit in with the schedules for specific operations), a combination of interface survey and timeline analysis was chosen, allowing for the following types of raw data to be recorded:

**(a) off-line, through documentation, interview and personal experience with existing training techniques (cadaveric temporal bone, CD-ROM training and synthetic skull dissections),**

**(b) in-theatre observation and verbalisation of and from practising surgeons,**

**(c) first-level review of video records of operations.**

| Task Analysis Technique | Description |
|---|---|
| Hierarchical Task Analysis (HTA) | A broad approach used to represent relationship between tasks and sub-tasks. HTA documents system requirements and the order in which tasks should take place. Useful to determine how the work should be organised to meet system goals. Applications range from taking a global look at a system to looking at specific details of a system, such as interface design. |
| Interface Surveys | A group of methods used for task and interface design to identify specific human factors problems or deficiencies. These methods require an analyst to conduct a systematic evaluation of the human-system interface and record specific features. Examples of these methods include control/display analysis, workplace posture, equipment wiring problems, etc. (see also Section 3.5). |
| Link Analysis | Used to identify relationships between human and machine/equipment components of a system. Provides a means to represent the nature, frequency, and/or importance of links between components within a system. |
| Operational Sequence Diagrams | Used to illustrate relations between personnel, equipment, and time. Identifies operations in the order in which they are carried out using standard symbols. Flowchart represents information flow and behaviour rather than the observable process. |
| Timeline Analysis | A set of principles rather than a precisely defined technique. Used to map operator's tasks along time to take into account task frequency, duration, and interactions with other tasks and personnel. |

**Table 1: A Selection of Task Analysis Techniques**[1]

[1] Based on table in: ***Human Factors Design Recommendations for Underground Mobile Mining Equipment***; Pittsburgh Research Laboratory, Mining Health and Safety Research.

## 1.2 Previous Related Studies (Temporal Bone & Task Analysis)

Before embarking on the task analyses, a literature search was conducted, initially via the Web and later with the Ergonomics Information Analysis Centre (University of Birmingham) and Medline. As has been discovered in the past with medical training and simulation projects, very few references of real relevance exist. The EIAC results (based on keyword searches under the titles of surgical task analysis and surgical competence, psychomotor surgical testing) uncovered a small number of already-known references on performance and error but most were too general and focused on surgical clothing, equipment and facilities. Certainly, the Web is awash with articles and short courses on human factors and task analyses for general design, training and organisational issues. However some articles were discovered, notably the oft-quoted paper by Johnston *et al.* (1996). On the basis of the paucity of articles discovered, it was decided to put slightly more effort into the present report than had first been anticipated.

The Web-based search also highlighted the existence of a CD-ROM product, the *Temporal Bone Dissector* Blevins *et al*. (1997). As this was the only available product of relevance to temporal bone anatomy and (loosely) training, it was acquired for further investigation and evaluation (see Section 2.7). Of relevance to the present project (although sadly lacking in thorough details of any task analysis performed) were the studies discussed briefly in the following sections.

### 1.2.1 University of Illinois at Chicago

The Virtual Temporal Bone demonstrators of the University of Illinois (UIC) are typically listed early in Web-based searches on the topic. UIC's VRMedLab networked facility (eg. http://www.bvis.uic.edu/vrml/Research/TemporalBone/researchTB.htm) is designed to provide an educational resource to surgeons of otolaryngology, enabling them to visualise bone-encased structures within the temporal bone using interactive 3D visualisation technologies. Digital sections of the human ear and temporal bone (prepared from actual glass slide specimens) make up the VR model, supplemented with special sculptures and converted CT records of objects too small to reconstruct from the physical samples (eg. the middle ear ossicles).

The VR system has not been designed to replace the cadaveric drilling experience. However, UIC researchers describe post-VR exposure drilling activities as being equipped with a mental model of the drilling site enabling them to experience working with "glass" rather than bone (Figure 1).

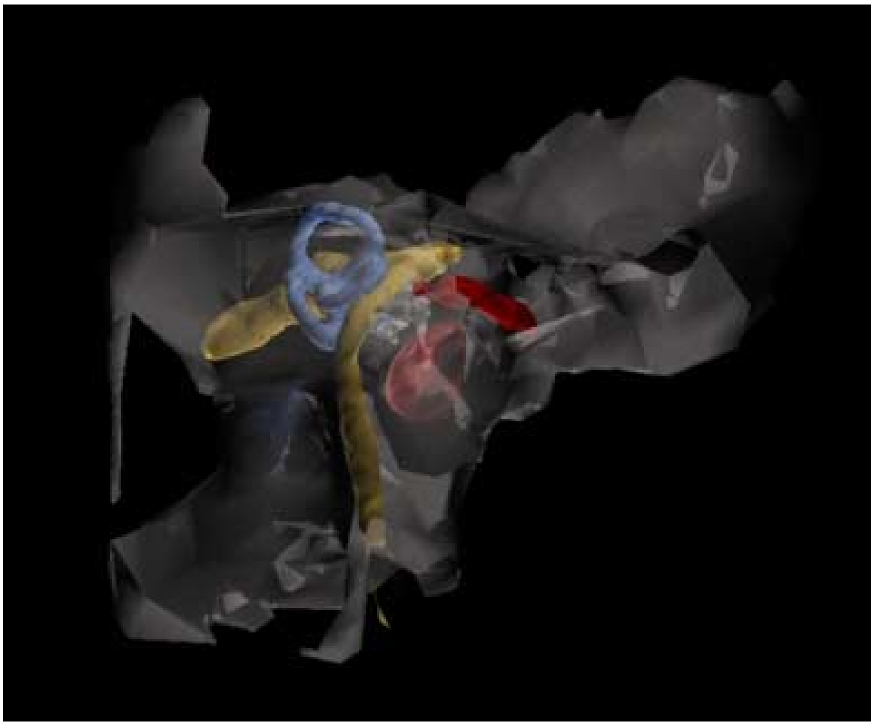

**Figure 1: UIC Temporal Bone Model**

As far as IERAPSI is concerned, the UIC Virtual Temporal Bone demonstrator is of more relevance to preoperative planning than actual hands on training. However, two issues need to be recorded here. The first is that, unlike the IERAPSI project, there appears to have been no task analysis conducted, nor a collation of user-stated needs. Secondly, the technological implementation of the UIC demonstrator is somewhat typical of current academic work in VR and medicine (indeed VR generally). In other words, rather than take a user- and market-driven approach to defining how such a demonstrator might be developed using accessible technologies, based on COTS Windows hardware and software, the UIC researchers have chosen (for no rationalised explanation) a somewhat expensive system implementation based on Silicon Graphics computers and *Immersadesk* viewing technology (with *CrystalEyes* field sequential, or "active" stereo glasses, and a hand-tracked wand – as shown in

**Figure 2: University of Illinois VRMedLab Cochlea/Semi-Circular Canal Model on an *Immersadesk***

Figure 2). It should also be noted that in many of the Web papers on the UIC facility, it appears that the system is neither undergoing trials nor yet being used *in situ* by trainee or consultant surgeons.

### 1.2.2 Department of Pædiatric Dentistry, University of Copenhagen

References to the University of Copenhagen's 3D-Lab work is very scarce (http://www.lab3d.odont.ku.dk/), although the initiative appears to be a collaborative venture on the part of the School of Dentistry, the University Hospital and the Department of Mathematical Modelling at the Technical University of Denmark. It seems that surgical drilling simulation work here has been under way since 1996 or 1997, although current status is unknown.

### 1.2.3 Ohio Supercomputing Center (OSC)

The work of OSC is well publicised over the Web and in slightly more detail than UIC's VRMedLab efforts. Unfortunately, their technological solution, whilst somewhat in line with envisaged developments in IERAPSI, is still a victim of "technology push" over "market or user pull". Furthermore, their solution focuses not so much on the planning stage of temporal bone activities, but on the actual hands-on surgical training for drilling.

In the OSC's most detailed Web paper (www.osc.edu/Biomed/NIDCD/), reference is made to a task analysis, the results of which are presented in fairly simplistic detail, even though the data sources are similar to those collated in the present study. The final interface (Figure 3) consists of a head-mounted display (a Virtual Research Inc. V8) and 2 Sensable Technologies Inc. *PHANToM*s, the Desktop version used for suction/irrigation and Model 1.5 for drilling – see also Figure 4).

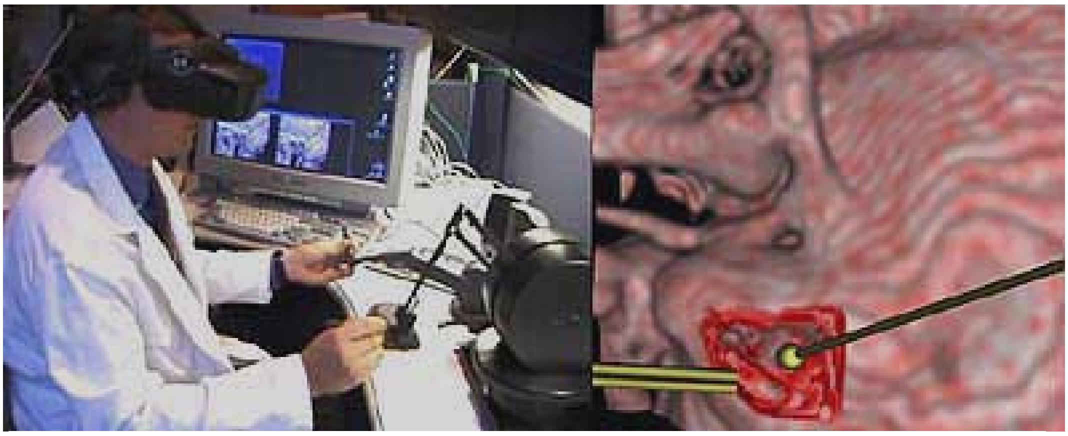

**Figure 3: OSC Temporal Bone Drilling Simulator Showing V8 HMD and Twin *PHANToM* Interface (left) and Virtual Training Environment (right)**

**Figure 4 (left to right): Virtual Research V8 HMD, *PHANToM* 1.5 and *PHANToM* Desktop**

In the same paper, the OSC claims that their use of a head-mounted display "reproduces the stereo microscope". Whilst this may have some support in fact from the perspective of *optical* field of view of the headset, the V8's resolution (VGA, or 640 x 484 at 60Hz refresh) leaves a lot to be desired, even though in many industrial VR applications it is adequate for short immersion exposure times. Another problem caused by the adoption of a headset visual interface is that, unlike a theatre microscope, the user has to don, doff and adjust the cumbersome headset (as opposed to simply look in and away in the case of the microscope).

All in all, these issues make it a very strange choice of viewing device from a human factors point of view. Another problem relates to the fact that HMDs are normally employed for immersive VR applications where users are required to make head movements in order to develop a good 3D spatial understanding of their virtual environments. To assist this, HMDs are retrofitted with a head tracking system, typically (although not exclusively) an electromagnetic device, as available from Polhemus Inc. or Ascension Inc. in the US. If one downloads the short video sequence available from OSC's Web Site (address given above), it is interesting to see how little the user moves his head whilst undertaking the virtual drilling process. Therefore, the use of a head–tracked, head-mounted display in this application must be questionable.

Another point to note is that the very early stages of mastoid cortex drilling are, at the Manchester Royal Infirmary at least, executed without the aid of a microscope (see Figure 12, for example). The microscope is only brought into use when facial nerve and middle ear structures are due to be exposed. From a visual perspective, the use of the *PHANToM* Desktop in the OSC demonstration was, it seemed, completely wasted. As will be seen later, irrigation/suction is necessary to remove the milky paste generated by bone dust and other debris. Otherwise, the target drilling area becomes obscured. There were no strong visual indications or cues in the OSC demonstration to indicate a need to introduce the irrigator/sucker. Therefore it was likely that the user could, quite quickly, forget its use. There is also a general concern on the part of the author that a second *PHANToM* may not represent a cost-effective solution for simulated irrigation/suction tasks. This issue will be revisited later in the report.

These criticisms to one side, the OSC facility is quite impressive, although closer attention to user needs and a better understanding of available technology (especially for visual image delivery) would have resulted in a more pragmatic solution. At least the researchers state that it is their intention to migrate down from high-end computing facilities to PC platforms in due course.

### 1.2.4 Harvard Medical School and Others

Another small Web site pertaining to virtual temporal bones is that of the Joint Center for Otolaryngology (Brigham and Women's Hospital, Harvard Medical School, Boston; http://splweb.bwh.harvard.edu:8000/pages/papers/vik/viroto/viroto.html). Here the researchers refer to the development of a virtual temporal bone model based on CT and MR images of a cadaveric head, processed using automated and manual segmentation techniques, for interactive or automatic exploration using a Sun Workstation. An ENT site hosted by the University of North Carolina (http://apollo.med.unc.edu/surgery/oto-hns/) listed a Temporal Bone Dissection Guide. However, the HTML link was inoperative. Another general site made use of during the task analysis phase of the present project was that hosting the *Froedtert Publications*, covering acoustic neuroma (http://www.froedtert.com/grandrounds/janmar2000/page2.html) and cochlear implantation (http://www.froedtert.com/grandrounds/janmar2000/page1.html).

### 1.2.5 Virtual Presence and Manchester Royal Infirmary

**Figure 5: MIST System in Use**

There are two reasons for including a section relating to previous VR training efforts on the part of two of the collaborators in the present project. The first is to emphasise the importance of conducting a context-specific task analysis; the second relates to the possibility of developing a simple skills trainer based not on high-fidelity anatomical and physiological fidelity, but on abstract task elements, as was achieved with the Minimally Invasive Surgical Trainer, MIST, now in service across the globe (Figure 5) and a mandatory component of basic and advanced medical courses at the European Surgical Institute near Hamburg, covering a wide range of techniques, from cholecystectomy to thoracic surgery.

The overall rationale behind the MIST system is presented in Stone (1999a). However, the task analyses conducted at the MRI were used to produce a structured decomposition of a range of minimally invasive tasks that could be defined in the form of "human performance primitives". It was found that each primitive could be implemented reasonably easily within a proprietary VR software package and each could be endowed with "academic credibility", particularly from the domains of applied/experimental psychology and human factors (eg. Boff & Lincoln, 1988).

MIST, then, is a surgical psychomotor **skills** trainer, based on a commercially-available instrumented laparoscopic interface, connected to an industry standard PC. Movements from the laparoscopic interface tools (recently redesigned by Virtual Presence and Immersion Corporation) are translated into 3D computer graphics that accurately track and represent the movements of those tools within a virtual "operating" volume. Within this volume, simple geometric shapes are generated and subsequently manipulated using the interface tools. The graphics have been intentionally kept simple in order that high frame rates may be maintained on relatively low cost equipment and to preserve the validity and reliability of the simulations when used in applied experimental research. Figure 6, for instance, shows the most difficult of the battery of 6 tasks, whereby (in essence) the trainee has to position and hold an object within a defined

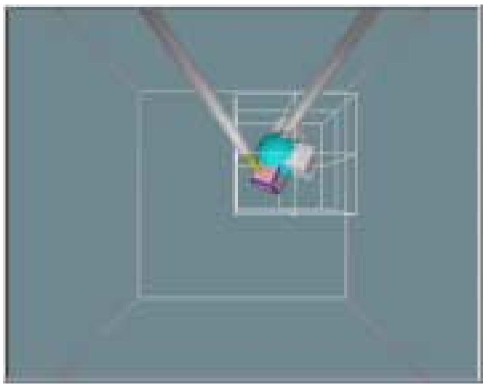

**Figure 6 : Abstract MIST Task 6 (Tissue Handling & Diathermy)**

volume, then apply diathermy (using a foot pedal) to small cuboids mounted on the exterior surface of a sphere. As the simulated current is applied, the cuboids turn red and then vanish, indicating a successful “burn” and a cue to the trainee to cease diathermy immediately.

# 2 Analysis Sessions

Given the short timescales involved and the need to coordinate schedules with the Manchester Royal Infirmary and ILO teams, the task analysis took the form of 3 main processes, as mentioned briefly in Section 1.1. These will be expanded in this part of the report and were:

- Training and familiarisation (on the part of the author) using a cadaveric temporal bone, backed up with appropriate literature,
- In-theatre video and verbal protocol sessions,
- Initial investigation of other, synthetic training techniques (CD-ROM and "plastic bones").

## 2.1 Basic Surgery Course and Cadaveric Temporal Bone Exercise

In order to overcome some of the initial limitations with understanding general surgical procedures during the early MIST task analysis sessions described in Section 1.2.5, an opportunity presented itself within the first month of the IERAPSI Project to attend a 3-day, assessed, Royal College of Surgeons of England Basic Surgical Skills Course at Manchester Royal Infirmary. Whilst this course did not touch on ENT/otolaryngological/temporal bone surgery, some of the basic procedures (eg. orthopædics, suturing, instrument familiarisation, diathermy) were of use in later analyses, as indeed was part of the laparoscopic course element.

**Figure 7: Cadaveric Temporal Bone Laboratory Set-up**

In addition, and prior to the first of the in-theatre sessions, the author was given a further opportunity to experience a cadaveric temporal bone procedure first-hand[2]. The laboratory set-up for this exercise is shown in Figure 7. The specimen is held in a special clamp, which also holds an irrigation saline drip tube. An ex-theatre microscope was provided, together with a pneumatic (foot pedal-actuated) drill and selection of toothed (hard cut) and diamond (soft cut/smooth) burrs. The drill was held in the right hand and a suction tube was

[2] **Again, grateful thanks here go to Prof. Ramsden and Dr Wheatley for their support in setting up this valuable experience. Cadaveric bone reference X141-00.**

held in the left hand. A small collection of other instruments (periosteal elevator, Beales, Hughes, dissectors – see Table 2, Section 2.4) were also available.

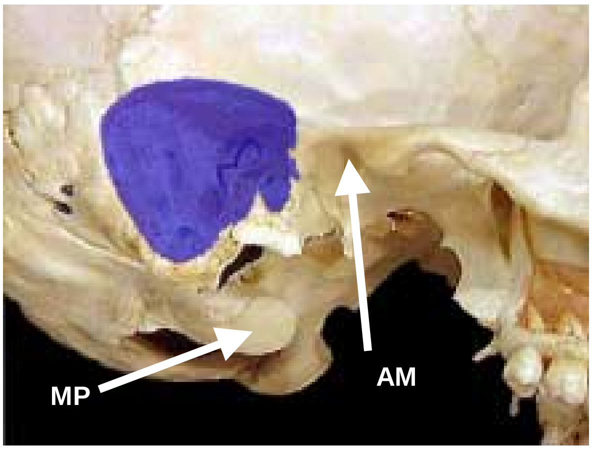


**Figure 8: Approximate Cortex Drill Area**

The instructions provided (in conjunction with procedures illustrated in Nelson (1983) and Anson & Donaldson (1981)) were to consider an initial drill site roughly similar to the shaded portion illustrated in another sample in Figure 8. This area is sometimes referred to as the mastoid cortex, part of the temporal bone, and requires a smooth, "unforced" sweeping action of the drill (using a 0.8 or 1.0mm burr), well above the mastoid process (MP) and taking care to preserve around 3-4mm of bone posterior to the external auditory meatus (AM) or auditory canal. Drilling was to occur in a rounded square or triangle aspect until dura was reached, removing all bone dust and debris regularly (bone dust forms an obscuring paste when in contact with saline from the drip) on a regular basis. Initial impressions of the drilling procedure were similar to those when using the small electric drills available to scale modellers, especially when applying pressure via some of the larger drill bits obliquely to the surface of a resin model or hardened "Milliput" filler. The haptic sensation of the more compliant dura was best described at the time as applying a blunt rod to the surface of a fairly taut recycled retail carrier bag (conveying a sense of a crinkled rather than smooth material finish)!

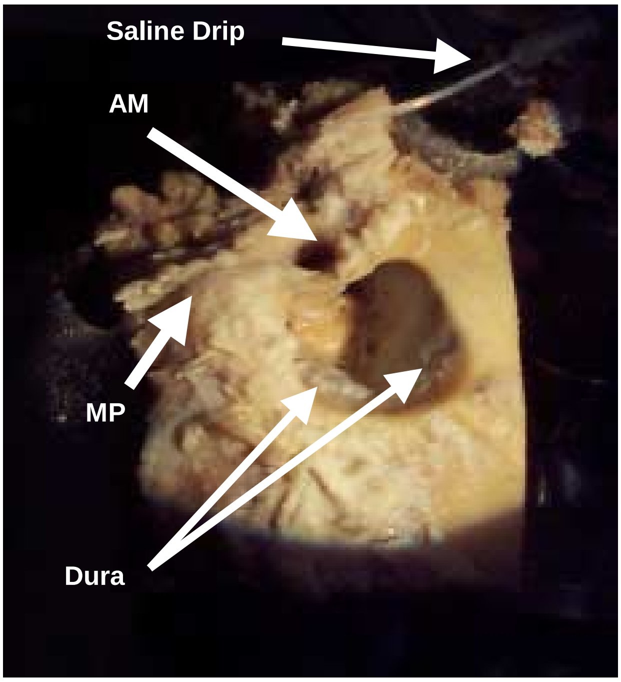


**Figure 9: Early Progress by Author in Exploratory Cadaveric Drill (left skull sagittal presentation, "face up")**

After initial drill appraisal by the resident specialists (Figure 9), drilling was to resume until the middle ear was opened, presenting the incus, malleus and stapes and the all-important facial nerve floor. The incus was removed first (in what appeared to be a simple unlocking manœuvre, followed by the stapes (intact). Movement of the malleus caused a corresponding deformation of the still-intact tympanic membrane. Further drilling exposed more familiar middle features, such as the round window (one important site in cochlear implant procedures), and the application of slightly too much pressure exposed the bony channel of the (lateral?) semicircular canal. At the point where dissection to Figure 10 was reached, it became obvious that the experience necessary to identify those middle/inner ear landmarks so graphically (and simplistically) presented to the author in ‘O’- and ‘A’-Level Biology texts, let alone the more “obscure” anatomical features (obscure, that is, to the untrained eye) must be built up with substantial practice and supervision. The situation is eased slightly when live tissue is presented, but even then the skill required to remove just enough bone to expose the relevant protective bone features of (for example) the semicircular canals and facial nerve is considerable.

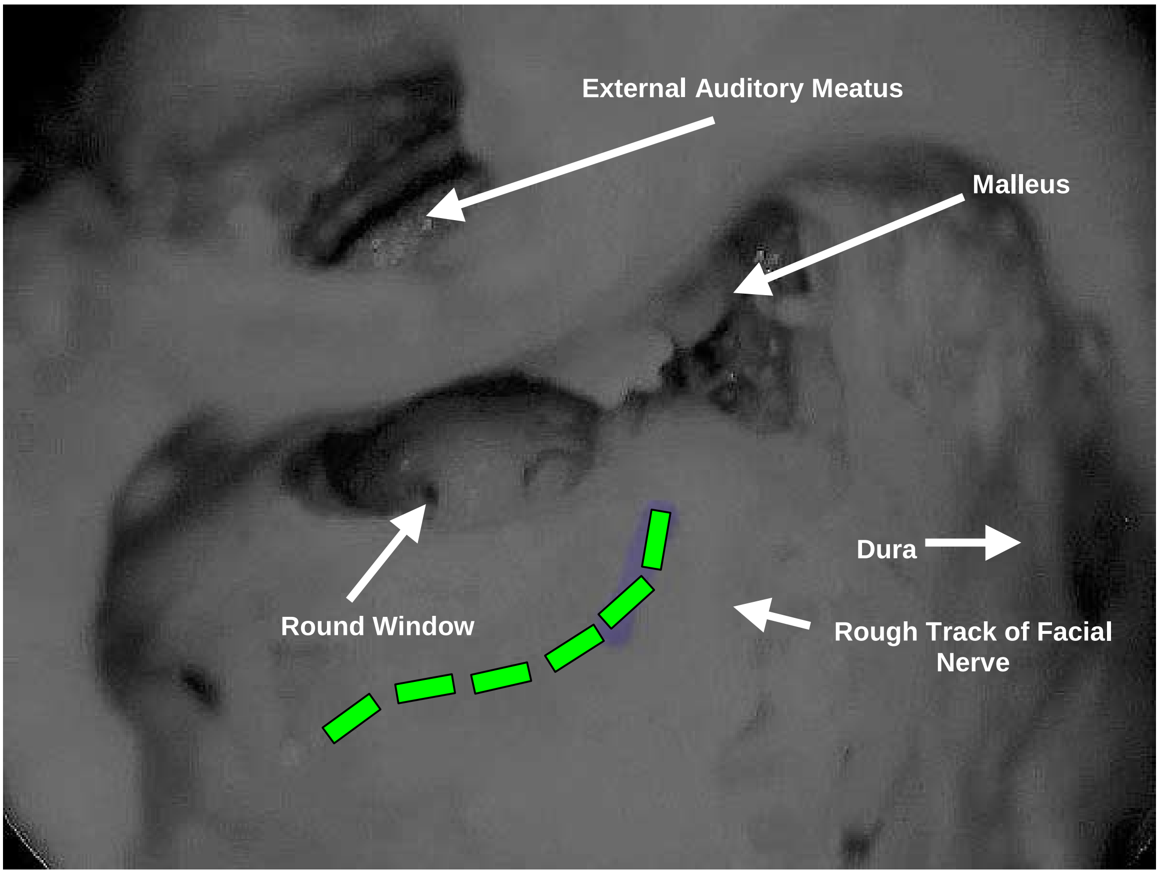


**Figure 10: End of Initial Temporal Bone Drilling Experience (grey scale image presented for clarity; the original digital image was too high in specular reflection from bone and moisture)**

## 2.2 In-Theatre Sessions: Task Analysis Constraints

With the support of the staff of the ENT unit, the Department of Otolaryngology, Head & Neck Surgery and the theatre personnel at Manchester’s Royal Infirmary, the author was permitted to observe and, where possible, video record (via the output from the Wild Heergbrugg microscope) surgeon performance and close-in drilling activities. Patient names were not recorded at any time, although in some cases, age and specific conditions were noted.

As space was somewhat at a premium and care had to be taken at all times when moving around the theatre (so as to prevent inadvertent contact with and infection of sterilised material), it was not always possible to obtain clear images of the surgeon’s immediate working area. Also, once the microscope was deployed, the surgeon’s choice of view through the optics was not always matched in focal clarity by the video feed from the microscope. Although surgeons were happy to oblige by repositioning the microscope on request, there were numerous occasions where such requests, it was felt, could compromise their performance (and, thus, patient safety). On such occasions, requests were postponed. Nevertheless, despite these constraints, the early briefings by surgical staff, plus the laboratory drilling experience helped to "fill the gaps" admirably. Five theatre sessions were analysed in detail for this report, each lasting an average of 6 hours:

- Infantile Cochlear Implant
- Middle Fossa Acoustic Neuroma
- Translabyrinthine Acoustic Neuroma (2 examples)
- Stapedectomy "Follow-Up" and Ossicle Prosthesis at ILO (*combined approach*)

## 2.3 In-Theatre Session 1: Cochlear Implant

The patient in this case was an infant of 3 years, profoundly deaf from birth. The cochlear implantation was, it was felt, likely to give the infant a 50-60% chance of reasonable hearing recovery, thereby helping to minimise problems with cognitive development over the coming years. The device provided was a CI *Nucleus* 24M cochlear implant (from Cochlear Ltd), possessing 22 intercochlear electrodes. Sterilised templates are provided for surgeons, thereby enabling them:

(a) to trace the outline of the skull mounting onto the skin or skin cover (prior to incisions being made; see Figure 11, illustrating this in another patient). Then, as drilling progresses,
(b) to ensure that the depth of the well drilled into the skull will house the receiver/stimulator accurately and comfortably and will accommodate any overhangs and wires (see also Figure 11).

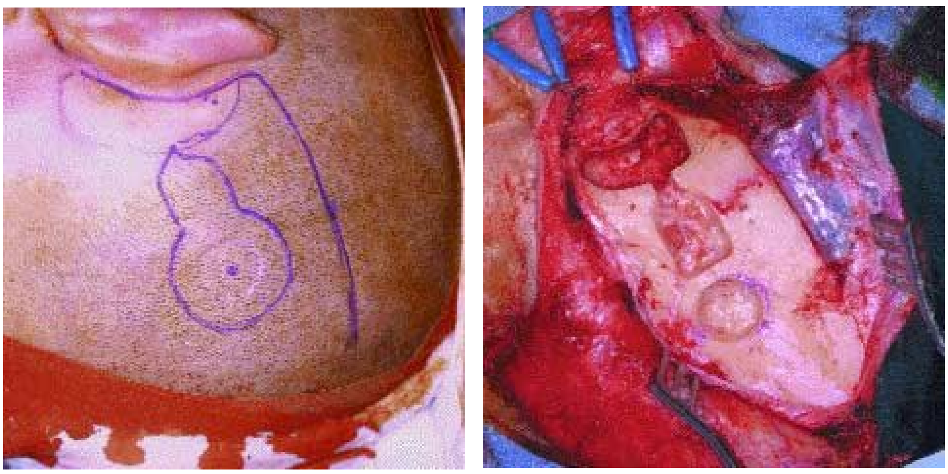

**Figure 11: Cochlear Implant Templates and Wells (mastoidectomy has been performed on right-hand image)**

In all the operations observed, the initial preparation and mastoidectomy work (down to middle/inner ear exposure) was performed by Specialist Registrars (Figure 12 in the case of this cochlear implant). Again in all operations observed, the patients' heads were covered after sensors and life support services had been applied. The operative site was, after a thorough application of iodine, covered with a "cling film"-like sheet, preventing any possible infection from the external auditory meatus. Where necessary, incision and cut paths were marked out on this sheet. Prof.

Ramsden attended theatre later in the operation to take direct charge of the actual focus of the operation, discussing progress with the Registrars as necessary. Patients' radiological records appeared to have been discussed during short briefing sessions with Prof. Ramsden beforehand and, interestingly, those records (2 sheets) pinned to the theatre light board were only consulted, on average, 2 or 3 times during an operation. This will be discussed later in light of the aims and goals of the IERAPSI project.

**Figure 12: Early Cochlear Implant Surgical Supervision & Assistance**

Figure 13 shows the drilling of wells and mastoidectomy progressing as normal, using appropriate cutting and diamond burrs with syringe irrigation provided by theatre nurse support and suction controlled by the surgeon. Video records show some trends in drilling behaviours depending on the type and depth of bone (eg. cortex *vs*. petrous). In the case of preparing the skull wells for the receiver/stimulator, burrs of around 0.8cm were used in conjunction with sweeping motions and curvilinear sweeps over 2-4cms coordinated by flexion and extension of the forefinger and thumb pinch grip around the drill.

The mastoidectomy was characterised by similar, albeit shorter (1-2cm) motions with rapid lateral strokes. For deeper drilling, ≤1cm strokes – down to 1 or 2mm – become evident (obviously with smaller diameter cutting and diamond burrs – down to 1-2mm in size for cochleostomy) with more of a "polishing" motion quality or very sensitive, almost exploratory motions, guided using the contours from prior drill procedures. "Static" drill handling was also noted, suggesting extreme caution on the part of the surgeon to simply allow the cutter to erode the bone tissue whilst maintaining minimal surface pressure. Of course, in the absence of any direct form of measuring drill motions and pressures, these observations are based on the subjective opinion of the author, albeit backed up by the earlier (and most valuable) laboratory cadaveric drill experience, plus verbalisations on the part of the surgeons during the operations.

**Figure 13: Mastoidectomy and Middle Ear Exposure (for Cochlear Implant) in Progress**

## 2.4 In-Theatre Session 2: Acoustic Neuroma – Middle Fossa Approach

An acoustic neuroma (neurilemmoma) is a benign encapsulated tumour that, depending on size, can produces symptoms which result from the pressure applied on other surrounding structures, such as the acoustic nerve or brainstem (as shown in the model in the Figure 14). There are a number of procedures available to surgeons to remove these tumours, although the choice of which to apply depends on such factors as the presence of residual hearing, the location of the tumour and the experience and preference of the surgeon. In the present case, the patient, an elderly female, presented a relatively small tumour and residual hearing. In this case a Middle (Cranial) Fossa[3] approach was recommended (typically employed for tumours that extend out of the internal auditory meatus by approximately 1cm towards the brainstem. This approach demands careful management of cerebrum and other brain tissue as, once the skull is opened, the approach progresses from *above* the ear, between the dura and cranium, with the surgeon having to drill down through the bone overlying the neuroma itself.

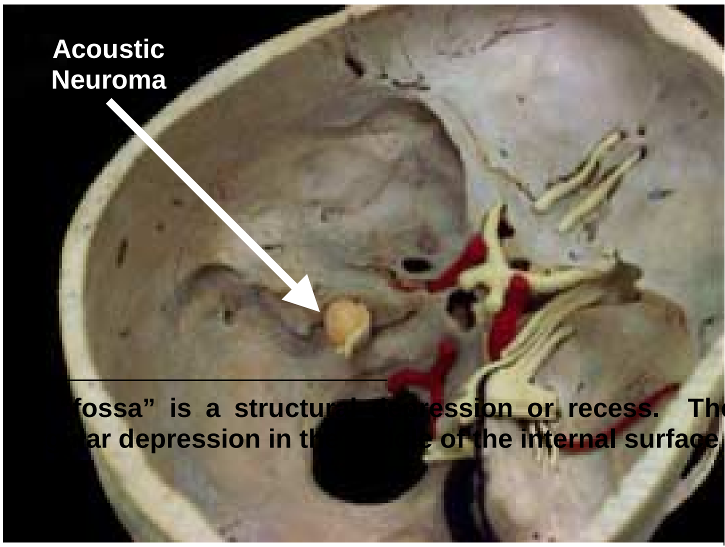


**Figure 14: Model Showing Location of Acoustic Neuroma**

**fossa" is a structu... ession or recess. The Middle Cranial Fossa is an ...ar depression in th... of the internal surface of the base of the cranium.**

During this procedure, the surgeon operates not at the side of the patient (as with the cochlear implantation and translabyrinthine neuroma approaches), but in line with his body. This applies to the initial cranial bone removal as well as the drilling procedures themselves (Figure 15). This working posture does have its disadvantages, as can be seen in Figure 15. Note the absence of wrist/hand support and the curvature (and subsequent drag) of the pneumatic pipe supplying the drill.

To all intents and purposes, and reiterating the importance of keeping the dura and cerebrum away from instruments whilst penetrating the temporal bone and Middle Fossa, many of the movements were similar to those witnessed during the deeper stages of mastoidectomy as discussed in Section 2.3. Additional help was sometimes requested from one of the registrars when it became necessary to introduce an instrument to shield the dura and brain tissue from the drill. During this procedure, slightly more attention was paid to other items of equipment and devices in the operating theatre. Two items that could well contribute to the fidelity of the final simulation environment are:

**Figure 15: Working Position of Surgeons During Middle Cranial Fossa Approach Acoustic Neuroma (Cranium Preparation Shown Left, Microsurgery Shown Right)**

- Diathermy. As well as the usual visual indicators of bipolar diathermy application, such as smoke, coagulation, bubbling and blackening, the diathermy panel (Figure 16, lower unit) produces its own fixed frequency audible signal. Diathermy is used more often than monopolar, due to the need to avoid deep tissue damage (the earth pad is placed under the patient, therefore encourages deeper monopolar current penetration).

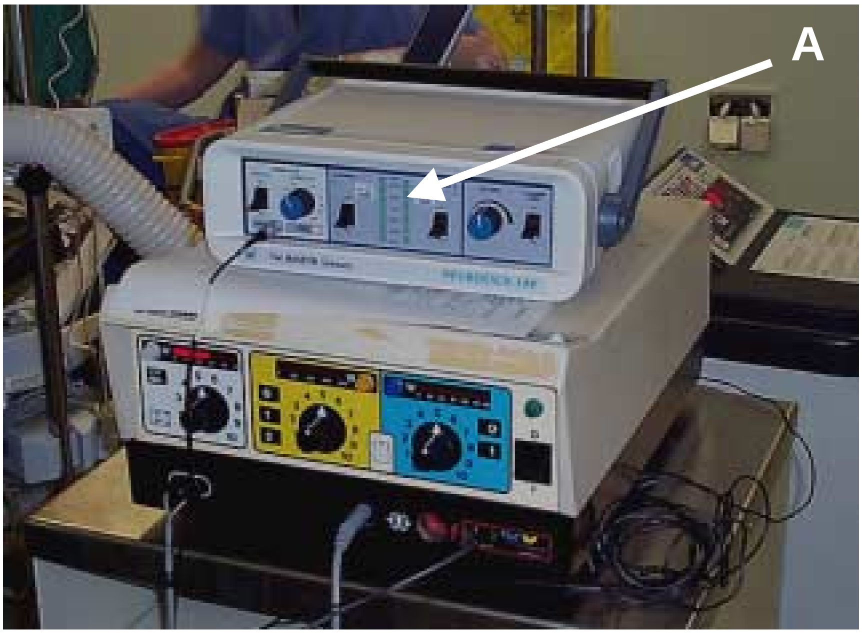


**Figure 16: Facial Stimulator (Upper Unit; 'A' is Visual Bar Display) and Diathermy Panels**

- Facial stimulator. This is a "safety net" item of equipment, designed to assist surgeons in establishing the track of the facial nerve, its location when masked by other tissue and the integrity of the nerve's function. During pre-operative preparation, once the patient is anaethsetised, electromyographical sensors are placed on his/her face. During the operation, the surgeon can call for the facial stimulator, which is a thin metal rod carrying a current to underlying tissue. When applied directly onto (or very near) the facial nerve, contractions occur in the facial muscles which are then detected by the EMG sensors. This results in a change to the horizontal bar display on the stimulator panel ('A' on Figure 16, upper unit) and an audible "knocking" noise. Other noises, described as "scratching", are considered to be indicative of adverse facial nerve conditions – irritation caused by cold water, nerve fibre stretching, or when diathermy is applied near the facial nerve, for example.

Finally, the opportunity was taken to record the common manual (non-powered) instruments and items used by the surgeons. The frequency of their deployment depended very much on the surgeon involved. Table 2 lists the most common items.

| Instrument Type / Item | Description |
|---|---|
| **Suckers** | **Zollner (small)**<br>**Lempert (larger)**<br>**Brackmann (for tumours)**<br>**Frazier (for large fluid/blood loss)** |
| **Elevators** | **Large Periosteal**<br>**Small Periosteal**<br>**Beales**<br><br>**Hughes**<br> |
| **Rhoton** | **Number 3** |

| | |
|---|---|
| | <br>**Number 4**<br><br>**Number 5**<br><br>**90° Dissector**<br><br>**45° Dissector**<br><br>**Bone Curette**<br> |
| **Scissors** | **Jacobsens Straight**<br>**Jacobsens Curve**<br>**Belucci**<br> |
| **Forceps** | **Tilleys (Cup)**<br> |
| | |
| ***Surgicel*** **TM** | **Clotting Mesh** |
| **Packing** | **Saline-Soaked with Blue Cord** |

**Table 2: Table and Simple Illustrations of Some Common Temporal Bone / ENT Instruments and Other Surgical Items**

## 2.5 In-Theatre Session 3: Acoustic Neuroma – Translabyrinthine Approach I

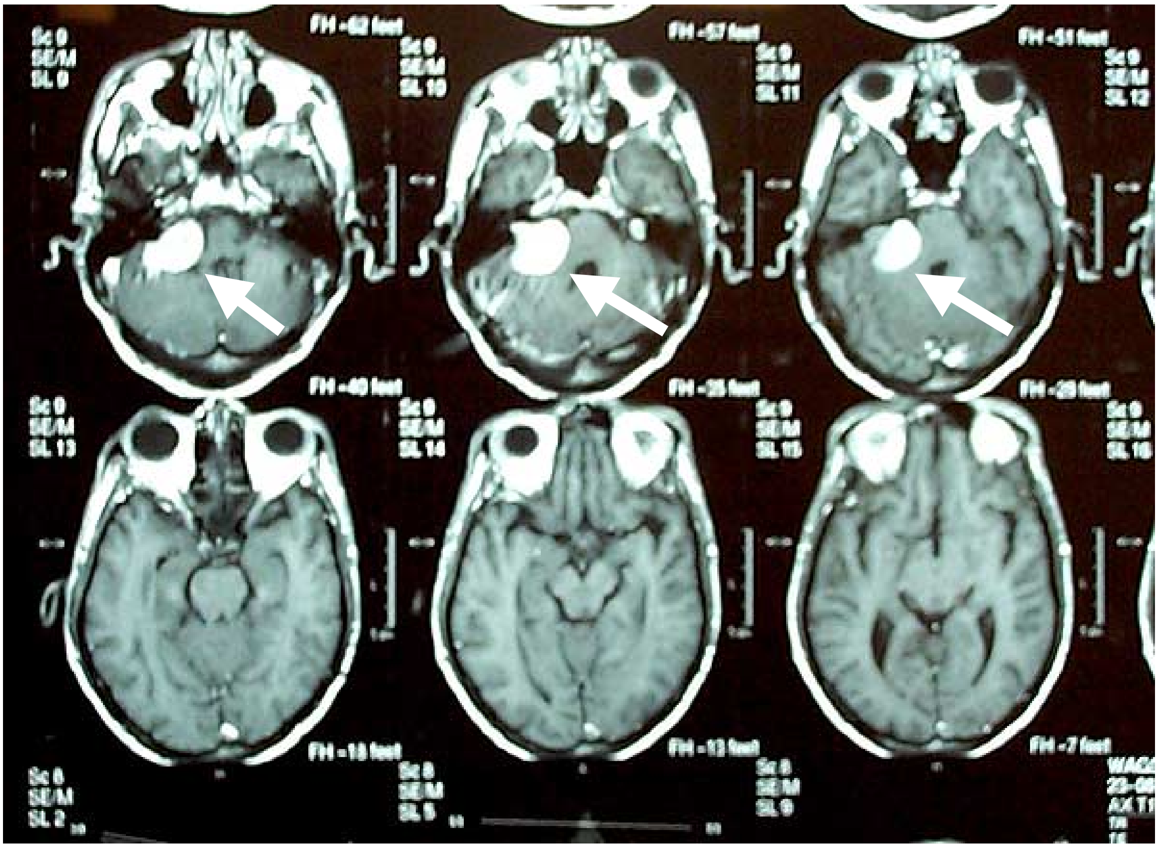

**Figure 18: Part of the Radiological Records for Right Translabyrinthine Acoustic Neuroma (3cms) Patient 1 (the neuroma is shown as the arrrowed white area in the upper 3 scans)**

The translabyrinthine approach to an acoustic neuroma involves a typical mastoidectomy, followed by penetration through the middle and inner ear, destroying the contents and, thus, hearing. In many of these patients, hearing has already been lost (or severely compromised), therefore the translabyrinthine approach is the only choice for removal of tumours of the size of this particular example (around 3cms – Figure 18).

This first patient, a male in his 30s, suffered from Neurofibromatosis Type 2 (a condition in which *bilateral* acoustic neuromas exist). This particular operation dealt with the right neuroma. Again, the video records show the same quality of drill and diamond burr motions as those witnessed for the infantile cochlear implant described in Section 2.3. Once the neuroma had been exposed to the satisfaction of the consultant surgeon (2 hours into the operation), with adequate clearance in the drilled bone pathway for tissue removal, the lengthy task of removing the benign tissue from within the sac or capsule could take place. This is a lengthy task and skilled task, characterised by what may be described as gentle “peeling” or “stroking” motions of an instrument such as one of the Rhoton variety (Table 2). There is very infrequent use of cutting instruments, due to risk of damage to the facial nerve or other sensitive tissue. Occasionally bipolar diathermy was applied to help break up the neuroma. After many, many peeling motions, small amounts of tumour would simply separate from underlying tissue and the surgeon would then repeat the activity until most, if not all of the tumour was removed. Unsurprisingly, there were noticeably more facial stimulator tests than had been observed in other operations. Also, more attention was paid to hand and wrist comfort in this form of operation than had been observed before (Figure 19).

During the present operation, a new hybrid diathermy-irrigation device was introduced by the Manchester team (see Figure 20). However, lack of experience with the MALIS device and the need for the sales representative to be present for initial training meant that its settings had not been optimised. Its use was postponed to a later operation (Section 2.6).

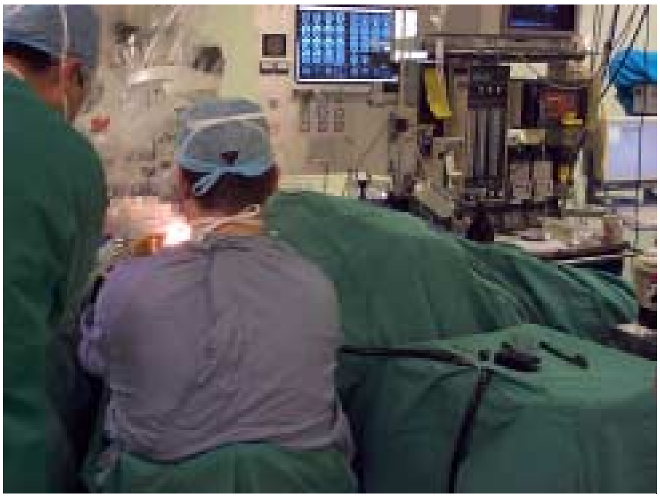

**Figure 19: Translabyrinthine Acoustic Neuroma Resection in Progress. Note the use of additional "greens" to support the surgeon's left wrist and the need to clip the drill pneumatic supply pipe to avoid drag.**

Also, frequent use of the sucker to hold tissue (especially dura) out of the way to clear a path for thin bone segment removal was observed. Another observation was the large amount of saline used for flushing in this kind of operation when compared to the cochlear implantation and Middle Fossa approach.

**Figure 20: MALIS Integrated Bipolar – Irrigation System**

## 2.6 In-Theatre Session 4: Acoustic Neuroma – Translabyrinthine Approach II

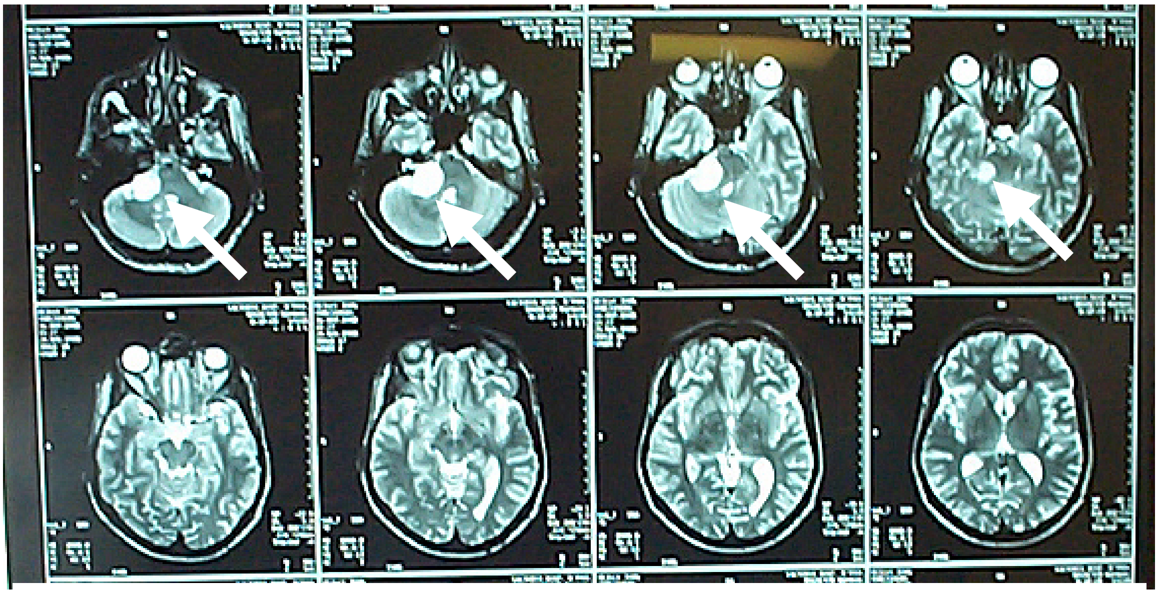

**Figure 21: Radiological Records for Right Translabyrinthine Acoustic Neuroma (3cms) Patient 2 (the neuroma is shown as the arrrowed white area in the upper 4 scans)**

The second patient attending for a translabyrinthine neuroma approach, a 52-year-old male, was of interest from a number of perspectives, not least of which was his late confession to the anaesthetist of being on a methadone drugs withdrawal programme and some visible markings suggesting recent intravenous substance injection. Not only did this delay the operation, it certainly warranted special medication and surveillance during the procedure (indeed, the patient showed signs of sporadic movement at one point during the changeover of anaesthetic syringe). The neuroma in this case was a right large (≥ 3cms) medial tumour with a small direct attachment to the facial nerve.

There were more examples of “hooking” activities in this procedure to remove thin bone layers or “plates” – especially those over delicate areas of neurological or vascular tissue and dura were often removed by sliding other instruments (eg. Rhoton/Beales/ Hughes/45$^{o}$ and 90$^{o}$ dissectors) under loosely fractured bone and then making upward hooking movements.

An interesting contingency event occurred just after 1 hour into the operation, whereby a reactive movement on the part of the patient seemed to be the cause of the drill making contact with sinus leading into the jugular bulb, resulting in a sinus hematoma. This caused considerable blood pooling in the drilled cavity and demanded immediate action. Many minutes later, the hematoma had been stopped using considerable amounts of *Surgicel* mesh, which had to be trimmed away later. *Surgicel* was used on numerous occasions during the operation to form a synthetic tissue volume that promotes rapid coagulation.

**Figure 22: MALIS Diathermy-Irrigation Hoop Instruments**

During this second translabyrinthine approach, better use was made of the new MALIS diathermy-irrigation device (with the regional sales person in theatre to advise on bipolar settings). Once Prof.

Ramsden took charge of the operation he began to use both the hoop (Figure 22) and forceps versions of the tool to excellent effect. Unlike the monotonous peeling activities witnessed in the previous two neuromas, here the tumour *debulking* process proceeded at quite a pace, with the MALIS device removing quite sizeable amounts of tissue (Figure 23 shows the system in use and on-screen). Again, the facial stimulator was used at regular intervals. One drawback of having these instruments in close proximity was the amount of tangled wiring evident over the patient (Figure 24). This caused a delay to the handing over of the bipolar instrument on at least 2 occasions. Furthermore, the introduction of a second foot pedal (next to the drill foot pedal) to control the current delivery from the new MALIS system also led to confusion and delays. **Putting to one side the aims of the IERAPSI project, it is evident that significant ergonomic input is required to the design and use of even the most basic of theatre equipment, thereby supporting the surgeon in his task, rather than hindering performance as is the case today.**

**Figure 23: Diathermy-Irrigation System in use (and on-screen)**

**Figure 24: Wire and Tubing Arrangement over Patient**

## 2.7 In-Theatre Session 5: Stapedectomy Follow-Up and Ossicle Prosthesis Insertion (*Combined Approach*)

As well as providing the IERAPSI Consortium with useful operative and instrument data at the outset, the contribution of the Institute of Laryngology and Otology of the University of London to the task analysis effort is to provide ongoing support and guidance in the iteration of the task analysis (together with user trials) throughout the project. Particular guidance is being provided in the second 6 months of the project to illustrate the fine differences involved in performing specific mastoidectomies. The results of this will be reported in later interim technical notes. However, at a meeting with the ILO team, an opportunity arose to observe the ILO's Prof. Taylor carry out a *combined approach* technique (mastoidectomy and external meatus approach through the cut Tympanic membrane) to insert a prosthesis into the middle ear of a 13-year-old male patient. This approach is carried out to maintain the integrity of the canal wall. The patient had a history of mechanical ear disease brought about by perforation (with subsequent tissue growth imparting pressure on surrounding structures) and had been subjected to several previous operations. A mastoidectomy had been performed 2 years prior and the extracted incus ("anvil") had been re-bedded within the tissue in the hope that suitable regeneration would occur. Unfortunately this was not the case and implanting the old ossicle had to be abandoned in favour of a prosthetic "piston".

The initial mastoidectomy (using an integrated drill and irrigator) opened the old wound. Prof. Taylor emphasised his approach to drilling, always drilling or burring "away from danger", carefully checking around white mastoid bone for pink tissue above dura and for a yellow ridge in the bone which he uses as a landmark for locating the facial nerve. Prof. Taylor has agreed to compile a list of essential and desirable anatomical and physiological features to assist in the programming of the

**Figure 25: "Crutch" Portion of Prosthesis in Thumb and Finger**

**Figure 26: Assembled Prosthesis (8-9mm)**

image segmentation process.

Once the mastoidectomy had been completed and no residual disease had been discovered, the task became one demanding extreme manual dexterity. The piston prosthesis consists of 2 pieces, one of which requires cutting to length (7-8mm!) prior to attachment to a much smaller shoe component. Figure 25 shows the cut ("crutch") portion of the prosthesis held between the gloved finger and thumb of Prof. Taylor. Figure 26 shows a screen shot (via the surgical microscope) of the assembled item.

The task the involved the careful positioning of the "crutch-shoe" item inside the middle ear, so as to provide a single mechanical linkage between the Tympanic membrane and the Oval Window (Figure 27). The crutch portion is design to sit softly under and support the Tympanum, which provides an elastic tension to help retain the position of the shoe over the Oval Window.


**Figure 27: The "Crutch-Shoe" Prosthesis in Situ (the Tympanum has been drawn back and the shoe is placed against the Oval Window)**

## 2.8 *Temporal Bone Dissector* CD-ROM

As well as the actual in-theatre experiences and the cadaveric bone opportunity described in Section, every attempt was made to investigate and evaluate other electronic or synthetic training products. The *Temporal Bone Dissector* CD, published by Mosby (Blevins *et al*., 1991) and costing approximately 420 Euro, is a highly informative ontology reference, if somewhat lacking in training quality. The CD has been developed using a combination of Macromedia animation and QuickTime movies. This CD was delivered to the author somewhat late in the initial task analysis period, but sufficient time was available to form an initial opinion. Had the CD been received earlier, the contents would have been of some considerable help in the general understanding of temporal bone activities. As with many attempts to illustrate the temporal bone and middle/inner ear contents and structures, the CD's interactive and atlas images show little relevance to what is found in the real world. To be fair, however, informative video sequences are included (although a few are rather out of focus) to back up the somewhat simplistic models and sections. Figure 28 shows some of the screens presented as part of the more interactive sections.

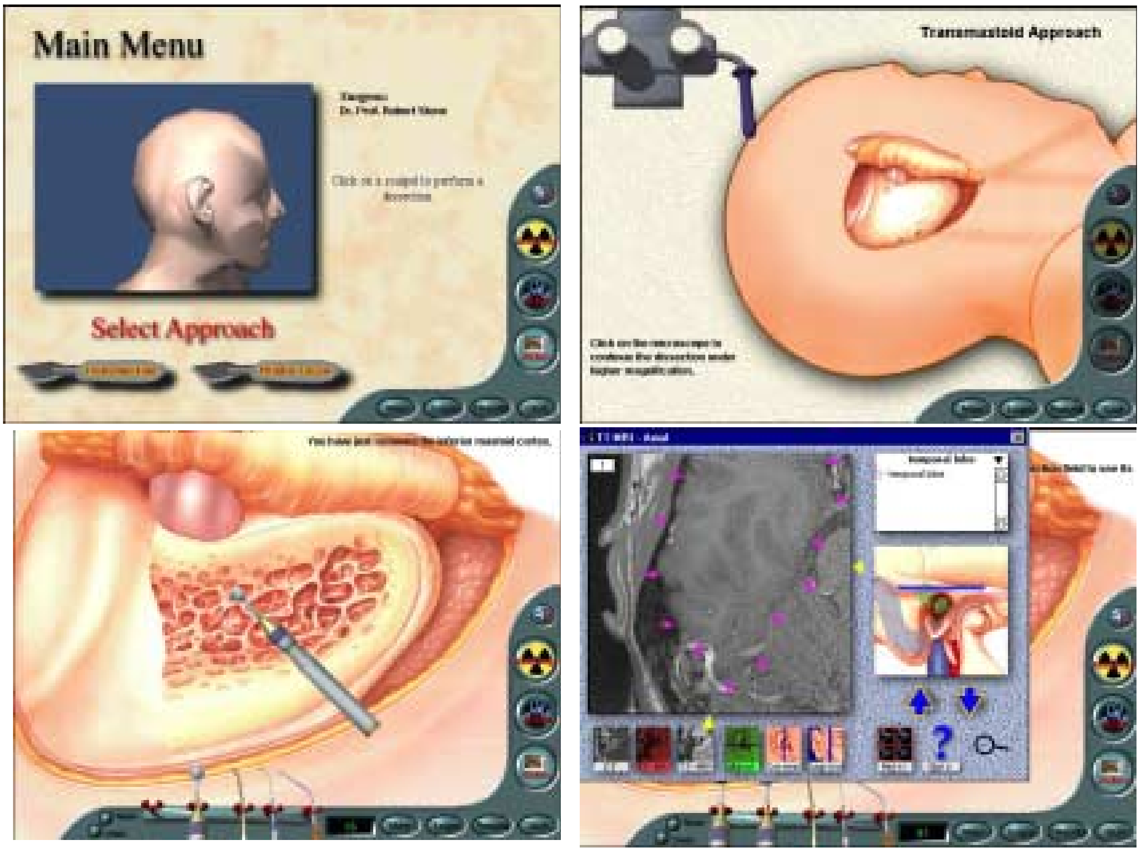


**Figure 28: *Temporal Bone Dissector* CD Screen Shots (top left, main menu; top right, microscope selection; bottom left, mastoidectomy in progress; bottom right, axial MRI scan in window**

In brief, the CD consists of a number of modules. Module 1, "The Dissector" is a Macromedia-based simulation (Figure 28) enabling users to select instruments and remove quite large sections of mastoid anatomy (simple sound effects are included). Errors, such as contact with blood vessels and the facial nerve are recorded and simplistic fluid "spills" (eg. venous haemorrhage or CSF leakage) can be brought under control by just a *single* application of the irrigation/sucker tool! As the simulation progresses, a timer shows elapsed time in seconds.

The Radiology Module (2) allows the trainee to view and interrogate structures shown on CT or MRI images, either using single image presentations or sequences. Module 3, the Atlas, consists of an impressive (if, again, visually simple) library of three-dimensional computer models of otological anatomy. The final module, the Video Collection, is a series of QuickTime movies showing actual procedures.

This CD possesses a wealth of good introductory information. Even though the operations are rather simplistic, trainees receive feedback on their performance, in the form of brief comments during drilling processes and in the form of a "happy" or dissatisfied (and ready-for-litigation) cartoon patient at the end of a full session.

## 2.9 Temporal Bone Models and Dissections

**Figure 29: Pettigrew Plastic Temporal Bones. Top: Complete Right Temporal Bone; Bottom: 6 Stages of Left Temporal Bone Drill**

As with the CD *Dissector* product the Pettigrew Plastic Temporal Bone series would have provided much useful insight into the temporal bone structure had it been available at the outset of the task analysis work. Pettigrew Plastic Temporal Bones have been developed by Alastair Pettigrew, an ENT consultant at Stirling's Royal Infirmary in Scotland and an Examiner (Final Fellowship) at the Royal College of Physicians and Surgeons in Glasgow. He is also one of the founding tutors on the Glasgow Temporal Bone Course, launched in 1976 and with a wide international reputation (http://www.temporal-bone.com/).

The two bone sets selected for investigation were "Bone 2" (Figure 29), a full right temporal bone with 10cms of adjacent skull (cost, approximately 107 Euro) and "Bones 51-56", a full left temporal bone dissection, from intact mastoid cortex down to the opening of the facial nerve and semicircular canals (see Figures 29 and 30; cost of set, approximately 98 Euro).

"Bone 2", the complete temporal bone, can be fully dissected, using standard theatre equipment, with a similar effect to that achieved during the cadaveric exercise described in Section 2.1. The bone has been prepared in 2 sections, with some clever canal modelling techniques and innovative use of material. The trainee is required to perform a mastoidectomy and then continue to expose and identify such features as the horizontal and vertical portions of the facial nerve, the ossicles, the round window niches, the lateral semicircular canal, and so on. Food dye has been added to create bleeding effects during irrigation. Spare ossicles can be purchased from Pettigrew.

Of course, these plastic bones cannot replace the experience of undertaking a temporal bone invasion, in just the same way as candy, grapes and chicken could not replace a full laparoscopic cholecystectomy experience, as was discovered during the MIST project. Nevertheless, one has to consider these quality products seriously. **Given the relatively low price of products such as Pettigrew's bones and the CD *Dissector* discussed in the previous section, any VR-based simulator must demonstrate a training performance and/or cost advantage over and above these contemporary techniques.**

**Figure 30: Pettigrew Bone 56, Showing Full Left Temporal Bone Dissection**

# 3 Interim Findings & Relevance to Ongoing IERAPSI Project

The following findings have been presented in summary form, as they are the first to emerge from the large amount of data collected by a relatively small number of laboratory and in-theatre investigations. The findings are expected to form the basis of discussions for input to the second part of WP2 dealing more with system architecture and functional specifications.

## 3.1 IERAPSI Planning Environment

Perhaps the most surprising and pertinent finding of this initial task analysis was the fact that very few references were made by both registrar and consultant surgeons to the patients' radiological references. It was apparent that records had been consulted by Prof. Ramsden before an operation (although in one of the acoustic neuroma cases, the records were over a year old) and used to brief his registrars, prior to them carrying out the initial temporal bone invasions. However, once the operation had started, the radiological records were only consulted 2 or 3 times and then at times when there was a "natural break" in activities. This, then, raises 2 questions:

- Are the patient records, once briefly reviewed, unnecessary or not needed for further operative planning, surgeons instead relying on their experience to locate key anatomical structures in a timely and safe fashion?
- If the records were presented in a different format and, possibly, made available to the surgeon during surgery by means of an ergonomically acceptable technique, would they be used more?

Current radiological records provide a certain amount of useful information for the surgeons to part-plan their task mentally. However, their three-dimensional mental model of the patient (which contributes towards their overall *situational awareness*) is riddled with uncertainly. Such uncertainty persists until a recognisable feature is detected or, in the worst case, an error is made.

Whilst IERAPSI concentrates on the development of software modules to support the processing of radiological data, the way in which surgeons actually use the data must be considered early and refined by consultation with users as the concepts emerge. This requires not just a 3D presentation of the key features of the middle and inner ear and surrounding critical items (facial nerve, jugular bulb, etc.), but the relationship between the location of these items vis-à-vis known bone or other anatomical landmarks. An initial human interface proposal would be to include the following:

- An off-line (pre-operative) system, based around a multi-user real-time 3D display and appropriate interactive 6-dof controls (haptic feedback is probably unnecessary for this interface concept). The system should be capable of providing a CD or DVD "summary" of the briefing for PC playback. This could take the form of an AVI, delivering a fly-through of the operative site, presenting those features highlighted automatically (after image segmentation) and/or manually by the surgeons during the briefings. Amongst the key anatomical features to be highlighted are the facial nerve (and any other key neuronal features), the jugular bulb and sigmoid sinus, blood vessels of secondary importance, the semi-circular canals and close proximity of brain tissue. The fly-through could be based on a pre-programmed route, with reference to now key features or on “way-points” injected by the surgeons, again during the briefing.

- An on-line (intra-operative), scaled-down version of the multi-user system, ergonomically located for maximum use by, and benefit to the surgeon (in a similar vein to the personal screens found in the armrests of business class aircraft seats). To avoid interference with the surgeon’s manual tasks, interaction via speech recognition and a limited command set might be considered (this is mentioned later with regard to requesting irrigation). The commands would invoke such features as anatomical highlighting (using colour or highlight coding), critical relationships (for example between facial nerve and surrounding anatomy), path-following (with stop and review function, for example, along the facial nerve), segment removal, simple 3D manipulation, zoom, sectioning and so on. THIS SUGGESTION IS, IN FACT, OUTSIDE THE SCOPE OF THE CURRENT IERAPSI PROJECT BUT MAY BE WORTH CONSIDERING FOR FUTURE PRODUCT EXTENSIONS.

### 3.2 IERAPSI Training Environment

The term training environment refers to those aspects of the surgeon’s task that will need to be replicated for the purposes of a procedural and skills trainer, as opposed to a system supporting pre- and intra-operative planning. The key features to support include:

- **Initial Bone Exposure.** The initial incision and cuts are fairly basic, from a surgical skills standpoint (and are well catered for in, for instance, the RCS (England) Basic Surgical Skills course). Therefore it is the author’s opinion that a high-fidelity tissue simulation for this stage in the task would be cost-ineffective. Certainly the training system should support some method whereby a standard shaved head graphical representation can be marked (as if using a clinical pen). Although surface marking was a standard procedure for acoustic implant planning, it is felt that the same facility could be provided in the training system to help ENT trainees plan their initial cuts for mastoidectomy operations and Middle Fossa (even Retrosigmoid) approaches.

  The head representation or section (including auricle) should be 3D in nature (in contrast to the simple image shown in the top, right-hand corner of Figure 25 in Section 2.7). However, stereoscopic viewing is not considered necessary for this task. There is no reason why a conventional, high-resolution display, together with the 6-/3-dof data input/haptic feedback device selected for the training system could not fulfil this rôle.

  Once the planned incision path and skin area markings were completed, the system should be capable of informing the surgeon of any gross errors between his marks and those of an optimised area (eg. mark deviations > 10mm (posterior) and 5mm anterior)). Other patient preparatory processes were undertaken during the operations observed (eg. subcutaneous abdominal fat removal for wound packing), but the skills for this type of activity are, again, well covered in the basic surgical skills courses and are not worth simulating.

- **Drilling/Burring** (sweep, spiral, contour and down-pressure). Subjective analysis of video records, as described earlier, together with *in-situ* observations highlighted a correlation between drilling behaviours and type and depth of bone. In the case of initial cortex burring and recess preparation for the cochlear implant receiver/stimulator, drill tip/burr motions of around 0.8cm together with sweeps over 2-4cms were evident, as were fine flexion and extension movements of the forefinger and thumb around the drill. Shorter (1-2cm) motions with rapid lateral strokes characterised the post-cortex mastoidectomy. For deeper drilling, ≤1cm strokes – down to 1 or 2mm – were evident with more of a "polishing" motion quality, guided using the contours from prior drill procedures. "Static" drill handling was also noted, eroding bone tissue whilst maintaining minimal surface pressure. From a training technology viewpoint, there is little doubt that the only commercially available and viable system capable of replicating these qualities is Sensable Technologies' *PHANToM* (desktop, 1.0, or 1.5A with stylus encoder). Note also that in some cases the pressure applied to the drill site was sufficient to move the head of the anaesthetised adult patients a good 5-10cms. **As it has not been possible to record actual exerted forces, representative users (as demanded in ISO 13407) must be employed to act as "perceptual judges" in the construction of a haptic sensation library for key temporal bone tasks.** Other relevant haptic cues will be considered later.

  As for the visual effect of the drill on the surface of the bone, the graphical process developed by the Ohio Supercomputing Center of is actually quite impressive (see Figure 3). However (as was noted earlier), its apparent failure to simulate drill site obscuration by bone dust paste might reduce the importance placed by a trainee on the need for regular irrigation and suction. Realistic and meaningful bleeding is a perennial problem for VR researchers. Again, the simple bleeding effects demonstrated in the OSC demonstration appear adequate. However, there is a need to simulate contingency events, such as the sinus puncture witnessed during the translabyrinthine neuroma approach (described in Section 2.6). The bleeding effect should be of much better visual fidelity than that of similar damage events presented by the *Temporal Bone Dissector* CD-ROM. The reaction time for introducing irrigation and suction, plus *Surgicel* (or other appropriate) application should be recorded.

  Visually, the actual drill representation need only be quite simple, and it is felt that representing the spinning of the cutter or diamond burr is unnecessary. What is necessary, from a functional standpoint, is an effective collision detection mechanism which not only copes with increased resolution as the virtual drill proceeds deeper into the temporal bone, but is also capable of generating error states when (for example) a large burr is inserted into a narrow drill site.

  As for the nature of the technology required for displaying drill, drill site, bone, and so on, there is no conclusive evidence or support for the premise that the use of a stereoscopic system will aid performance in this case. However, the very fact that binocular viewing systems are deployed in the operating theatre and used by surgeons, then stereoscopic imaging should be available as baseline. Certainly the wearing of any form of stereoscopic display, such as a head-mounted display or liquid crystal shutter glasses (as featured in the UIC and OSC examples discussed in Section 1.2) should be avoided. If the simulation achieves a reasonable level of fidelity, then the combination of high-resolution images and haptic feedback will, more than likely, suffice.

As well as the visual and 6-dof input/3-dof haptic feedback qualities of the *PHANToM* for drill simulation (including high frequency vibration), the training system would, it is felt, be enhanced by the inclusion of **sound**. Some surgeons suggest that they are able to detect subtle changes in sound depending on the nature of the bone they are working with (eg. cortex *vs.* petrous). However, this quality is considered to be "overkill" in a training system such as that being considered in IERAPSI. The simulated auditory feedback should be constrained to the following:

- drill not in contact with any material (high frequency),
- drill in initial or momentary contact (low pressure, high frequency),
- drill in sustained contact (high pressure, low frequency),
- drill in transition (low-to-high pressure, high-to-low frequency),
- The sound of the main pneumatic valve actuation when the drill foot pedal is released.

Other important auditory cues will be considered later.

- **Other Instruments and Materials**. Many instruments and materials were deployed during the course of the observed operations. Only those considered of major importance to a temporal bone training system are covered here. The main visual and/or haptic representations should include (see also Table 2 at the end of Section 2.4):

  - Instruments used for hooking (eg. thin bone), probing (eg. manual testing for dura or bone) and peeling (eg. neuroma tissue); **visual and haptic representations**,
  - Instruments used for special purposes (eg. diathermy – standard probe and hoop; facial stimulator), **visual and haptic representations** including on-screen visual representation of current / sensitivity settings (hidden until icon selected by user),
  - Materials used for soaking or coagulation (eg. *Surgicel* mesh or swab representations); **visual only**,
  - Instruments used for cleaning (eg. irrigation and sucker); **visual and (possibly limited) haptic representations** (verbal requests for irrigation could be implemented by simple speech recognition).

  If the use of a stereoscopic display is to be of any practical use at all in this project, then it is in the deployment of other instruments and materials, where quite accurate positioning is required as the instrument is brought within the field of view. Also, the nature of the operative site when standard instruments are used is typically "cleaner" than during drilling, with more anatomical features visible (an obvious exception is profuse bleeding). Irrigation is not continuous, unlike during drilling procedures where the advantages offered by stereo viewing are minimal.

However, there is, yet again, no conclusive support that dictates a requirement for stereo and it is highly possible that equivalent performance will be attained through the combination of a high-resolution display and some form of haptic feedback. If stereoscopic viewing *is* considered to be of value by the users (by virtue of its presence in-theatre), then its implementation should be as functionally close to the surgical set-up as possible. Two candidate technologies are ReachIn Technologies' Desktop Display (Figure 31, shown with a *PHANToM*, Spacemouse and CrystalEyes LCD stereo glasses) and, more representative, Fakespace's *PUSH* 1280 (Figure 32), a stereoscopic/biocular desktop viewer with motion input.

One of the human factors concerns with the ReachIn concept and the autostereoscopic display system proposed by Dresden is that, whilst they present images of reasonable stereoscopic quality, they are both essentially fixed location devices. In other words, any input on the part of the user (via PHANToM, mouse Spacemouse, joystick, etc.) would typically alter the position and orientation of the **image** within a fixed frame, rather than alter the **view of a fixed image**, as one finds with the surgical microscope moving around a patient. The size of movements are not great (and would be more or less accommodated by the PUSH 1280). Briefly, the mimimum requirement would be for motion in 4-degrees-of-freedom movements as follows (roughly estimated):

- Translation left and right (relative to centre of surgeon's face): +/- 10cms (approx.),
- Translation up and down: +/- 5 to 10 cms
- Translation in and out: +/- 5cms
- Rotation of eyepiece unit (in pitch - away from and back to surgeon's face): +/- 30 to 45 degrees

Careful consideration must be given to the display-control stereotypes expected by temporal bone surgeons. Otherwise, a fixed display/moveable image solution might foster negative transfer of training from the virtual to the real.

**Figure 31: ReachIn Desktop Display 2A/2B**

**Figure 32: Fakespace PUSH 1280**

The application of haptic technologies to the use of simulated instruments other than the main drill has to be questioned from a functional and price perspective. Of those instruments listed above, the first 3 categories are actually deployed by the surgeon using his dominant hand (right hand in every case during the present analyses). The use of suction tubes was governed by his left/non-dominant hand and irrigation was provided on demand either by the theatre nurse or by the integral mechanism of the MALIS diathermy system. One has to question, therefore, the need for a second *PHANToM* device for what is, essentially, a minor task involving suction. The only real support for using a full *PHANToM* system was the finding that the suction tube was occasionally used for retrieving flat bone tissue or holding dura in place. There is a distinct possibility that other, less expensive technologies with limited degrees of freedom (eg. the Haptech/Immersion Corporation *PenCAT Pro*, an advanced version of which is shown in Figure 33[4]) could fulfill the job of accommodating the haptic requirements of the trainee surgeon's non-dominant hand. This issue requires careful consideration by the IERAPSI team, especially in light of the anticipated market requirements and tolerances to technology.

**Figure 33: Haptech/Immersion PenCAT Pro Advanced Design**

There are acoustic requirements associated with the use of non-drilling instruments. For example, both the facial stimulator and diathermy systems are endowed with audible cues, in most cases pre-set by the surgeon. These cues were outlined in Section 2.4. One also has to consider "cross-talk" between

**[4] No evidence of the existence of the PenCAT Pro could be established at the 2000 Siggraph Exhibition. It is likely that the system exists in concept only and has been shelved as a result of Immersion Corp's preoccupation with acquisition.**

instruments, such as the triggering of facial stimulator signals during the application of diathermy close to the facial nerve.

- Errors and Performance. Finally, a brief mention of the need to design the virtual training environment and integrate device drivers with evaluation and human performance assessment in mind. Further effort is required to specify the scope of tasks expected of trainees. This should be kept in mind as the human-system interface develops and consultation with future users is essential to ensure the correct selection of tasks and measures. These may include overall time, reaction time to contingencies, multiple errors whilst marking out head incision and cut area, contact with key anatomical features (eg. facial nerve, jugular bulb, sigmoid sinus, brain tissue), inadequate drill/burr selection, over-pressure whilst using the *PHANToM* and so on.

  Virtual Reality, coupled with a competently programmed database management system, offers the means by which subjectivity in performance assessment can be significantly reduced, even removed altogether. However, this statement is only true if the VR system, or the peripheral technology used, is selected and implemented so that **it measures what the researcher intended it to measure**. This is typically referred to as the *ecological validity* of an instrument or experimental design and will be a major factor in deciding whether or not the simulation is a credible instrument for assessing surgical *competency*. Competency refers to an individual’s knowledge, skills or abilities (sometimes called “KSAs”) performed to an acceptable standard when observed or recorded in the individual’s place of work. At the time of writing, this is a major issue under investigation by professional surgical bodies the world over.

# 4 Temporal Bone Task Abstraction

Although not a requirement of the IERAPSI project, it was decided to analyse the available data to a slightly deeper level, to see if, like the MIST laparoscopic cholecystectomy project, the surgeon’s behaviours could be decomposed to a level where a simple skills trainer could be developed, based on abstract task elements. This section briefly presents some initial thoughts on this issue.

One key point has to be raised here. As was asserted in the previous section, the very nature of temporal bone tasks demands the use of some form of haptic feedback, at least in the simulation of drilling activities. Therefore, an abstract content task simulator, such as that outlined here, cannot expect to stand alone in the training of future ENT surgeons. However, as a part-task simple skills trainer, made available on PC, there is some merit in considering a MIST-like decomposition.

A number of basic and common task elements/surgical behaviours were noted during the course of the surgical observations. These were:

- “deep” drill positioning,
- sensitive structure visual avoidance (sometimes with the added protection of an additional instrument, forming a barrier between drill and structure),
- thin bone “hooking” (whereby the ends of $90^o$ dissectors were carefully tucked under the translucent thin bone and then forcibly withdrawn causing bone plate breakage),
- bone structure contour following (primarily haptic, but strong ridge shadows were available for visual accuracy and fine predictive tracking),
- simple linear tracking,
- deep drilling under conditions of partial visual obscuration of the smallest of burrs,
- reliance on certain auditory cues.

In order to foster/test trainee performance in these task elements (with the exception of auditory cues), the geometrical structures described below have been designed. Note that these are not intended to represent the final abstracted task elements. As with the MIST system, they merely serve to structure initial thoughts on component perceptual-motor skills and would require further refinement and investigation before presenting valid and reliable test conditions.

**Figure 34: Abstract Task Main (Start) Element**

The basic test structure is an irregular octagon, as shown in Figure 34. This is a 3-dimensional block, as can be seen, segmented for reasons that will become apparent shortly. On the upper face of the block are, initially, 6 marked-out, semi-transparent areas. To begin the task, the trainee has to use his instrument (probably a simple representation of a large-diameter burr) to make contact with each of the marked-out areas (1-6; “Task A”). Contact is required to be very accurate in terms of depth into the screen (with the surface appropriately colour coded) and the instrument position is to be held for a period of 5 seconds. Deviations from position (depth) of greater than 2mm are recorded as an error. Any contacts with the border of the octagon, the middle cruciform or the 4 outer semicircles are also recorded as errors. On completing the 5-second position hold, the marked-out area vanishes. The task is repeated for each of the 6 areas. As they each vanish, they gradually expose further, underlying 3D structures. Using a small burr representation, the trainee is requested to make contact with the circular object in the middle of the 4 cruciform blocks ("Task B"). The circle is, in fact, the cross-section of a cylinder lying between 5 and 10mm down from the upper face of the cruciform blocks. Contacts with the surrounding edges of the cruciform blocks are recorded as errors. The cylinder changes colour on good contact and vanishes after the trainee is prompted to withdraw the drill representation.

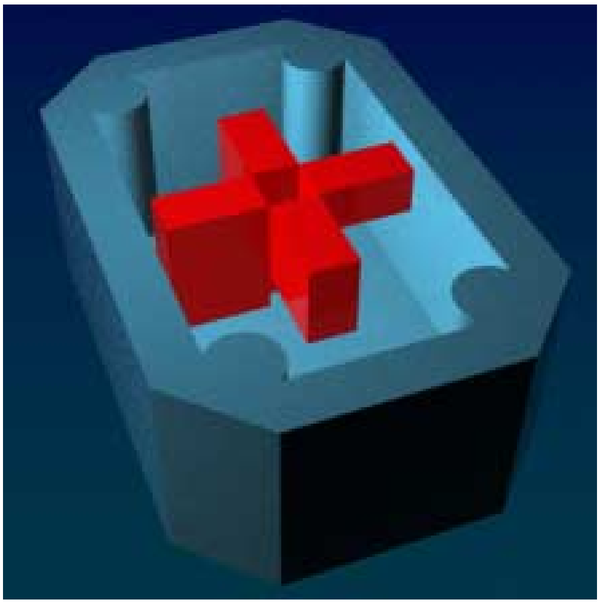

**Figure 35: Abstract Task Element with Surface and Cylinder Removed, Exposing Cruciform Blocks of Varying Depth**

On reappearing, the instrument takes the form of a 90° dissector. The task of the trainee now is to insert the dissector into the free areas between the internal octagon surface and penetrate to a depth below that of each of the blocks (**each block penetrates the internal octagon block to a different depth** ("Task C"), as shown in Figure 35). Contacts with the internal octagon edges and any part of the half-cylinder structures are registered as errors. To assist the trainee in depth perception, function keys (or some other appropriate input method) will oscillate the octagon-instrument combination left-right or up-down, thereby exposing the head of the dissector vis-à-vis the base of the cruciform block. On releasing the function key, the image is re-centralised and control of the instrument is passed back to the trainee (this concept may well need considerable refinement). The hook of the dissector is then to be rotated under the cruciform block and lifted. A successful operation will result in the block vanishing.

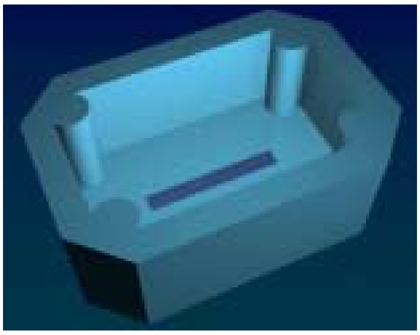

**Figure 36: Linear Track on Base of Octagonal Task Element**

On removing all 4 cruciform blocks, the base of the octagon is revealed with a simple linear track (Figure 36). The task of the trainee now, using a very small burr, is to make contact with the linear track, to "penetrate" the track to a depth of about 2-3mm (supported by appropriate colour, possibly acoustic coding) and to move the burr accurately along the track ("Task D"). A successful operation (assuming a track tolerance of 1mm either side) is cued by the track taking the form of a "backless trench". The final task of the trainee is to withdraw the small burr and to re-approach the trench, this time with a 90° dissector (automatically replaced on withdrawal; “Task E”). The trainee is required to insert the dissector, hook facing right, into the left-hand part of the track, rotate the hook through 180$^{o}$, so that it faces left under the octagon base, accurately track to the right-hand extreme of the track, rotate the hook through 360$^{o}$ and withdraw. Appropriate coding options/techniques to assist the trainee in these tasks are suggested in Table 3.

| TASK | SUB-TASK | “GREEN” CONDITION | “RED” CONDITION | “BLUE” CONDITION |
|---|---|---|---|---|
| A | Surface Contact, 6 Sectors | Surface: Good Contact (set to “off” if penetration ≥ 2mm) | Contact with Octagon Sides or Semi-Circular Surfaces | Instrument: Adequate Penetration |
| B | Circle Surface Contact | Good Contact | Cruciform Coded Red when Contacted | Instrument: Adequate Penetration |
| C | “Hook & Remove” | Not Used | Contact with any Structure During Penetration | Instrument: Adequate Penetration |
| D | Base Contact & Track | Good Contact with Track | Contact with any Non-Track Element (1mm Tolerance) | Adequate Penetration of Base |
| E | “Hook Tracking” | Not Used | Applied to Base when Track Tolerance is Exceeded | Adequate Penetration of Base |

**Table 3: Possible Cueing Techniques for Abstracted Task Performance**

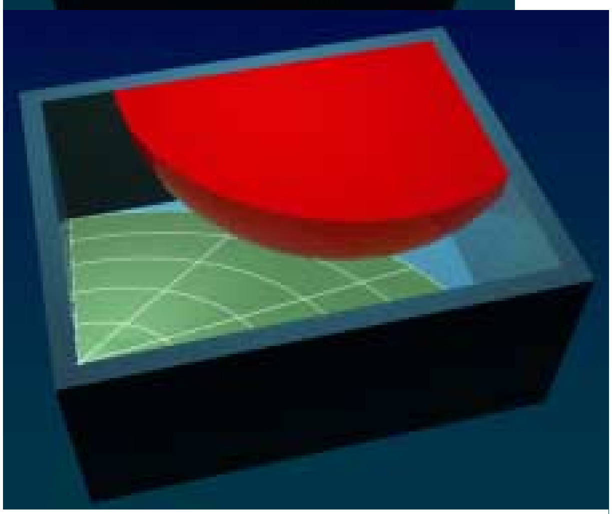

**Figure 38: Translucent Surface Removed, Showing Dome and Cone Sections**

To conclude this short section, an alternative (or even additional task) is illustrated in Figure 37. This shows a hollow cube where a substantial volume of one of the internal corners is taken up by a large “bowl”-like structure. The opposite corner is host to a quadrant of a cone, marked out in contact areas. The upper plane of the cube is first exposed to the trainee as a series of translucent areas. His task, first using a 90$^{o}$ dissector, then an appropriate burr, is to “hook and remove” each of the translucent areas, then gradually “remove” each of the cone segments.

It can be seen in Figure 38 that the deeper the penetration of the burr as the trainee attempts to make contact with each of the marked areas on the cone, the greater the obscuration caused by the dome object, therefore the more difficult the task.

Again, it must be emphasised that the ideas presented above have been generated following a first-level analysis of the video records from the MRI observation sessions and are not intended to represent hard-and-fast specifications for a part-task or skills trainer. They are registered here should, as the IERAPSI project progress, it be decided to look into the task abstraction approach as an alternative or supplementary form of training.

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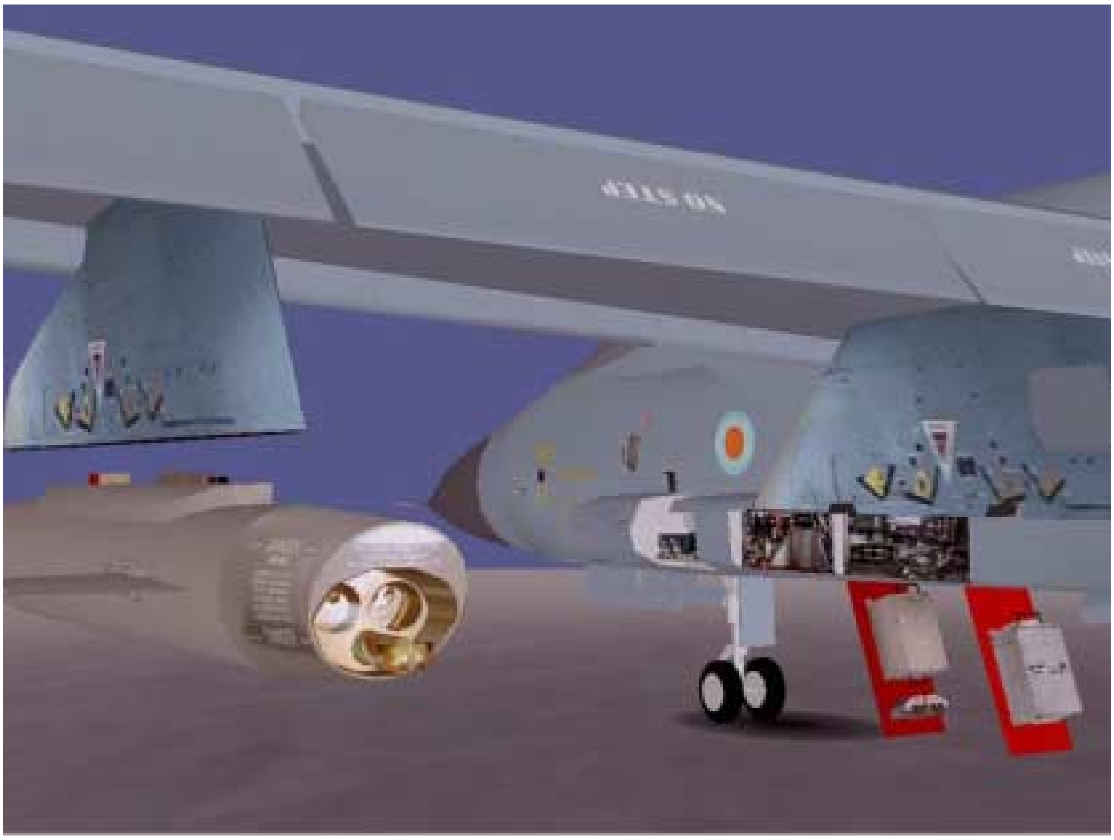


# RAF *Tornado* F3 Avionics Training Facility

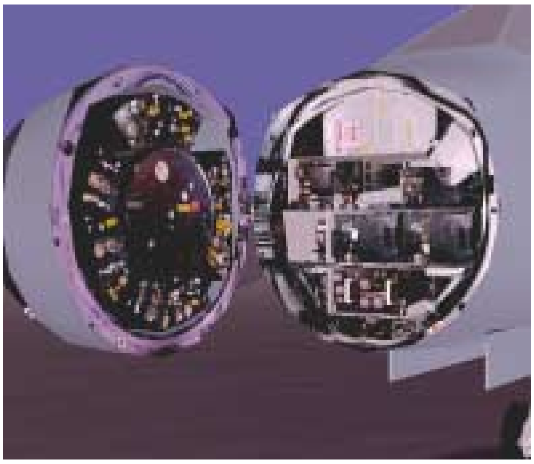
The *Tornado* ADV, or Air Defence Variant, later designated F3 by the RAF, entered service in 1985 and, following the announcement of a comprehensive weapons, radar and avionics upgrade in 1996, is today the UK's principal air defence aircraft, pending the introduction of the Eurofighter or *Typhoon*. To support such operational rôles as air defence and long-range interception, the testing and maintenance of electrical, mechanical and computerised systems onboard the aircraft must conform to exceptionally high standards. Consequently, avionics maintenance training is intensive and the technical expertise of qualified RAF ground crew is second to none. However, as with many other applications in the military sector, gaining access to appropriate hardware for maintenance training, be it a complete aircraft or even individual functional components (Line Replaceable Units, or LRUs), can never be completely guaranteed, given the demanding defence and policing duties performed by RAF *Tornado* squadrons across Europe and further abroad.

Overcoming these problems by employing Virtual Reality technologies in the classroom was the focus of a project undertaken by Virtual Presence under contract to Alenia Marconi Systems. On the basis of Virtual Presence's track record in aerospace maintenance projects[1] and experience in defence human factors[2], the company was subcontracted to develop the avionics training simulator for the *Tornado* Maintenance School (TMS) at RAF Marham, using proven VR modelling techniques and open systems run-time software. The system is hosted on a high-specification Windows NT system and, uniquely, features 3 screens per

[1] **See also Applications Sheet No. Eng/Apps/RR.98.1**
[2] **See also Applications Sheet No. HF/Apps/Ergo.98.1**

workstation, each displaying different working views of the aircraft, avionics bays, LRUs and/or virtual test equipment. 10 such workstations were produced, fully networked, allowing a **minimum** of 8 students to be trained and supervised by 2 instructors in basic and advanced *Tornado* F3 avionics maintenance routines, with collaboration between students supported over the local area network as necessary.

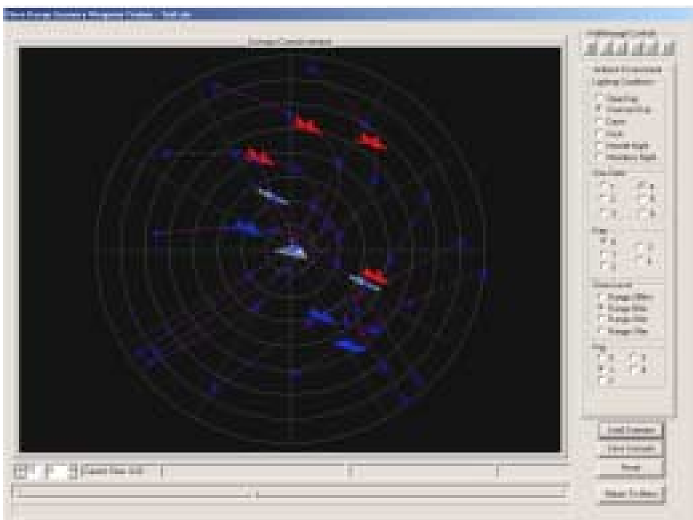
As well as the virtual aircraft shell itself (around which students are free to move), all moving surfaces are present (removable and hinged panels, flight control surfaces and radome), as are internal and external aircraft systems connector points. Full cockpit detail and functionality has also been delivered, for both the pilot and navigator positions. To produce this level of visual and interactive fidelity, 5 of VP's developers spent an entire week creating digital still and video footage, plus some 1300 film images of an F3 *Tornado*. The images were also used in conjunction with 3D drawings, again constructed by the VP team (in the absence of any CAD data) to construct a faithful VR representation of the aircraft shell. Over 450 LRUs feature in the simulation, located in equipment bays around the aircraft and as control and display units within the cockpit. Once the TMS trainers have programmed individual faults or sequences of faults, the students can explore the aircraft, opening hinged panels and selecting LRUs for removal, inspection and test using any of around 50 additional virtual test sets. Every control input made by the trainee results in a realistic and accurate change of state within the virtual *Tornado*, be it the movement of external flight surfaces, down to the illumination of individual LRU/test indicators.



In contrast to previous hardware and CBT-based training facilities at TMS (the main facility based on physical cockpit mock-ups costing over £UK 14 million), ATF has, since its operational debut in 1999, reduced training time from 13 to 9 weeks and downtime – time in which the waiting students do nothing – from 3 to zero weeks. The TMS Marham trainers believe the course could be shortened even further, but are reluctant to do so, choosing instead to increase course content and promote retention through "consolidation breaks" and extra-mural self-pace refresh trials). Feedback from the Marham trainers suggests that, in contrast to previous courses, ATF students "grasp the concept" (ie. gain enhanced spatial and procedural knowledge) up to 40% faster than achieved by previous non-ATF students. The modified *Tornado* F2 rig, as used by the GR4 course students, is still considered to be important, in order to deliver health and safety training associated with lifting procedures for some of the heavier LRUs, for example. Of particular interest is the cost of the ATF facility. In total this amounted to just over **one-tenth** of the cost of previous non-VR set-ups!

# Close-Range Weapons Simulation Facility
# HMS Collingwood

With the closure of the coastal firing range at HMS Cambridge near Plymouth in March 2001, 20 and 30mm naval weapons students are being trained today using a special simulation facility at HMS Collingwood near Portsmouth. Using state-of-the-art Virtual Reality techniques, including the latest in head-mounted display (HMD) technology, weapons students are now able to undertake realistic firing exercises, engaging targets as if located on an actual Royal Navy vessel. The simulators were commissioned by NRTA and developed by Virtual Presence Ltd over a period of just 6 months.



By means of a specially designed computer interface, weapons instructors can design and save a variety of training scenarios by using simple mouse and keyboard inputs. A wide range of hostile platforms (aircraft, surface vessels and missiles) can be programmed to approach the student's "own ship" from different bearings and ranges, and at different heights and speeds. Friendly and neutral aircraft or vessels can also be introduced into each scenario. Once the instructor has introduced a particular threat it is then possible to program its future route or profile by inserting one or more waypoints. Each waypoint can be associated with a change in direction, height or speed, thereby endowing the platforms with realistic behaviours. Quite complex scenarios can be generated in this fashion, with aircraft and ships even releasing missiles at certain points during their pre-programmed profiles.

During the training exercises themselves, these pre-programmed behaviours are displayed via HMDs to the student 20/30mm weapon aimers and, for simple tracking training, via a video projector to students manning a general-purpose machine gun (GPMG). The view through the aimer's HMD is that of a virtual weapon emplacement on the starboard side of their "own ship". The environment in which the scenario takes place can itself be programmed to include sea states from zero (calm) to 6, mist and fog levels, time of day and rain effects. In addition to the weapon aimer's position, 2 trainee Weapon Directors Visual (WDVs) stand on a purpose-built Gunner Director's Platform (GDP) within the HMS Collingwood simulator facility. The WDVs are also equipped with HMDs, each having been modified by the addition of a small switch. Pressing the switch magnifies the view available to the WDV, thereby simulating the use of binoculars. Calling out and acting on instructions, the WDV and weapons aimers interact to engage incoming targets. On firing the virtual 20/30mm weapon, realistic barrel motions can be seen, together with smoke and tracer effects. Successfully destroyed aircraft explode and fall to the sea. Sound effects have also been provided, including weapons discharge and an ambient, background naval vessel noise. Once a scenario has been run as a training exercise, it can be replayed by the instructors for debrief purposes.

Another component of the training system, located in a separate facility at HMS Collingwood relates to the observation and reporting of fall-of-shot, in this case for the ranging of larger calibre weapons (eg. the 4.5", Mk. 8 gun). Here, the virtual world images are fed into a special pair of virtual binoculars, mounted in place of the optical unit of a Director Aimer Sight (DAS). The instructor can test the student's splash-spotting skills by interactively selecting an impact point for a virtual projectile in the available DAS field of view. As well as seascape scenarios, the DAS students can also be presented with a landmass, consisting of static trees, building and vehicle targets. The weapons and DAS simulators are fully DIS compatible. This development could, for example, allow one or more of the simulators to fulfill a defensive role on a virtual ship taking part in a synthetic warfare exercise, irrespective of whether the vessel was hosted on a different simulator within HMS Collingwood, elsewhere in the UK, or even further abroad. In January, 2002, the CRWS team at Collingwood fired their one millionth virtual round, an event that was highlighted not only by the presentation of a trophy, but by a recognition on the part of all concerned that, had this been real ammunition, the cost to the RN would have been well in excess of £25 million!

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# THE IMPORTANCE OF A STRUCTURED HUMAN FACTORS APPROACH TO THE DESIGN OF AVIONICS MAINTENANCE & SUBMARINE QUALIFICATION VIRTUAL ENVIRONMENT TRAINERS[1]

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**Abstract**

Defence establishments and military forces across the globe have long been exploiters of virtual environment technology (or "synthetic environments"), primarily in large-scale simulators designed for such activities as operations planning, war gaming, command-control-communications and intelligence ($C^3I$) and, of course tri-service pilot, navigator and driver training. However, this exploitation has, of recent years, extended to part-task or "off-mission" activities, such as those military trainers which endow basic CAD or VR models of military platform subsystems with realistic behaviours, thereby enhancing the training of such procedures as familiarisation, maintenance, fault-finding and refit. Virtual Reality (VR) has been developed to create realistic military environments for such tasks as helicopter machine gun training, parachuting experience, explosive ordnance disposal, naval helicopter deck landing, submarine and surface ship blind piloting, officer of the watch training and many more. Also, as military hardware becomes more advanced, the inevitable reduction in real systems available for training means that computer-based lessons, many featuring VR, will become an essential tool of the military classroom, helping to familiarise tri-service personnel with the spatial and behavioural aspects of weapons platforms subsystems. However, the push for classroom VR trainers, designed to replace ageing conventional techniques such as "chalk-and-talk", overhead projection, simple video, even 2D CBT brings with it new challenges. Not only the challenge of delivering high performance and visual fidelity with the emerging range of low-cost NT workstations, but the challenge of delivering open systems architectures (thus assuring the longevity and reusability of the application), standardised techniques for 3D computer modelling, protocols for the integration of behavioural simulation with multi-display rendering and "best practice" human factors design and implementation techniques. This paper addresses some of these issues by illustrating two recent case studies: the development of an Avionics Training Facility (ATF) for the British RAF F3 *Tornado* and a feasibility project to assess the use of VR in the UK submarine qualification (SMQ) process.

**Biographical Sketch:**

Prof. Bob Stone is Scientific Director of MUSE Technologies Inc., based at the company's Virtual Presence subsidiary in Manchester, UK. His background is in Applied Psychology and Ergonomics, and he currently holds the positions of Visiting Professor of VR within the Faculty of Medicine at Manchester University and the School of Computing within the University of Plymouth and is an Academician of the International Higher Education Academy of Science (Moscow). He is Director of VR Studies at the North of England Wolfson Centre for Minimally Invasive Therapy and is a member of a Royal College of Surgeons' working party on assessment of surgical competence. In 1987 he became one of the first Britons to experience the early NASA VR systems during a telerobotics R&D project for the European Space Agency. In 1993, after 4 years of telerobotics and VR research at the UK's National Advanced Robotics Research Centre, he brought together some 15 companies to launch a unique nationwide project demonstrating the commercial and industrial uses of VR. Bob lectures across the globe on VR and is the President of Japan's Virtual Systems & Multi Media Society. Bob is recognised internationally as one of the world's foremost pioneers in VR developments and has won a number of prestigious awards for his human factors and VR-related research, most recently the 1999 RSA (Royal Society for Arts, Manufacture & Commerce) Howorth Medal, for "…distinguished contributions, over time, to successful industrial or commercial achievement … through outstanding innovation and enterprise…".

[1] To be published in Proceedings of ITEC (2001)

# The Importance of a Structured Human Factors Approach To the Design of Avionics Maintenance and Submarine Qualification Virtual Environment Trainers

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## INTRODUCTION

"Computer-controlled" technology, as applied to training generally, has been in existence for over 35 years. From programmed text delivery to flight simulation, computer-based training (CBT) in one form or another has gradually become the norm, rather than the exception.

Yet the spread of adoption of CBT techniques and especially those based on Virtual Environment or Virtual Reality (VR) technologies, has not been straightforward. Each time computer technology has been used to introduce a new level of functionality into a training paradigm, be it based on classroom delivery, or reliant on access to full-scale mock-ups, even real operational equipment or plant, it seems that the same sceptical issues are raised.

Will CBT improve the effectiveness with which knowledge is delivered or assimilated? Will it reduce reliance on scarce operational systems or costly hardware-based training materiel? Does it offer anything over and above conventional training methods? Can previous investments in technology be protected, or must new, non-commercial-off-the-shelf (COTS) resources be procured? Will students be more motivated and, thus retain more? Will students and trainers actually use the technology? Will there be a positive transfer of training (or knowledge) from the computerised setting to the real operational environment?

Virtual Reality has not escaped this cross-examination. Far from it. Indeed, there are those who firmly believe that VR has become a victim of its own early hype. Certainly, there was much damage caused in the early 1990s by those organisations forcing potential users to accept the inevitability of immersion technologies. Fortunately, the emergence of a number of extremely impressive industrial applications across the globe, many being driven by strong commercial reasoning, has help stimulate a "revival" of interest in VR, in both immersive and desktop forms.

Only quite recently have powerful toolkits based on interactive 3D audio-visual images and VR have become available. In parallel with this "technology push" there has been a "market pull", with potential CBT users demanding lower technology costs, more efficient utilisation of students and trainers and hard evidence of the cost benefits and manpower performance improvements the technology offers. To the developers of VR technologies, and to those working closely with industrial pioneers to produce real applications, the value of VR has been unquestionable.

Gradually, more and more valid and reliable (ie. less anecdotal) results are appearing in reputable journals, based on experimental trials from the growing installed base of experimental simulator prototypes (the shift of commercial applications from the expensive graphics "supercomputers" to more affordable Windows-based machines has contributed enormously here).

However, to achieve validity and reliability in one's development and evaluation programmes, one has to turn from the outset to the ergonomics and applied psychology community, not just for guidance in the appropriate design of experimental programmes (eg. Meister, 1985, 1986; see also AIAA, 1993) but for guidance in the structured analysis of real-world tasks (or even proposed tasks for an as-yet unbuilt system). Additionally, one needs to be able to use the results of such an analysis to specify the possible abstraction of the real-world task elements into their VR counterparts (which may or may not be of a high visual fidelity or high in terms of visual realism).

A task analysis is a process by which one can formally describe the interactions between a human operator and his/her working environment (including special-purpose tools or instruments), at a level appropriate to a pre-defined end goal (typically the evaluation of an existing system or the definition of the functional and ergonomic features of a new system). An excellent definition of task analysis was put forward by Bradley of axsWave Software, Inc., based on two IBM documents compiled by Terrio & Vreeland (1980) and Snyder (1991):

> *A task analysis is an ordered sequence of tasks and subtasks, which identifies the performer or user; the action, activities or operations; the environment; the starting state; the goal state; the requirements to complete a task such as hardware, software or information.*

Without a properly executed task analysis, one runs the risk of specifying or designing a VR (or any computer-based, experiential) system that fails to deliver clear sensory and perceptual components that aid users' understanding (cognition) of the target application. One also jeopardises the future integrity of any programme – experimental or otherwise – that sets out to validate one's concepts for content and deliver, not to mention the transfer of training from the virtual to the real (if applicable).

There is no one "magical" formula for executing a task analysis. The type of analysis employed depends on the human factors specialist involved, whether or not the task exists in reality, the goal of the analysis (eg. are the results required for new system design or training procedures?) and any constraints imposed by the analysis environment. The task analysis should form an early and central component of any project that involves a major human-centred component.

Indeed, recognition of this has recently been formalised by the publication of International Standard ISO 13407, *Human-Centred Design Processes for Interactive Systems* (ISO, 1999). ISO 13407 specifies 4 general principles of human-centred design and 4 further principles of human-centred design activities, namely:

**Principles of Human–Centred Design**

**(a)** Ensure active involvement of users and a clear understanding of user and task requirements (including context of use and how users might work with any future system evolving from the project – if at all),
**(b)** Allocate functions between users and technology (recognising that today's technology, rather than de-skilling users, can actually extend their capabilities into new applications and skill domains),
**(c)** Ensure iteration of design solutions (by involving users at as many stages of the design and implementation process as is reasonable practical),
**(d)** Ensure the design is the result of a multidisciplinary input (again this emphasises the importance of user feedback, but also stresses the need for input from such disciplines as marketing, ergonomics, software engineering, technical authors, etc.).

**Human–Centred Design Activities**

**(a)** Understand and specify the context of use (including the characteristics of the intended users; the tasks the users perform, or *are* to perform; the environment in which users use, or *are* to use the system; relevant characteristics of the physical environment),
**(b)** Specify user and organisational requirements (this includes aspects of team working, health and safety issues, user reporting structures and responsibilities),
**(c)** Produce design solutions (with multidisciplinary team and user involvement),
**(d)** Evaluate designs against requirements (a continuous process throughout the design cycle).

There are many techniques for carrying out a task analysis. Some involve observational and/or interview techniques (often backed up with video and/or audio records). Others can employ quite sophisticated computer-based solutions, from mixed media data recording (video, keystrokes, physiological parameters, voice, etc.) to simulations based on human performance parameters and cognitive models.

The methodology chosen for the examples described herein was based on a combination of observational and *in situ* interview techniques, generating results of relevance to the *Human–Centred Design Activities* components of ISO 13407, listed above. In addition, use was made of the contents of documents recommended within ISO 13407 together with established UK and US human factors reference texts. Finally, the experience of the author in analysing tasks in other application domains was brought to bear. These included projects requiring the analysis of remotely operated submersible missions (Stone, 1984), offshore diving supervision tasks (Stone, 1991), the food processing industry (Stone, 1994), laparoscopic cholecystectomy tasks (Stone, 1999a) and, more recently, the integration of haptic feedback technologies in a virtual mannequin aerospace maintenance training demonstrator (Stone, 1999b).

## EXAMPLE 1: THE *TORNADO* F3 AVIONICS TRAINER

The UK Royal Air Force's variable geometry, all-weather *Tornado* ADV, or Air Defence Variant, later designated F3 by the RAF, entered service in 1985 and, following the announcement of a comprehensive weapons, radar and avionics upgrade in 1996, is today the UK's principal air defence aircraft, pending the introduction of the Eurofighter (*Typhoon*). To support such operational rôles as air defence, long-range interception and even aerobatics duties (in the case of the RAF's F3 Display Team), the testing and maintenance of electrical, mechanical and computerised systems onboard the aircraft must conform to exceptionally high standards. Consequently, avionics maintenance training is intensive and the technical expertise of qualified RAF ground crew is second to none.

However, as with many other applications in the military sector, gaining access to appropriate hardware for maintenance training, be it a complete aircraft or even individual functional components (Line Replaceable Units, or LRUs), can never be completely guaranteed, given the demanding defence and policing duties performed by RAF *Tornado* squadrons across Europe and further abroad.

### The Avionics Training Facility (ATF)

The ATF initiative arose not only as a result of limited access to airframe hardware, but also as a requirement to reduce training times and costs. Prior to the existence of the ATF, students at the *Tornado* Maintenance School (TMS) at RAF Marham were trained using a variety of systems, such as a comprehensive selection of instrumented mock-ups relating to the *Tornado* GR4 strike aircraft.

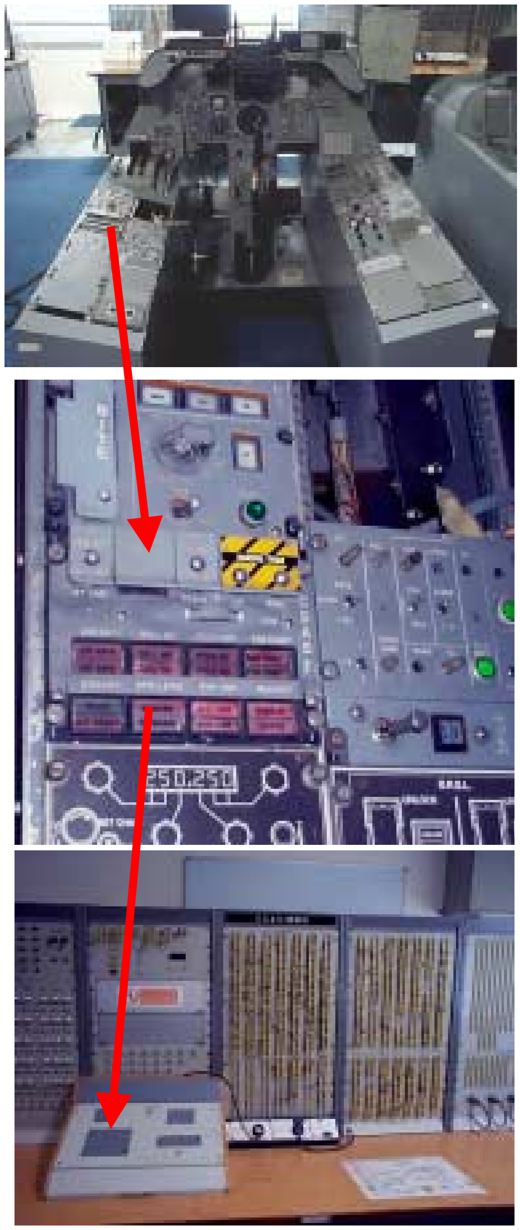

***Figure 1. From Cockpit Mock-Up to Bench Trainer – the CSAS System***

This £UK14 million ($US35 million) facility has been in existence for just over a year and provides students with a 13-week course. In addition, an "old" F3 rig in use before ATF was introduced – the Avionics Ground Training Rig (AGTR) – achieved an 11-week course duration. However, as these facilities are based on physical rigs and quite limited bench avionics training devices, only 2 students plus 1 instructor can be present on a rig at a time.

One good example of the need for a more flexible training delivery mechanism is the Command Stability Augmentation System (CSAS), an avionics system that, put basically, smoothes out pilots' inputs to the fly-by-wire system in order to promote efficient and stable flight performance.

CSAS subsystem training requires the line replaceable unit to be removed from the cockpit mock-up and inserted into a nearby bench trainer. Here, faults are simulated by means of a complex set of wiring combinations, reminiscent of an old telephone exchange (CSAS and the bench trainer are shown in Figure 1).

As a result of these practices, each and every student experiences a downtime totalling some 3 weeks – 3 weeks where the student does nothing at all!

The GR4 facility supports avionics training in all major systems (navigation, communications, weapons aiming, flight guidance, etc.) except defensive. The students also have access to a full aircraft rig, based on a *Tornado* F2 airframe, (see Figure 2) modified using F3 and GR4 components, such as LRUs, wing pylons, and so on.

***Figure 2. Modified F2 Aircraft***

The main requirements laid down by the RAF for the ATF system included the following:

- Ten networked Windows NT workstations (2 instructor stations and 8 student stations) supporting student collaboration in real-time, the "injection" by the instructor of LRU faults and a capability for the instructor to "snoop" on individual workstations.
- Multi-screen display (see below).
- Real-time 3D navigation and interaction by simple mouse-and-function key interface
- Integration of underlying ATF simulation (developed by Alenia Marconi) with the virtual *Tornado*, via a core real-time event manager.
- Provision for future interface upgrades (head-mounted display, stereo projection, special immersive displays, etc.)
- A software guarantee to allow for ATF support, modification and upgrades over a minimum 10-year period.

Consequently, each workstation in the ATF system is based on a high-specification Intergraph Windows NT computer equipped with 3 Wildcat Series 4000 graphics cards, each driving a 17-inch monitor (Panoram Technologies' PowerView 290 triple-screen display, shown in Figure 3, is also supported).

Each screen displays different working views of the aircraft, avionics bays, LRUs and/or virtual test equipment. Alternatively, the entire aircraft can be displayed as a "panorama" across the 3 screens. The workstations allow a minimum of 8 students to be trained and supervised by 2 instructors in basic and advanced *Tornado* F3 avionics maintenance routines.

As well as the virtual aircraft shell itself (around which students are free to move), all moving surfaces are present (removable and hinged panels, flight control surfaces and radome), as are internal and external aircraft systems connector points.

Full cockpit detail has also been delivered, for both the pilot and navigator positions, and include geometric and operable representations of toggle switches, safety covers, rotary switches, push buttons, pedals, throttles and joysticks.

***Figure 3.  Panoram PV290 Display***

To produce this level of visual and interactive fidelity, 5 VR developers spent two weeks creating digital still and video footage, plus some 1300 film images of a loaned F3 *Tornado*!  Photographs of the real LRUs were then used to generate texture maps, used subsequently to endow their virtual counterparts with high visual fidelity and to provide a template for locating virtual rotary controls, switches, digital and analogue dials and counters. The images were also used in conjunction with CAD drawings to construct a faithful VR representation of the aircraft shell.

It should be noted that no formal CAD records of the F3 aircraft existed. Consequently, the aircraft and its constituent components had to be measured to millimetre accuracy for subsequent modelling in 3D Studio Max. The LRUs and their textured surfaces were also archived for future review and manipulation as VRML files (eg. via Cosmo, Cortona, GeoVRML, etc.).  Such files are easily transmitted as e-mail attachments (eg. 6 VRML LRUs can fit onto a standard 1.5" floppy disk).

Over 450 LRUs feature in the simulation, located in equipment bays around the aircraft and as control and display units within the cockpit.  Once in the vicinity of an LRU or equipment bay, hinged panels can be opened and units can be selected and removed by the students and manipulated in 3D.  The LRUs can be tested (using any of approximately 50 additional items of virtual test equipment, each with their associated external and internal connection sockets) and subsequently refitted or replaced.

Each function is endowed within the simulation with a pre-set performance time and a simulator clock is constantly monitoring task performance time. For example, a student's decision to *replace* an LRU will be accompanied by a time "penalty" of 0.75 to 1.5 hours (reflecting the time taken to obtain a new unit from spares), in contrast to that associated with a decision to *refit* (0.25 to 0.5 hours) after test and immediate repair.

Control inputs are, wherever possible (and ergonomically acceptable), restricted to a conventional mouse (2-button+wheel) and single function key, delivering discrete, momentary and continuous input functions, supporting:

- Aircraft walk-around
- Panel opening
- Withdrawal, inspection and test of LRUs
- Cockpit, LRU and test set display/ control operation.

Every control input made by the student results in a realistic and accurate change of state within the virtual *Tornado*, be it the movement of external flight surfaces, down to the illumination of individual LRU/test indicators.

**Recent Findings**

In contrast to the GR4 and AGTR facilities described earlier, the ATF facility (one of the workstations is shown in Figure 4) has, at the time of writing, been in existence for only 10 months.  In that period, the course time has been reduced from 13 (GR4) and 11 (AGTR) to 9 weeks with no downtime. The TMS Marham trainers believe the course could be shortened even further, but are reluctant to do so, choosing instead to increase course content and promote retention through "consolidation breaks" and extra-mural self-pace refresh trials).

***Figure 4. One of the ATF Workstations at RAF Marham***

ATF supports 8 students (and 2 trainers), although there is no reason why each workstation could not support 2 or 3 students. All avionics modules are supported. Initial feedback from the Marham trainers suggests that, in contrast to previous courses, ATF students "grasp the concept" (ie. gain enhanced spatial and procedural knowledge) after only two-thirds of the time taken by previous non-ATF students.

The modified *Tornado* F2 rig, as used by the GR4 course students, is still considered to be important, in order to replace some of the obvious shortcomings in the VR *Tornado* – health and safety issues associated with lifting some of the heavier LRUs, for example. The real aircraft can also be used in other health and safety training procedures, such as highlighting very hot areas once the aircraft has landed, or components capable of delivering electrical shock. Of particular interest is the cost of the ATF facility. In total this amounted to **£1.5 million** – a fraction of that of other non-VR-based set-ups.

## EXAMPLE 2: SUBMARINE QUALIFICATION TRAINING

As witnessed in the military aerospace domain, the use of simulation in the design and management of naval vessels and in the training of their personnel is gaining rapid international support. New computer-based part-task trainers using a wide range of presentational and interaction techniques – many unproven from a human-centred standpoint – are announced almost on a monthly basis at marine and defence exhibitions across the globe.

Based on similar experiences in delivering the ATF system for the RAF, this paper describes a recent project conducted for the UK Royal Navy's Flag Officer Submarines (FOSM). Although the original project was based on the early training and vessel familiarisation needs for submariners destined to serve on the UK's fleet of *Trafalgar* Class (SSN) boats (see Figure 5), the results of the project are currently being given serious consideration for other submarine classes, and future platforms such as *Astute* (also known as "Batch 2" *Trafalgar*).

***Figure 5. Trafalgar Class SSN at Dockside***

A well-reported submarine VR project in the US, *VESUB* (Virtual Environment for SUBmarine Officer of the Deck ship handling training technology demonstrator Seamon *et al*., 1999) was conducted at the US Submarine Training Facility in Norfolk, Virginia and at the Naval Submarine School in Groton.

Unlike many of the CBT systems in existence today, VESUB was based on *immersive* VR technology, using proprietary head-mounted displays (initially the Virtual Research *VR4*, later n-Vision's high resolution *DataVisor*), speech recognition and a Silicon Graphics *InfiniteRealityEngine* computing platform.

The immersive facilities were used to create virtual environment views as if the user were located on the fin of a typical US submarine. Some 41 VESUB users were used in the trials, all naval personnel (involved with submarines) ranging in experience from Junior Officers to qualified Officers of the Deck and Commanding Officers. The subjects were exposed to three scenarios in the VESUB system:

- an orientation scenario to help them become familiar with the capabilities and operation of the VR system,
- a training scenario comprising several boat handling tasks (eg. position determination, contact location and evaluation, getting underway, manoeuvering (including rudder checks), man overboard, vessel crossing (“rules of the road”), and
- an actual test scenario where task improvements were recorded.

Results from the latter scenario demonstrated a significant improvement in learning between training and test sessions, almost regardless of experience level. For example, students improved 39% in checking range markers, 33% in visually checking the rudder, 57% in contact management and 44% in reaction time in a man overboard event.

In contrast to the VESUB project, the overall Royal Navy (RN) requirements for what is referred to as the submarine qualification (SMQ) system relate to the initial provision of a PC-based trainer which will enable students to become familiar with the layout of the target class of boat, including decks, compartments, key items of equipment, main service routes (eg. high-pressure air), safety equipment and so on.

Furthermore, the system is required to preserve the RN’s investment over a long period, by demonstrating features that support:

- Upgrading (to account for boat-to-boat differences, refit planning, special system upgrades/ equipment additions);
- Upgrading (enhancing the overall fidelity of the model as technology and resources permit)
- Database links (with existing and planned training material);
- Reusability, in whole or in part, for (for example):
    - New submarine classes,
    - Diving training (eg. hull inspection),
    - In-service training (Extension of the model for operational and contingency planning),
    - Navigation (including channel and “blind” pilotage, as with VESUB),
    - Officer of the Watch/Deck training (as with VESUB),
    - Dockside deck procedures,
    - Special incident rehearsal (eg. helicopter CASEVAC).

Following a period of close liaison with the potential customer and shore-/boat-based users of an SMQ training environment (as defined within items (a) through (c) of the Human–Centred Design Activities within ISO 13407), the approach recommended for developing and delivering the training system was hybrid VR-multimedia in nature, relying on a carefully implemented blend of:

- 3D engineering data,
- digital images (eg. photographic records of a boat, training manuals),
- digital videos (mpegs/avis),
- digital panoramas (based on *QuickTime VR*, *Ipix* or *RealityStudio*),
- basic (ie. VRML) 3D models of selected items of equipment, with animated features as deemed necessary

These data are all structured within a 3D virtual geometric “submarine” shell (itself based on converted CAD data from the submarine developers). Interaction with, and display of the hybrid data sources is carried out via a “minimalistic” user interface (for both students and instructors, as with the *Tornado* ATF system), the design of which will also adhere to the guidelines laid down in ISO 13407 and related usability standards/best practices. The source CAD data are converted (using proprietary and in-house data conversion procedures) into a form suitable for re-working into a fully interactive and real-time virtual submarine model, supplementing the data with unique items of geometry as necessary (eg. using other proprietary modelling packages). By doing this the processing speed on the part of the host computer is optimized by employing such cost-effective techniques as zone (eg. compartment) culling and level-of-detail management.

The SMQ lesson style is anticipated to take the form of an initial series of virtual "tours" of the 3D submarine model, to demonstrate the user interface components and the functionality of the software. The SMQ training personnel will undertake a number of examples that will be displayed to the student group using a large-screen video projector.

A series of exercises will be developed which will require students to locate and (where necessary) actuate shipboard components. Students can "walk" through the virtual submarine on predefined paths. At any point, they are free to turn, look around and interact with "active" scene items, as appropriately identified on-screen. On entering a virtual compartment or zone of interest, the student is confronted with a virtual space – textured as necessary. The compartment possesses visually recognisable features – lockers, fire equipment, consoles, ladders, large-bore piping, and unique components (see Figure 6).

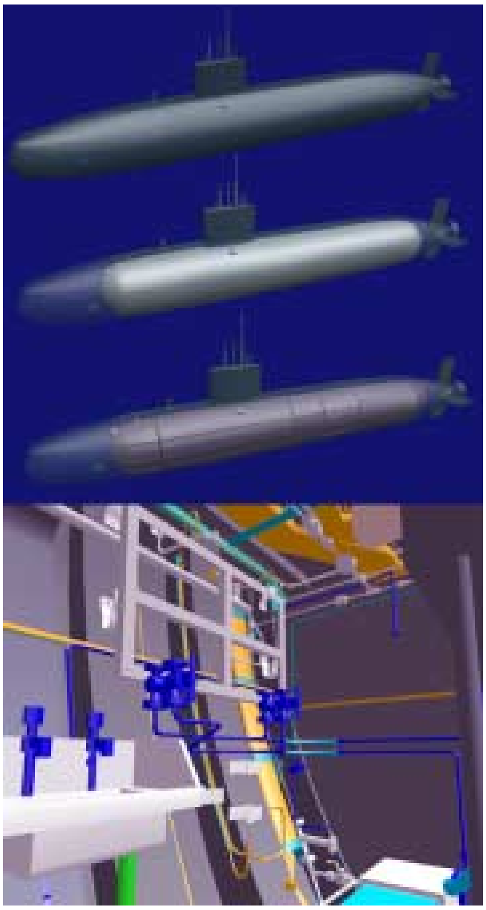

***Figure 6. Virtual Submarine Levels of Detail***

For those compartments where additional detail and realism is required, panoramic VR techniques are implemented. Fixed nodes and viewpoints are linked to "higher realism databases", such that the call-up of active scene items, static and panoramic images match visually with their respective locations within the geometric compartment layout. The actual paths and times taken by students in pursuit of the set tasks is recorded and made available for replay/archiving. Finally, "hot spots" within the panorama are linked to additional 3D geometric databases (VRML), containing recognisable models of important and safety-critical equipment (eg. high-pressure blow valves) or digitised textual/video extracts from existing training and informational sources. In the case of the 3D models, once the hot spot has been interrogated (simple mouse click), the VRML object appears, with textured features and labels (where relevant to the identification and operational part of the SMQ task). The student is then able to initiate any animated or interactive features to demonstrate operation and, in the case where the operation of safety equipment can originate from elsewhere in the submarine (eg. operations compartment), warning displays are also presented.

## CONCLUSIONS

In 1996, J.D. Fletcher published an excellent review paper, entitled "Does This Stuff Work?" (Fletcher, 1996). This work left few in doubt that Fletcher was laying a defiant "challenge to read" at the doors of the world's CBT sceptics! He listed a series of military studies that demonstrated clearly that computer-based instruction improved trainee performance when compared to standard lectures, text-based materials, laboratory work or hands-on experience with real equipment. Furthermore, the use of "interactive multimedia instruction" (as Fletcher described it) resulted in even more impressive performance figures, suggesting an improvement in attainment from 50$^{th}$ to 75$^{th}$ percentile. Fletcher also cited other studies that show that computer-based instruction is typically associated with a reduction of around 30% in the time required to achieve course objectives, when compared to conventional delivery techniques. This is in line with some of the early findings of the *Tornado* ATF VR simulator. The past 18 months have seen a number of similarly impressive results emerge from the defence community, leading one to conclude that VR technologies are finally capable of demonstrating true cost-benefits, in terms of improved human skills and financial returns brought about by improved training efficiency.

The adoption of VR technologies by defence organisations is no longer just a case of vendors trying to impress potential users with the capabilities of an exciting technology. Understanding the capabilities and limitations of the individual user and his or her organisation is essential to the future development of VR as a stable form of computer-based training. It is all too easy to fall to strive for visual excellence at the expense of usability and content, not to mention losing sight of the wider market needs of the user organisation. In 1997, the author wrote:

> "...many developers (especially in the human factors field) believe that one effect brought about by the existence of advanced [VR] hardware and software technologies has been a reduction in the application of scientific rigour to the design of human-system interfaces. Suddenly, reasonably user-friendly software tools have become readily available which have, in some cases, permitted the designers of information displays to "go to town" in their design approach. The result? "3D works of art" - visually impressive interface formats - but of questionable usability. The drive for visual impact appears to have over-shadowed the crucial issue of concentrating on the underpinning human factors issues surrounding the need for sophisticated 3D display formats...".

VR is, first and foremost, a suite of technologies which provides the ergonomics and human factors community with a "toolkit" for optimising the design of the human-system interface for numerous applications. Ergonomics, sometimes (ignorantly) underrated as a technological field of endeavour, has a significant contribution to make to the development of VR into this Millennium. Not just as a means of alerting VR users to negative and sometimes scare-mongering issues, such as the potential side effects of "immersion", but in the development of methodologies to measure and report the positive effects of applying this exciting human-centred technology throughout industry. As concluded by the author in a recent encyclopaedia (Stone, 2000), ergonomics is often defined as the study of the relationship between the human and his or her working environment. It should make no difference whatsoever if that working environment is real or virtual.

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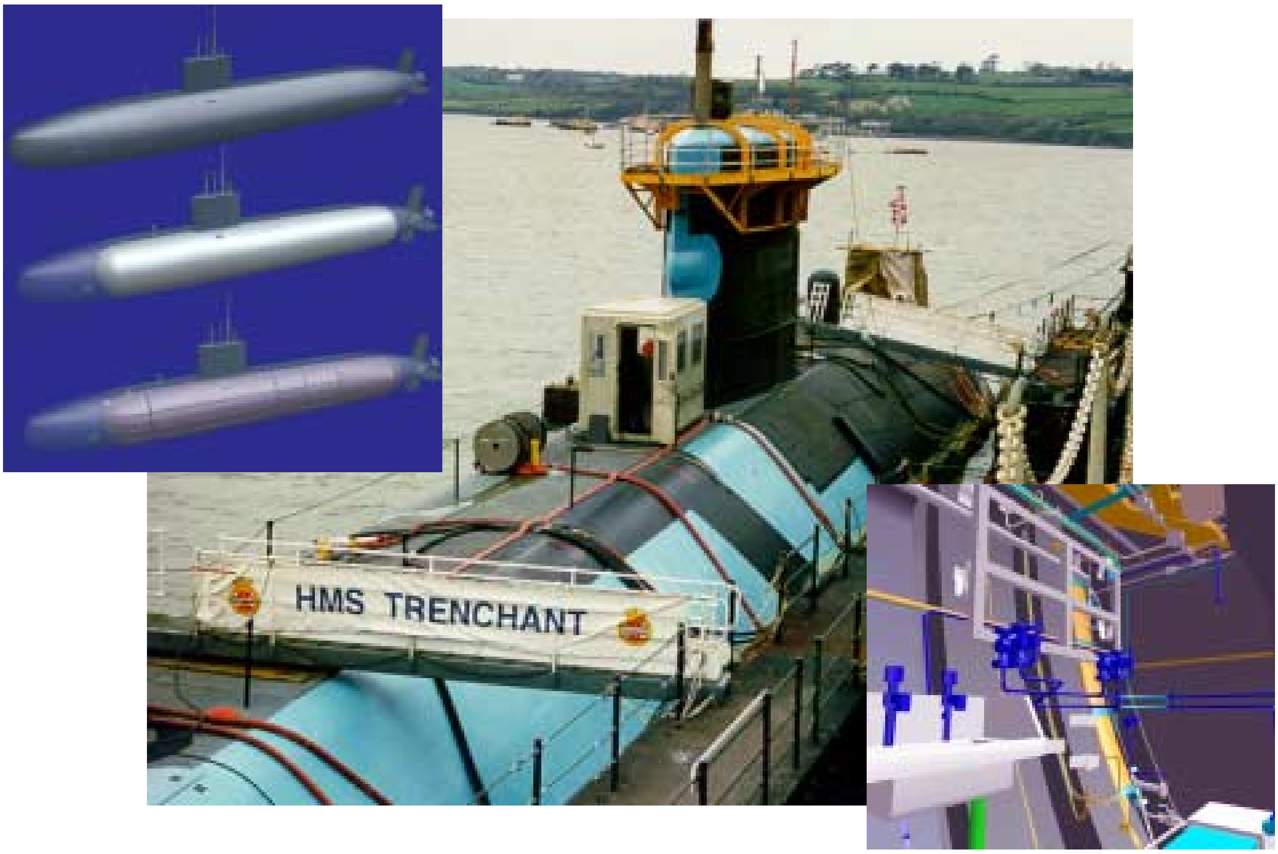


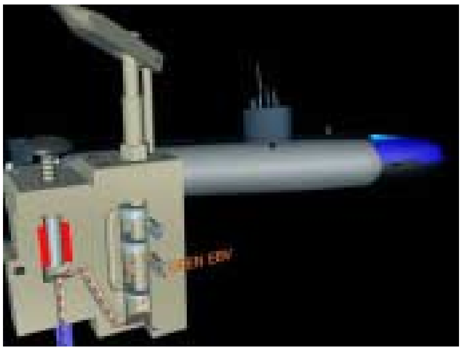

## SUBMARINE QUALIFICATION (SMQ) TRAINING

As already witnessed in the military aerospace domain, the use of simulation in the design and management of naval vessels and in the training of their personnel is delivering significant benefits and cost savings for minimal initial outlay. Based on similar experiences in delivering the Avionics Training Facility for the RAF's F3 *Tornado* aircraft, and resulting from over a decade of work with British submarine developers and users (including the Royal Navy's Flag Officer Submarines, FOSM), VP Defence has developed a "mixed media" solution, called *VOCS*™ (Vessel Orientation & Critical Systems), capable of delivering effective classroom familiarisation training for submariners. *VOCS* is a human-centred methodology that results in the delivery of meaningful training and design content – hosted on commercial, off-the-shelf (COTS) PCs and based on available source data, including 2D/3D drawings, 2D/3D CAD, photogrammetry and interactive photographic, video and hypertext material.

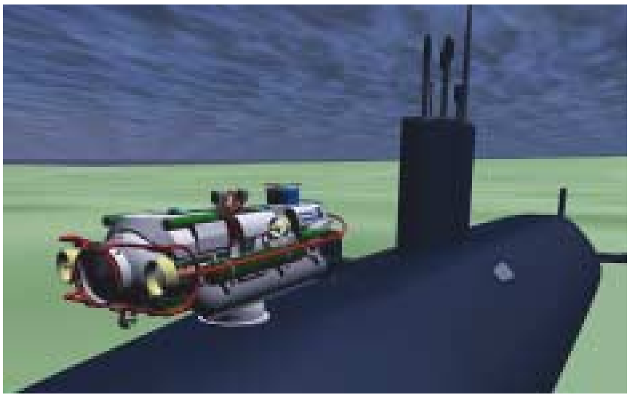
Although the original project for FOSM was based on the early training and vessel familiarisation needs for submariners destined to serve on the UK's fleet of *Trafalgar* Class (SSN) boats (such as HMS *Trenchant* shown above), the results of the project are equally relevant to other national and international submarine classes, such as the *Vanguard* SSBN vessels, and future platforms such as *Astute*. The original RN requirements for SMQ system related to the initial provision of a PC-based trainer that would enable students to become familiar with the layout of the target class of boat, including decks, compartments, key items of equipment, main service routes (eg. high-pressure air), safety equipment and so on. ***The Safe Submariner*** concept is central to VP's *VOCS* methodology. Furthermore, the system is required to preserve the RN's investment over a long period, by demonstrating features that support:

- Simple upgrading (to account for boat-to-boat differences, refit planning, special system upgrades/equipment additions)

- Fidelity upgrading (as technology and resources permit)
- Database links (with existing and planned interactive electronic training material)
- Diver training (eg. hull inspection)
- In-service training (extension of the model for operational and contingency planning)
- Navigation (including channel and "blind" pilotage) and Officer of the Watch/Deck training (as with the US Virtual Environment Submarine, or *VESUB* programme, using immersive VR technologies to simulate bridge/fin OOD location)
- Dockside deck and incident procedures
- Special and safety-critical incident rehearsal (eg. casualty airlift, distressed submarine – *DISSUB* – evacuation (see below and separate applications sheet))



An SMQ exercise demonstrator has been developed by VP Defence that requires the student to describe, locate and actuate the emergency blow control valve (EBCV), within the forward escape compartment of a *Trafalgar* class submarine. Students can explore the virtual compartment on predefined paths. At any point, they are free to turn, look around and interact with "active" scene items. On entering the virtual forward escape compartment, the student is confronted with visually recognisable 3D features – lockers, fire equipment, consoles, ladders, large-bore piping, and unique components These 3D objects can be modelled using data sourced from CAD, photogrammetry, scale models, even simple illustrations and photographs. Where additional detail and realism is required, panoramic (360$^{o}$) images fade in and out on demand, their location in space closely matching their 3D counterparts. "Hot spots" within the panoramas are linked to additional 3D objects, containing recognisable models of important and safety-critical equipment (such as the ECBV) or digitised text/video extracts from existing training and informational sources (including IETMs). In the case of the 3D objects, once the hot spot has been interrogated (single mouse click), the object appears, complete with textured features and labels (relevant to its identification and operation). The student is then able to initiate any animated or interactive features (including sound effects) to demonstrate procedures and processes (eg. solenoid actuation, HP air transfer to main ballast tanks). In the case where the operation of safety equipment originates from elsewhere in the submarine (eg. operations compartment), warning displays are also presented.



With regard to the issue of evacuating a disabled submarine, VP Defence was also a member of the NATO Submarine Rescue System (NSRS) PD Study team, addressing the high-level training requirements for future manned or unmanned rescue vehicle solutions and ensuring commonality of training (where appropriate) between NSRS and SMQ. Since that project was completed, a *VOCS* demonstrator has been completed, showing the ease with which an existing 3D model of the UK Submarine Rescue System (kindly provided by RUMIC Ltd, operators of the LR5 submersible) can be integrated with the current SMQ demonstrator of the *Trafalgar* Class submarine.


## SUBMARINE RESCUE
## SYNTHETIC ENVIRONMENTS TRAINING

In 2001, VP Defence completed a Human Factors and Training Needs Analysis Scoping Study under subcontract to WS Atkins, who had been commissioned to conduct the overall Project Definition Study for the NATO Submarine Rescue System (NSRS), reporting to the Integrated Project Team (IPT) of the same name within the UK Ministry of Defence. VP's involvement with WS Atkins came about not only as a result of the company's pioneering work in delivering virtual or synthetic training systems to the defence arena, but also due to the fact that members of the company had participated in the UK's *Bondi* Initiative (1979 to 1983), an R&D programme designed to evaluate emerging technologies suitable for replacing humans from subsea oil and gas exploration environments. Whilst at BAe, one of today's VP personnel took part in trials undertaken in 1982 at the Fort William/Loch Linnhe diving facility in Scotland, which involved two ROVs (including an early *Scorpio* system) and the British Oceanics *LR2*, the 3-person, single-atmosphere, predecessor of the *LR5*, operated today by RUMIC as part of the UK Submarine rescue System (UKSRS).

At the time of publishing the PD Study, the NSRS concept had not been defined to the extent that it will take the form of a manned rescue vehicle (SRV), a single/limited crew remotely operated rescue vehicle (RORV) or, as is presently the case, an SRV with remotely operated vehicle (ROV) support. Consequently, VP's TNA scoping report was written to cover 3 alternative system options. These were (a) manned submersible only (SRV), (b) manned submersible with remotely operated submersible support (SRV + ROV) and remotely operated submersible with single/limited number support crew *in situ* (RORV). The VP report concluded that a good proportion of the basic engineering and support tasks associated with a future rescue submersible system can be trained in a cost effective way by exposing trainees to actual equipment in a dry (dockside/storage facility), using actual equipment. However, there were a number of critical tasks that could not be effectively trained in this manner, such as submersible dive and navigation procedures under a range of subsea and bottom conditions, DISSUB inspection and debris clearance and manipulator/special tool handling. Consequently an affordable (PC-based) virtual environment simulation facility was suggested that would (a) re-use simulation software already commissioned by the MoD/RN (eg. the seascape, weather modules and 3D naval objects used for the close-range gunnery trainer at HMS Collingwood and the virtual *Trafalgar* Class submarine constructed for FOSM), and (b) deliver the following key training elements:

- Variable sea states at launch
- Variable strength subsea currents with fixed or changing bearings
- Variable degrees of water turbidity
- Variable DISSUB bottom angles
- Pre-set DISSUB external lighting arrangements
- SRS external manipulator functions
- Water jet cleaning of silt on deck
- Emergency Life Support Stores (ELSS) "pod posting"
- Attachment of Distressed Submarine Depressurisation System (DSDS) hose
- Variable SRS subsystems reliability (thrusters, lights, etc.)
- Simulated evacuation procedures using synthetic mannequins

The final point listed above is of particular interest, given parallel efforts internationally in the use of synthetic environment training technologies for various aspects of submarine training (eg. VESUB, Submarine Qualification, "Dry" (SMQ(D)) for the British *Astute* SSNs). VP's report concluded that training policy should ensure, where possible, the integration of future development effort to ensure that both DISSUB rescuers *and* evacuees will benefit from the existence of a submarine/submarine rescue simulator.

Since this study was completed VP has conducted its own in-house effort to prove the feasibility of the company's NSRS training concept. Using open standard, license-free software, together with 3D objects archived in an ISO-standard format (including a 3D model of the *LR5* submersible supplied by RUMIC), a variety of mini-demonstrators have been developed, including visualising the evacuation path from a submarine forward escape compartment through the TUP skirt, into the *LR5* SRS interior.

VP Defence is now looking to partner with the successful prime contractor for the NSRS system and would welcome further enquiries from organisations interested in including a cost effective synthetic environment training system and/or a recognised award-winning human factors capability within their proposals. VP Defence also welcomes general enquiries for company papers and publications that describe recent successes in the application of PC-based virtual environments to defence applications.

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# NATO SUBMARINE RESCUE SYSTEM TRAINING NEEDS ANALYSIS SCOPING STUDY

**(Combined, General Release Version)**

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**Under Contract to W S Atkins Limited**

**Date of Issue: 14 February, 2002**

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## SUMMARY

The NATO Submarine Rescue System, NSRS, is a potential future MoD DISSUB (DIStressed SUBmarine) rescue asset, based on an as-yet undefined configuration of vehicle(s), manned or unmanned. The aim of this TNA Scoping Report is to catalogue as many of the key issues as possible with respect to the training requirements for NSRS (including the concept of a NATO distributed synthetic exercise system), thereby supporting the future conduct of a full Training Needs Analysis (TNA) by the RN TNA Cell or its nominated authority. A secondary aim is to provide a contribution to discussions at workshops held during the Project Definition Study programme. Ultimately, the TNA will provide a definitive statement on the training requirements for the NSRS Operational Team and will enable the most cost-effective delivery mechanisms to be specified. Preliminary high-level breakdowns of tasks and personnel are presented for 3 NSRS options:

- A Rescue Vehicle (SRV), a manned submersible characterised by at least two distinct life support areas – the pilot's chamber and the DISSUB rescue chamber, the latter accessible to DISSUB personnel via a suitable transfer under pressure (TUP) escape route.
- A Rescue Vehicle (SRV) with Remotely Operated Vehicle (ROV) support. The ROV is a tethered powered platform under the direct control of a surface-based human operator. The ROV may possess a range of sensors, from basic transponders to sonar and video systems of varying complexity.
- A Remotely Operated Rescue Vehicle (RORV), a tethered platform under the direct control of a surface-based human operator (within normal operational conditions). The RORV consists of a centralised life support chamber under the supervision of one or more rescue/medical specialists who may be capable of taking control of the vehicle in safety critical situations.

The main conclusion drawn in this early analysis is that a good proportion of the basic engineering and support tasks associated with a future DISSUB rescue submersible system can be trained in a cost effective way by exposing students/trainees to actual equipment in a dry (dockside/storage facility) or wet (limited trial dives) context. However, there are certain tasks that cannot, it is felt, be trained to a total level of adequacy in this manner, or would benefit substantially from the introduction of TBT at the early stages of training, notably:

- SRV/ROV/RORV initial flight and navigation training,
- DISSUB inspection training,
- Manipulator and/or special subsea tool (eg. ELSS, DSDS) deployment control,
- DISSUB rendezvous and mating under variable subsea conditions,
- RORV rendezvous and mating control by in-chamber operator,
- RORV emergency withdraw procedures by in-chamber operator,
- RORV collaborative control (between topside and in-chamber operators).

These tasks lend themselves extremely well to simulation or VR implementation in that they demand the real-time participation and skills execution on the part of the trainee. They also call for an ability on the part of instructors to vary the degree of difficulty in the tasks being trained, from poor external visual cues to subsea currents of varying strength, or from serious power or thruster failures to DISSUB mating angles.

There is an additional argument that suggests that, once a simulation or VR model has been developed, certain of those basic engineering and support tasks previously best performed using real equipment, might be performed more effectively by using the same computer-generated models. Adapting the computer-generated models to fulfil these additional training roles will not necessarily replace the need for hands-on access to real NSRS equipment (because of health and safety regulations), but may well reduce the number of times trainees need to monopolise that equipment. This will require further detailed analysis during the TNA.

**Acknowledgement**

The author and Virtual Presence Ltd would like to acknowledge the important contribution of Mr Roger Chapman (RUMIC Ltd) in the early stages of this study, particularly in helping clarify the current command team structure and roles of those involved in the UKSRS organisation.

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## ABBREVIATIONS

| | |
|---|---|
| 2D | Two dimensions (or two-dimensional) |
| 3D | Three dimensions (or three-dimensional) |
| AR | Augmented Reality |
| AUV | Autonomous Undersea (Unmanned) Vehicle |
| CAI | Computer-Assisted Instruction |
| CBT | Computer-Based Training |
| CRF | Coordinator Rescue Forces |
| CRWS | Close-Range Weapon(s) System(s) |
| DSRV | Deep Submergence Rescue Vehicle (US) |
| d.o.f. | Degrees of Freedom |
| DIS | Distributed Interactive Simulation |
| DISSUB | Distressed Submarine |
| DSDS | Distressed Submarine Depressurisation System |
| ELSS | Emergency Life Support Stores |
| FOSM | Flag Officer Submarines |
| HFI | Human Factors Integration |
| HSI | Human-System Interface |
| IETM | Interactive Electronic Training Manuals |
| INTO | Integrated Navigation & Tracking Organisation |
| IPT | Integrated Project Team |
| ITT | Invitation to Tender |
| LAN | Local Area Network |
| MoD | Ministry of Defence |
| MOSHIP | Mother Ship |
| NATO | North Atlantic Treaty Organisation |
| NRTA | Naval Recruitment & Training Agency |
| NSRS | NATO Submarine Rescue System |
| OSO | Offshore Supplies Office |
| OTJ | On the Job |
| p/a | Per Annum |
| PA | Power-Assisted |
| RORV | Remotely Operated Rescue Vehicle |
| ROV | Remotely Operated Vehicle |
| RVM | Rendezvous & Mating |
| RN | Royal Navy |
| RNSETT | Royal Navy School of Educational & Training Technology |
| SERP | Submarine Emergency Rescue Party |
| SME | Subject Matter Expert |
| SMO | Senior Medical Officer |
| SMQ(D) | Submarine Qualification (Dry) |
| SPAG | Submarine Parachute Assistance Group |
| SRV | Submarine Rescue Vehicle |
| TBT | Technology-Based Training |
| TD | Training Delivery |
| TMA | Training Media Analysis |
| TNA | Training Needs Analysis |
| TOA | Training Options Analysis |
| TUP | Transfer Under Pressure |
| UKSRS | United Kingdom Submarine Rescue System |
| US | United States |
| VE | Virtual Environment |
| VR | Virtual Reality |
| VRML | Virtual Reality Modelling (sometimes "Mark-Up") Language |
| WAN | Wide Area Network |

**RELEVANT DEFINITIONS**

**Augmented Reality (AR).** Augmented Reality is a special form of Virtual Reality (see below) and makes use of special head-mounted displays, or modified optical instruments to superimpose meaningful virtual images onto the user's view of the real world.

**Computer-Based Training (CBT).** Computer-Based Training is a general term used to describe the delivery of training media to students using a computer (in stand-alone mode or on-line, in the case of Internet delivery). For the purposes of this study, CBT can take on many forms, from simple text-based content to fully interactive 3D graphics. Note that this differs slightly from the RNSETT definitions of CBT, as opposed to Computer-Assisted Instruction (CAI). Note that RNSETT makes a distinction based on computer-led tuition (CBT) as opposed to instructor-led tuition (CAI).

**Multimedia.** Multimedia is another general term applied here to cover the use of different forms of media to deliver meaningful content from within a CBT/CAI package. A multimedia interface might consist of text, images, graphics, digital video, sound, even touch, displayed as individual items or in some acceptable combination. For the purpose of this Study, Interactive Electronic Training Manuals (IETMs) fall under the category of multimedia, in that they can be embedded within a CBT/CAI package and displayed in a format at run time that is ergonomically acceptable for interaction.

**Situational Awareness**. In broad terms Situational Awareness is a term used to describe a human operator's perception of reality. Based on the interpretation of available information the human will, at any given time, hold a set of beliefs about what is happening in the world around him and what action he should take. If a discrepancy exists between his beliefs and the reality of the situation (as might occur in conditions of high mental or physical workload, or as a result of the poor display of information), situational awareness becomes degraded, possibly leading to a chain of errors.

**Teleoperation.** Teleoperation is the process by which a human operator controls the behaviour of a remotely operated system, such as an ROV. The operator may be equipped with a variety of human interface devices (a) to aid his perception of the remote environment in which the system exists, (b) to navigate through that environment and (c) to manipulate objects in that environment. Safe and efficient teleoperation may be supported by automation, as is the case in station keeping and auto-piloting.

**Virtual Reality (VR) / Virtual Environments (VE).** Virtual Reality refers to a suite of technologies supporting intuitive, real-time interaction with three-dimensional computerised databases. "Immersive" VR, whereby the user dons a head-mounted display and interacts with a 3D world using special hand controllers or gloves, is but one variation of VR interface technology. More popular are interfaces based on standard desktop screens or large data/video projection displays (in 2D or 3D) used in conjunction with ergonomically acceptable desktop controls. In the context of the present report, there are 3 VR interaction styles or techniques under consideration:

**"Constrained Path VR"** is a term applied to a human-system interaction style whereby limited or fixed motion paths or "corridors" have been defined within the virtual environments. For example, users may be free to move forward or backward through the 3D scene and, at any point, stop and "look around", using whatever human interface technology has been considered appropriate for such actions.

**"Panoramic VR"** is a special case of "Constrained Path VR" in that digital photographs are used to create a $360^{o}$ panorama or "vista" of a particular environment. The user can explore the environment by "jumping" between pre-defined points or "nodes" in the environment. Each node is associated with a high-quality panorama, giving the user the opportunity to look around, and up and down, using simple mouse control. Areas within panoramas can be endowed with interactive "hot spots", linked to such task-relevant features as databases, simplified 3D objects, other panoramas, even IETMs.

**"Free-Play VR"**, in contrast to "Constrained Path VR", is a term applied to a human-system interaction style whereby the user is, in the main, free to explore and interact with whatever component of the virtual environment he or she is interested in. In an extreme (and often unsatisfactory) case this will allow the user full 6-d.o.f. motion in the virtual world (translation in *x*, *y* and *z*, plus *roll*, *pitch* and *yaw*). As the computing system has to record the movements of the user's virtual "body" constantly during Free-Play VR (and, thus, calculate intentional and unintentional collisions with features of the virtual environment), the computational overhead associated with Free-Play VR is often greater than that associated with Constrained Path VR.

**Workload**. Workload is a general term used to define the effect of a task on the physical and mental qualities and well being of the human operator. The elements of a task that have a bearing on the workload of an operator can be defined with reasonable accuracy during human factors analyses. Such analyses will be able to pinpoint "primary" task characteristics (those elements that directly affect the human's performance) and "secondary" characteristics (ie. elements that may occur infrequently, but distract the operator's attention from his primary mission). It is important to realise that performance degradation (eg. lower reaction times, decreased vigilance, erroneous decision-making), increased error rates, fatigue can result when a human is overloaded (ie. during periods of high mental and/or physical activity) or *under*-loaded (ie. during long periods of inactivity).

## 1. INTRODUCTION & BACKGROUND

The NATO Submarine Rescue System, NSRS, is a potential future MoD DISSUB (DIStressed SUBmarine) rescue asset, based on an as-yet undefined configuration of vehicle(s), existing or conceptual, manned or unmanned. This Scoping Report has been written as part of the NSRS Project Definition Study and attempts to summarise the key issues with respect to possible future training requirements for NSRS, thereby supporting the future conduct of a full Training Needs Analysis (TNA) by the RN TNA Cell or its nominated authority.

It is MoD policy to maintain a UK-based rapid reaction submarine rescue system to rescue live personnel from a DISSUB. At the time of writing, the principal UKSRS (UK Submarine Rescue System) assets are based on the MoD-owned and civilian-operated manned submersible *LR5(X)* and a *Scorpio* ROV. The latter is typically deployed at the outset of a DISSUB incident for the purposes of inspection, debris clearance, ELSS (Emergency Life Support Stores) delivery, DSDS (Distressed Submarine Depressurisation System) connection, and so on.

NATO policy will most likely be based on an international rapid reaction NSRS capability, geographically based to ensure minimum deployment times for NATO DISSUBs and *best endeavours* deployment times in the case of a non-NATO DISSUB scenario.

> **"Any country in the world that has a submarine problem can ask NATO for help…. Everything NATO has can be called upon to make up a 'menu' of assets available"**. Source: Captain Hanson, Chief of Staff for Submarines East Atlantic & Allied Forces North, "Surviving SUBSUNK"; Article from *Navy International*:
> http://www.janes.com/defence/naval_forces/news/jni/jni010219_1_n.shtml

In the case of the UKSRS, the civilian operators of the *LR5(X)* are, by virtue of their history in the subsea oil and gas industry, highly experienced, "hands-on" submersible personnel. However, this has meant that training policies for commercial operations and UKSRS have evolved through practice and experience in the field, as noted in the TNA documents associated with the UK system.

Training – albeit limited (due to high experience levels and low turnover of the personnel involved) – consists of dockside exercises, infrequent training dives and trials with actual NATO submarines. According to the UKSRS TNA Scoping Report (Anon., 2000), *LR5(X)* pilots are trained to the standard expected by Lloyds Register Regulations. However, Lloyds is not proactive in the development of manned submersible training and the unique situation found with the UKSRS cannot be guaranteed in the case of future NSRS operational teams.

*Scorpio* ROV operators are exposed to initial and "refresher" training as part of their additional duties (outside UKSRS operations), such as weapons recovery. Taking a more international perspective, as will be required with NSRS, it should be noted that there is a reasonable international pool of freelance ROV operators, unlike the case for manned submersible interventions. However, quality and security issues associated with hiring international freelance ROV personnel mean that their participation in a NATO system is highly unlikely. Nevertheless, these issues must be borne in mind during the TNA.

Although the UKSRS benefits today from a highly experienced crew, this cannot be guaranteed at the outset in the case of NSRS. Hence the need for serious consideration to be allocated to defining training needs and potential delivery mechanisms and technologies.

## 2. PREVIOUS ASSOCIATED STUDIES

Few, if any studies of the training requirements of manned and remotely operated vehicles in a DISSUB configuration have been undertaken and published. The unique nature of the DISSUB operation, the inability to predict the occurrence of a major incident and the limited opportunities to take part in NATO trials have all contributed to the absence of relevant material. In contrast, there have been a number of studies published in oil and gas-related conference proceedings (such as the Society for Underwater Technology) since the late 1970s relating to specific human factors aspects of submersible systems (eg. camera control, the use of stereoscopic video, force feedback, etc.).

In the UK, the last time a comprehensive study of subsea intervention was conducted was between 1979 and 1983, under the *Bondi* Initiative, named after the then Chief Scientist of the Department of Energy (D.En, 1983). This Initiative (in which the author took part) included a period of trials undertaken in 1982 at the Fort William/Loch Linnhe diving facility in Scotland and involved two ROVs (including an early *Scorpio* system) and the British Oceanics *LR2*, a 3-man, 1-Atmosphere, non-lock-out predecessor of the *LR5*. Trial results were published (as were the results of other parts of the Initiative) and may still be available from the publishers CIRIA (http://www.ciria.org.uk/).

It was between the mid-1970s and 80s that most of the best subsea publications relating to manned and ROV operation were published (eg. Busby, 1976; Sisman, 1982). These have not been updated since that time, although their contents are still considered by many to be highly relevant, since today's subsea intervention technology – with the exception of specific items of payload and instrumentation – does not differ significantly from that of the 1980s. A more recent publication of relevance to submersible systems design is that by Allmendinger (1990).

## 3. CURRENT SYSTEM ARCHITECTURE

A simplified representation of the current UKSRS architecture, summarising the communications channels and roles of the team members and their assets, is presented in Figures 1 and 2. These figures are based on previous experience on the part of the author, coupled with valuable input from RUMIC Ltd., the current operators of *LR5(X)*.

The UKSRS, by virtue of its history, is a blend of personnel for the Royal Navy and commercial sectors. This may not be the case for NSRS, where naval personnel may well have overall responsibility for the system. Nevertheless it is believed that

Figures 1 and 2 contain the main system elements which would, more or less, be integrated to form the NSRS architecture.

It should be stressed that any similar architecture developed for NSRS should ensure that the overall "system" includes those components of relevance to the surviving personnel onboard the DISSUB as well. In other words any TNA should focus not only on the personnel and equipment associated with the rescuing system, but should also consider the personnel *being rescued* and any equipment or tasks of relevance to them.

## 4. AIM

As part of the NSRS Project Definition Study, the aim of this TNA Scoping Report is to catalogue as many of the key issues as possible with respect to the training requirements for the future NATO Submarine Rescue System (NSRS), including a high-level investigation into the concept of a Distributed Synthetic Environment Exercise Trainer (combining the rescue vehicle training simulator with a command and control / communications functionality for conducting training solutions and synthetic exercises across multi-sites and countries). A secondary aim is to provide a contribution for discussion at a *Human Factors and Training Workshop,* to be held during the Project Definition Study programme, at which, it is hoped, further refinements to the issues raised herein will be forthcoming.

The structure of this report loosely follows that provided by RNSETT for the UKSRS. However, due to early uncertainties associated with the overall system concept for NSRS, the report has also addressed some of the key TNA issues in slightly more detail and associated some of the more innovative TBT solutions with project cost estimates. These, too, will be subject to refinement following the Human Factors & Training Workshop.

Ultimately, the TNA will provide a definitive statement on the training requirements for the NSRS Operational Team and will enable the most cost-effective delivery mechanisms to be specified, from the perspective of initial outlay – development and material – and minimised through-life costs.

## 5. TARGET AUDIENCE

This particular report has been written to fulfil some of the informational needs of numerous participants in the NSRS Project Definition Study, including representatives from the NSRS IPT, RNSETT, Project Management, Human Factors and Financial Planning (system through-life) Specialists. It has also been written with the aim of stimulating dialogue with the current UKSRS operational team. It is recommended that this report, together with the subsequent TNA is also distributed to those personnel within FOSM and HMS Raleigh who are currently involved in SMQ(D) programmes associated with *Astute*, *Trafalgar* and *Vanguard* submarine classes. This comment applies equally to other countries participating in the NSRS programme.

## 6. CONSTRAINTS & ASSUMPTIONS

At the time of writing, the NSRS concept has not been defined to the extent that it will take the form of a manned rescue vehicle (SRV), a single/limited crew remotely operated rescue vehicle (RORV) or, as is presently the case, an SRV with remotely operated vehicle (ROV) support. Consequently, this scoping report has been written to cover analyses for 3 alternative system options. These are based on combinations of Figures 1 and 2, illustrating the main personnel and equipment hierarchies currently in place with the UKSRS (*LR5(X)*- and *Scorpio*-based) system:

- Manned submersible only (SRV)
- Manned Submersible with Remotely Operated Submersible Support (SRV + ROV)
- Remotely Operated Submersible Single/Limited Number Crew (RORV)

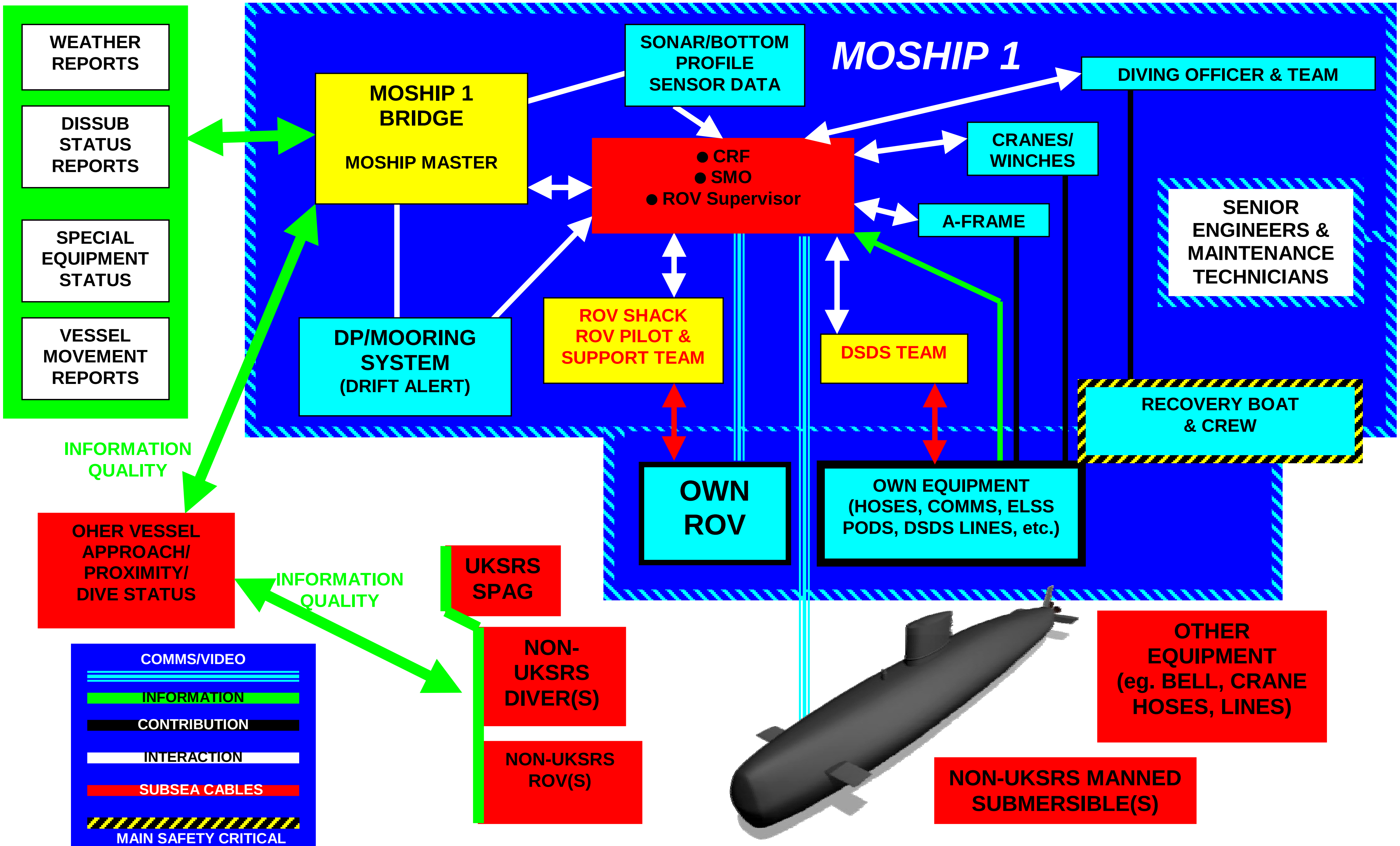


**FIGURE 1: Simplified UKSRS Personnel and Equipment Hierarchy (MOSHIP 1 – Initial ROV Deployment)**

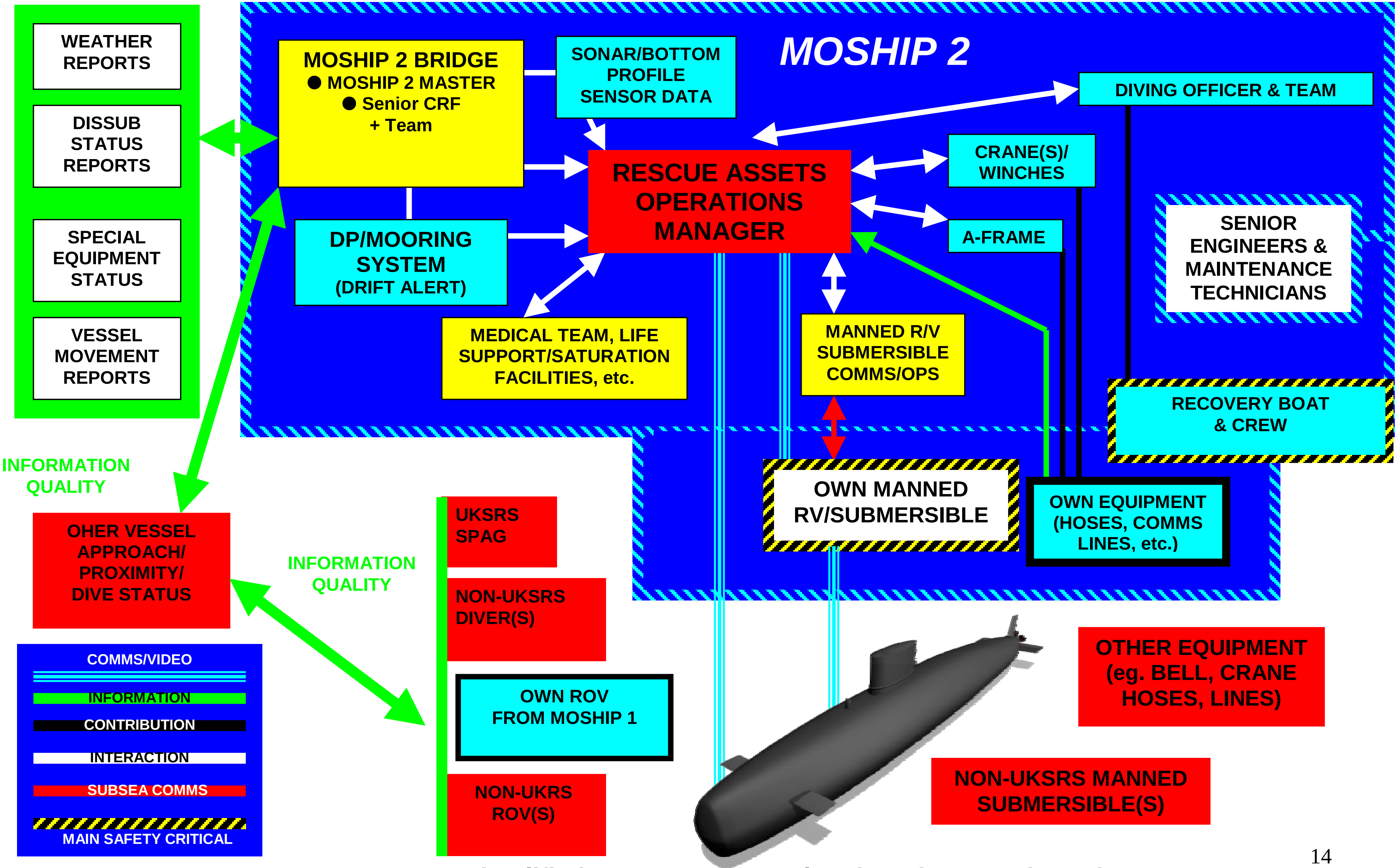




**FIGURE 2: Simplified UKSRS Personnel and Equipment Hierarchy (MOSHIP 2 – Manned Submersible) Deployment)**

## 7. NSRS TRAINING POLICY

It is also assumed that, due to the fact the NSRS does not yet exist, and bearing in mind that the final system may possess certain innovative technological features, every attempt will be made to evaluate human factors and training recommendations during the actual system design phases. Where 3D computer-generated imagery is used during these phases (eg. CAD), it is highly recommended that short ergonomic evaluation studies be conducted using appropriate VR or human mannequin design tools.

It is also recommended, given parallel efforts in the use of advanced training technologies such as VR for various aspects of submarine training in the UK (SMQ(D) for *Trafalgar*/*Astute* SSN and *Vanguard* SSBN) that training policy should ensure, where possible, the integration of TBT for **both DISSUB rescuers *and* evacuees**. Thus, future training systems developed for submarines should seriously consider the added value of integrating developments with those under way for NSRS training and *vice versa*.

## 8. PERSONNEL

The TNA will address the training for the individual, sub-team and team level. The following list is not definitive and may be expanded during the course of the PDS and at appropriate times thereafter. For a diagrammatic representation of the position of these personnel within the current UKSRS architecture, refer to Figures 1 and 2, bearing in mind that NSRS may well result in an integrated architecture. The TNA should attempt to define the anticipated baseline skill and qualification levels for these personnel, combining human factors knowledge from current UKSRS and commercial subsea operations with the results of the NSRS Task Analysis.

### 8.1. NSRS Subsea System.

(1) Pilots and co-pilot(s)/subsea support team (where, in the case of an RORV solution, for example, the co-pilot(s) or other support team members may also fulfil the rôle of manipulator or special tooling operators – DSDS or ELSS equipment, water jet, etc).

(2) NSRS Chamber Operator.
(3) Submariners requiring introduction to pre-TUP procedures and a basic orientation experience simulating TUP from DISSUB into NSRS.

### 8.2. Surface Command Team.

(1) Senior Coordinator Rescue Forces (CRF).
(2) Submarine Emergency Rescue Party (SERP) Representative
(3) CRF Team, including Junior CRF, Rescue Assets Operations Manager(s), communications support personnel.
(4) Senior Medical Officer.
(5) MOSHIP Master (liaising with SERP) and key MOSHIP personnel (eg. DP operators, mooring supervisors, etc.).

(6) Integrated Navigation & Tracking Organisation (INTO) Operator (liaising with SERP).

### 8.3. Surface Medical Team. (Reporting to Senior RN Medical Officer)

(1) Medics (surface chamber, internal/external).
(2) Medical and Radiation Advisers.
(3) Surface Chamber Operators.

### 8.4. Deck Team & NSRS Technicians

(1) Diving Officer.
(2) Safety/Recovery Boat Crew/Surface Divers.
(3) A-Frame Operators and Deck Stabilisation Team.
(4) Senior NSRS Engineer.
(5) NSRS Technical Preparation, Maintenance & Repair Team.

## 9. EQUIPMENT

The specific equipment deployed in support of a DISSUB mission will depend on the final nature of the submarine rescue system. Assuming 3 possible system options (SRV, SRV+ROV, RORV), the following (non-exhaustive) tables of equipment and associated high-level task descriptions will be addressed by the TNA.

### 9.1. Assuming Rescue Vehicle (SRV) Only

For the purposes of this scoping report, the SRV is a manned, onboard-powered rescue submersible characterised by two or more distinct life support areas – the pilot's chamber (with/without co-pilot/systems engineer), typically maintained at a pressure of 1 Atmosphere, and the variable pressure DISSUB rescue chamber, under the supervision of one or more rescue/medical specialists. A DISSUB mating system, permitting TUP, is also a key feature of the SRV. Current examples include: the MoD/RUMIC *LR5(X)*, the DSRVs *Mystic* and *Avalon*.

**Table 1 - Equipment and High-Level Task Summary for SRV**

| EQUIPMENT | HIGH-LEVEL TASK(S) |
|---|---|
| **Fixed or Portable A-Frame Assembly** | **Assembly/Disassembly (in the case of a portable A-Frame), Launch/Recovery Operation** |
| **SRV System Preparation/Maintenance** | **Routine internal and external maintenance, safety critical item maintenance and test (eg. life support, chamber functions, hatch integrity, TUP skirt and mating module, SRV transponders/beacons), sensor fit (sonar/cameras) test/fault diagnosis/repair, manipulator test/repair, viewport/dome (if any) integrity test** |

| | |
|---|---|
| **SRV Pilot/Co-Pilot Workstation(s)** | **Pre- and post-dive checks, own life support, launch/recovery, MOSHIP location awareness, sea state awareness, dive/surface procedures, flight, navigation, MOSHIP and DISSUB communication, station keeping, camera operation, manipulator deployment, emergency procedures chamber and topside communications** |
| **SRV Chamber (NSRS bias)** | **Pressurisation and equalisation activities, DISSUB hatch testing and opening (manual, or with special PA equipment), evacuation supervision and discipline, immediate medical intervention** |
| **SRV Chamber (DISSUB Evacuees bias)** | **Evacuee TUP from submarine into SRV chamber – initial experience and orientation** |
| **ALL (Including Launch/Recovery Dive/Boat Team)** | **Health & Safety – including A-Frame loaded/unloaded operations, on-deck SRV thrusters and manipulator testing, diver (in-water) SRV thruster awareness, cable/rope attachment and handling procedures** |

## 9.2. Assuming Rescue Vehicle with Remotely Operated Vehicle (ROV) Support

For the purposes of this scoping report, an ROV is a tethered platform, powered primarily from a combination of surface-based and onboard energy resources and under the direct control of a human operator ("teleoperation"). The ROV may possess a range of sensors, from basic transponders to sonar and video systems of varying complexity. The ROV may also be equipped with effectors of varying complexity, from basic grab mechanisms to multiple-d.o.f. manipulators. One or more ROVs and associated support vessel may be the first subsea intervention system to arrive on the scene of a DISSUB rescue mission and may fulfil a number of roles, such as external hull inspection, delivery of ELSS pods, connection of DSDS services and the surveillance of later SRV/RORV dives and mating procedures. Some ROVs may be equipped with "intelligent" functions, including station-keeping, simple path following, and so on. However, for the purposes of this report, the truly autonomous unmanned undersea vehicle (AUV), by virtue of the current state of international developments, is not included within the ROV category and human teleoperation is still considered to be the norm. Current examples include: *Scorpio*, *Super Scorpio*, *Hyball*.

**Table 2 - Equipment and High-Level Task Summary for SRV + ROV**

List as for SRV (Table 1), plus:

| EQUIPMENT | HIGH-LEVEL TASK(S) |
|---|---|
| **SRV Pilot/Co-Pilot Workstation(s)** | **Dynamic situational awareness associated with ROV in close proximity** |
| **Winch & Umbilical Handling Systems (including garage if present)** | **Operation, communications with ROV and other relevant personnel, maintenance (including cable repair)** |

| | |
|---|---|
| **ROV** | **Routine external maintenance, transponders/beacons, sensor fit (sonar/cameras) test/fault diagnosis/repair, manipulator test/repair, seal integrity tests** |
| **ROV Pilot Workstation(s)** | **Pre- and post-dive checks, launch/recovery, deck communications, MOSHIP location awareness, sea state awareness, dive/surface procedures, flight, navigation, umbilical awareness and checks, station keeping, operation in proximity of DISSUB and/or SRV, inspection procedures (including radiation monitoring), manipulator deployment, other tool deployment (eg. water jet), emergency procedures (recovery/jettison)** |
| **DSDS and ELSS "Pods"** | **Special manipulator handling procedures (probes, clump weights, hoses, pod attachments, etc.)** |
| **ALL** | **Health & Safety (especially relating to launch and recovery and MOSHIP deck testing of manipulators and thrusters)** |

### 9.3. Assuming Remotely Operated Rescue Vehicle (RORV)

For the purposes of this scoping report, an RORV is a tethered platform, powered from a combination of surface-based and onboard energy resources and, within normal operational conditions, under the direct teleoperation control of a surface-based human operator. The RORV consists of a centralised life support chamber under the supervision of one or more rescue/medical specialists who may be capable of taking control of the vehicle in safety critical situations. A DISSUB mating system, permitting TUP, is also a key feature of the RORV. The RORV may possess a range of sensors, from basic transponders to sonar and video systems of varying complexity. The RORV may also be equipped with effectors of varying complexity, from basic grab mechanisms to multiple-d.o.f. manipulators. Current example is the Australian *Remora*.

**Table 3 - Equipment and High-Level Task Summary for RORV**

| EQUIPMENT | HIGH-LEVEL TASK(S) |
|---|---|
| **A-Frame/Crane & Umbilical Handling Systems** | **Operation, communications with RORV and other relevant personnel, maintenance (including cable repair)** |
| **RORV** | **Routine internal and external maintenance, safety critical item maintenance and test (eg. life support, chamber functions, hatch integrity, TUP skirt and mating module, RORV transponders/beacons), sensor fit (sonar/cameras) test/fault diagnosis/repair, special equipment operation (eg. special tooling for DISSUB hatch opening/sealing)** |

| | |
|---|---|
| **RORV Chamber Workstation(s)** | **Procedures relating to special and safety critical functions controllable from within the RORV chamber (eg. manipulator deployment, manoeuvering – own control or special collaborative control processes[1] with topside pilots, emergency withdrawal and surfacing routine, etc.), pressurisation and equalisation activities, DISSUB hatch testing and opening (manual, or with special PA equipment), evacuation supervision and discipline, immediate medical intervention** |
| **RORV Chamber (DISSUB Evacuees bias)** | **Evacuee TUP from submarine into RORV chamber – initial experience and orientation** |
| **RORV Topside Pilot Workstation(s)** | **Pre- and post-dive checks, launch/recovery, deck communications, MOSHIP location awareness, sea state awareness, dive/surface procedures, flight, navigation, umbilical awareness and checks, station keeping, operation in proximity of (and RVM with) DISSUB, inspection procedures (including radiation monitoring), manipulator deployment, other tool deployment, emergency procedures (recovery/jettison), special collaborative control processes with chamber specialist** |
| **ELSS, DSDS and related systems (deployed from internal and/or external RORV sites)** | **Special manual and manipulator handling procedures (probes, clump weights, hoses, etc.)** |
| **ALL** | **Health & Safety (as for SRV and RORV)** |

**Notes:**

**1.** An example illustrating the possibility of "collaborative" control between chamber and topside operators of an RORV would be in the case of autopilot or station-keeping subsystems failure. Here it is conceivable that the topside RORV pilot might take responsibility for maintaining the orientation and stability of the vehicle, whilst the chamber operator carries out fine approach and mating manoeuvres. Another example might be a similar scenario to that described above as far as the topside operator is concerned, but where the chamber operator has to deploy the RORV manipulator or some other specialised tool system. In any event, any TBT delivered to address this feature will have to be based on a sound and early allocation of function process, carried out as part of the HFI plan.

## 10. TRAINING MEDIA

RNSETT's Training Guide No. 5, *Training Media* (October, 2000), was developed to support the decision making and implementation of Technology-Based Training (TBT) to meet the evolving requirements of RN personnel. The Training Guide delivers many useful recommendations and selection/implementation guidelines with regard to the use of various forms of media and presents a useful taxonomy of TBT methods and media.

### 10.1. Cautionary Comments

Caution is recommended in the use of the Training Media Guide, however. Experience suggests that taxonomies such as that mentioned above, plus associated comments relating to the advantages and disadvantages of different methods and media, become out-dated very quickly. One of the underlying reasons for this is that the scope of the taxonomy is biased towards historical or contemporary methods and media. References to innovative training media, such as Reconfigurable Skills Trainers, Simulation, Virtual Reality and Augmented Reality sometimes contain misleading or emotive comments that do not stand up to present-day scrutiny. For example, the guide makes reference to a proprietary desktop VR product that, since 1999, has been withdrawn from the market and is no longer supported by the company concerned. Also, the phrase "virtual sickness" is presented in one of the Guide's summary tables without clarification. The immaturity and major development requirements of "Augmented Reality" (AR) are not declared (AR is not currently (2001) a realistic option for RN training applications). A recent example where a successful contractor challenged an ITT demonstrated that only by using **immersive** VR technology – not considered in the ITT (and previously, one might assume, the TNA) – could the desired location and resolution of targets be presented consistently to multiple close-range weapons (CRWS) trainees over a specified in-cover (azimuth/elevation) volume.

The point being made here is that it is essential that any TNA involving innovative TBT makes use of support of external (and where possible independent) **industrial** SMEs (academics should **only** be consulted where it can be demonstrated that they have strong practical experience of applying TBT). Furthermore, TNA Cell personnel should be proactive in organising briefings where industrial specialists are invited to present the latest evidence (**and not sales rhetoric**) relevant to their field (**and not products**). This is particularly important in the case of NSRS, where innovation and advanced technologies are likely to feature strongly in some – but not all – of the human interface requirements, from design through to training.

### 10.2. Support for Innovative TBT (see also Stone, 2001a)

"Computer-controlled" technology, as applied to training generally, has been in existence for over 35 years. From programmed text delivery to flight simulation, CBT and CAI in one form or another have gradually become the norm, rather than the exception.

Yet the spread of adoption of CBT/CAI techniques, and especially those based on innovative interactive computer-generated imagery technologies (such as Virtual

Reality), has not been straightforward. Each time computer technology has been used to introduce a new level of functionality into a training paradigm, be it based on classroom delivery, or reliant on access to full-scale mock-ups, even real operational equipment or plant, it seems that the same sceptical issues are raised. Will CBT/CAI/VR improve the effectiveness with which knowledge is delivered or assimilated? Will it reduce reliance on scarce operational systems or costly hardware-based training materiel? Does it offer anything over and above conventional training methods? Can previous investments in technology be protected, or must new, non-commercial-off-the-shelf (COTS) resources be procured? Will students be more motivated and, thus retain more? Will students and trainers actually use the technology? Will there be a positive transfer of training (or knowledge) from the computerised setting to the real operational environment?

Only quite recently have powerful toolkits based on interactive 3D audio-visual images and VR have become available. Furthermore, the evolution of low-cost (ie. sub-£200), high-performance graphics cards for industry standard PCs has introduced VR to many more potential users than would have been the case with so-called graphics supercomputers costing many tens of thousands of dollars. In parallel with this "technology push" there has been a "market pull", with potential CBT users demanding lower technology costs, more efficient utilisation of students and trainers and hard evidence of the cost benefits and manpower performance improvements the technology offers. To the developers of VR technologies, and to those working closely with industrial pioneers to produce real applications, the value of VR has been unquestionable. Gradually, more and more valid and reliable (ie. less anecdotal) results have appeared in reputable journals, based on experimental trials from the growing installed base of experimental simulator prototypes (the shift of commercial applications from the expensive graphics "supercomputers" to more affordable Windows-based machines has contributed enormously here). For example, trainee performance improvements of up to 40% have been reported in the aerospace maintenance arena, accompanied by over 25% reductions in course lengths (ie. from 13 to 8 weeks) and the total elimination of downtime previously inflicted on students as a result of limited access to physical hardware (eg. Stone, 2001b). Navies are now adopting VR for the purposes of weapons training, future carrier ergonomics studies and submarine qualification, even training for individual equipment fits. In 2002, the RAF Defence Helicopter Flying School at RAF Shawbury and Valley will be using VR, hosted on standard, off-the-shelf PCs, for voice marshalling training.

## 11. NSRS TRAINING DELIVERY OPTIONS MATRIX

The following table (Table 4) presents a first-level scoring of the appropriateness of conventional and innovative technology-based training (TBT) delivery techniques as they might apply to the personnel/equipment/task breakdowns given in Tables 1 to 3. The scoring has been arrived at primarily through the experience of the author and will need refining later in training media analyses (TMA) and training options analyses (TOA).

Briefly, the main training delivery options are as follows (a review of most of these techniques can be found in RNSETT's Training Guide No. 5, *Training Media* (October, 2000), although the cautionary comments raised earlier with regard to some of the contents of this document apply):

- **On-the-Job Training:** trainees learn whilst on operational missions, alongside subject matter experts (who are on operational DISSUB duty). This can **only** be recommended when a trainee's observation of deck activities, launch and recovery does not conflict with mission resources and progress. It is assumed that a trainee's participation in dive, RVM and evacuation processes is forbidden.
- **Classroom Conventional Delivery:** subject matter expert delivery of lectures using 35mm slides, overhead projection, PowerPoint, black/whiteboard, etc.
- **Dry Access (with SME) to Actual Equipment:** trainees gain limited hands-on experience and instruction using actual physical equipment or systems at the dockside or submersible's home base.
- **Wet Access (with SME) to Actual Equipment:** trainees gain limited hands-on experience and instruction using actual physical equipment or systems during trials or during at-sea system tests/refit/shake-down. This does NOT include on-the-job training.
- **Video:** training procedures are delivered in a non-interactive fashion using conventional video techniques, with or without a subject matter expert.
- **Basic CBT:** simple procedural instruction (eg. using PowerPoint or HTML), essentially reformatting text and some pictures for computer-mediated presentation. May include exercises/multiple-choice questions
- **Multi-Media CBT (2D):** procedural instruction using dedicated preparation packages (eg. Macromedia) capable of hosting text, simple graphics and images, digital videos and possibly panoramic VR. Also supports some interaction with 2D graphical contents.
- **Multi-Media CBT + 3D Animation:** As for Multi-Media CBT (2D), but supporting the use of 3D animation with limited real-time interaction (eg: VRML objects via Web Browsers such as Cosmo, Cortona, GeoVRML, Blaxxun, etc.). This category includes the use of human mannequin/computerised ergonomics packages.
- For definitions associated with various forms of **Virtual Reality**, refer to the *Relevant Definitions* section of this document.

## Table 4 - Conventional & Innovative TBT Delivery for NSRS Variants (SRV, SRV+ROV, RORV)

Key:

**0** No perceived human factors, technological and financial (or legal, in the case of Health & Safety) benefits in adopting this training delivery technique.

**1** Training delivery technique could be used but similar or better results can be achieved using other conventional (and possibly less costly or more practical/"hands-on") techniques.

**2** Should not be discounted without further investigation. May be effective (eg. reduce the need for access to real equipment) if combined with other delivery technique.

**3** Significant human factors and technological benefits, plus value for money and high confidence in content uptake and skills transfer in adopting this training delivery technique.

| | CONVENTIONAL "TBT" | | | | | | | INNOVATIVE TBT | | |
|---|---|---|---|---|---|---|---|---|---|---|
| TD OPTIONS ▼ PERSONNEL/ EQUIPMENT/TASK | OTJ | CLASSROOM CONVENTIONAL DELIVERY (SME "CHALK & TALK") | DRY ACCESS (WITH SME) TO ACTUAL EQUIPMENT | WET ACCESS (WITH SME) TO ACTUAL EQUIPMENT | VIDEO | BASIC CBT | MULTI-MEDIA CBT (2D) | MULTI-MEDIA CBT + 3D ANIMATION | "CONSTRAINED PATH" VR (P = PANORAMIC VR) | "FREE-PLAY" VR |
| **Rescue Vehicle ONLY** | | | | | | | | | | |
| Fixed or Portable A-Frame Team | 1 | 1 | 3 | 3 | 1 | 0 | 0 | 1 | 0 | 1 |
| Surface Support Team Health & Safety | 0 | 1 | 3 | 3 | 1 | 1 | 1 | 1 | 0 | 2 |
| SRV System Preparation/ Maintenance | 1 | 1 | 3 | 3 | 1 | 1 | 1 | 1 | 0 | 2 |
| SRV Pilot/Co-Pilot System Basic SRV Education | 0 | 1 | 2 | 3 | 1 | 0 | 1 | 0 | 2 | 2 |
| SRV Pilot/Co-Pilot System Preparation & Checks | 0 | 1 | 2 | 3 | 1 | 0 | 1 | 0 | 1 | 2 |
| Initial SRV Pilot/Co-Pilot Submersible Control & Navigation | 0 | 0 | 2 | 3 | 0 | 0 | 0 | 0 | 0 | 3 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| SRV Pilot/Co-Pilot RVM with DISSUB[1] | 0 | 0 | 0 | 2 | 1 | 0 | 0 | 0 | 0 | 3 |
| RORV Topside Health & Safety | 1 | 1 | 3 | 3 | 1 | 1 | 1 | 1 | 0 | 2 |
| SRV Chamber Basic Education | 0 | 1 | 2 | 3 | 0 | 1 | 2 | 2 | 2(P) | 2 |
| SRV Chamber System Preparation, Pre-Dive Checks & Mission Operation | 0 | 1 | 1 | 3 | 1 | 1 | 1 | 0 | 0 | 1 |
| SRV Chamber DISSUB Mission | 0 | 0 | 0 | 3 | 1 | 0 | 0 | 0 | 0 | 2 |
| SRV Chamber DISSUB Evacuees Bias | 0 | 0 | 0 | 3 | 0 | 0 | 0 | 2 | 0 | 2 |
| Subsea Team Health & Safety | 1 | 1 | 3 | 3 | 2 | 1 | 1 | 1 | 0 | 2 |
| **Rescue Vehicle + Remotely Operated Vehicle. As for Rescue Vehicle plus:** | | | | | | | | | | |
| SRV Pilot/Co-Pilot Workstation(s) – ROV Proximity Awareness | 0 | 0 | 0 | 3 | 0 | 0 | 0 | 1 | 0 | 3 |
| Winch/Umbilical/Garage Handling Systems | 1 | 0 | 2 | 3 | 1 | 0 | 0 | 1 | 0 | 1 |
| ROV Preparation/ Maintenance | 1 | 1 | 2 | 3 | 1 | 1 | 1 | 0 | 0 | 1 |
| ROV Piloting, Navigation & DISSUB Inspection[1] | 0 | 0 | 0 | 3 | 1 | 0 | 0 | 0 | 0 | 3 |
| ROV Manipulator Control | 0 | 0 | 2 | 3 | 1 | 0 | 0 | 1 | 0 | 3 |
| ROV Team Health & Safety | 1 | 1 | 2 | 3 | 1 | 0 | 0 | 1 | 0 | 2 |
| **Remotely Operated Rescue Vehicle** | | | | | | | | | | |
| Fixed or Portable A-Frame Team | 1 | 1 | 3 | 3 | 1 | 0 | 0 | 1 | 0 | 0 |
| Surface Support Team Health & Safety | 1 | 1 | 3 | 3 | 1 | 1 | 1 | 1 | 0 | 1 |
| RORV System Preparation/Maintenance | 1 | 1 | 2 | 3 | 1 | 1 | 1 | 1 | 0 | 2 |
| RORV Pilot/Co-Pilot (Topside) System Basic RORV Education | 0 | 1 | 2 | 3 | 1 | 0 | 1 | 0 | 0 | 2 |
| RORV Pilot/Co-Pilot System Preparation & Checks | 0 | 1 | 2 | 3 | 1 | 0 | 1 | 0 | 1 | 2 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Initial RORV Pilot/Co-Pilot Submersible Control & Navigation | 0 | 0 | 1 | 3 | 0 | 0 | 0 | 0 | 1 | 3 |
| RORV Pilot/Co-Pilot RVM with DISSUB[1] | 0 | 0 | 0 | 2 | 1 | 0 | 0 | 1 | 0 | 3 |
| RORV Topside Health & Safety | 1 | 1 | 3 | 3 | 1 | 1 | 1 | 1 | 0 | 2 |
| RORV Chamber Basic Education | 0 | 1 | 2 | 3 | 0 | 1 | 2 | 2 | 2(P) | 2 |
| RORV Chamber System Preparation, Pre-Dive Checks & Mission Operation | 0 | 1 | 0 | 3 | 1 | 0 | 0 | 0 | 2 | 2 |
| RORV Chamber DISSUB Evacuees Bias | 0 | 0 | 0 | 3 | 0 | 0 | 0 | 2 | 0 | 2 |
| RORV In-Chamber Control of DISSUB RVM Mission[1] | 0 | 0 | 0 | 3 | 0 | 0 | 0 | 1 | 0 | 3 |
| RORV In-Chamber Control of Emergency Withdrawal | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 3 |
| RORV Topside-Chamber Collaborative Control/ Control Transfer | 0 | 0 | 0 | 3 | 0 | 0 | 0 | 0 | 0 | 3 |
| Chamber/Subsea Health & Safety | 1 | 1 | 3 | 3 | 2 | 1 | 1 | 1 | 0 | 2 |

**Notes:**

1. **DISSUB RVM Procedures –** locate, approach, inspect, dock in **varying conditions of visibility and current strength/direction**.

## 11.1 Initial Training Delivery Options Conclusions

The main conclusion drawn in this early analysis is that a good proportion of the basic engineering and support tasks associated with a future DISSUB rescue submersible system can be trained in a cost effective way by exposing students/trainees to actual equipment in a dry (dockside/storage facility) or wet (limited trial dives) context, using actual equipment. However, there are certain tasks that cannot be fully trained in this manner, notably:

- SRV/ROV/RORV initial flight and navigation training (including dive/surface procedures, vehicle handling characteristics, manual station-keeping, object surface tracking, operating in vicinity of other vehicles),
- DISSUB inspection training (including special submarine stand-off and tracking procedures, hull feature recognition, etc.),
- Manipulator and/or special subsea tool (eg. ELSS, DSDS) deployment control (also debris clearance),
- DISSUB rendezvous and mating by SRV or RORV under variable subsea conditions,
- RORV rendezvous and mating control by *in-chamber* operator,
- RORV emergency withdraw procedures by *in-chamber* operator,
- RORV **collaborative** control (between topside and in-chamber operators).

These tasks lend themselves extremely well to simulation or VR implementation in that they demand the real-time participation and skills execution on the part of the trainee. They also call for an ability on the part of instructors to vary the degree of difficulty in the tasks being trained, from poor external visual cues to subsea currents of varying strength, or from serious power or thruster failures to DISSUB mating angles.

The analysis also shows that some of the more innovative forms of training delivery (eg. multi-media CBT + 3D animation and VR) score quite high in certain areas where equivalent scores have **already** been noted for other more conventional or "hands-on" forms of training. The reason for this is that if one particular form of delivery option has been recommended and used for one task, **it may well be cost effective to use the same training data for other tasks**, suitably modified.

For example, if a comprehensive VR model of an SRV has been developed for DISSUB RVM procedures, there is no reason why that same model could not be used for delivering training in health and safety, system preparation or maintenance (for example). Similarly, if a computer-generated model of an SRV or RORV has been used during design phases in conjunction with a simulated human mannequin package (eg. *Jack, Safework*), it might be well worth considering the use of the package for subsequent training (eg. using mannequins for simulated evacuation procedures).

This characteristic of reusability, together with the emerging evidence in support of such technologies as simulation, VR and the like (see earlier), not to mention the significant reductions in computing costs witnessed over the past 2-3 years, have prompted specific financial consideration of the category of "Innovative TBT".

## 12. TNA METHODOLOGY

As well as addressing those issues discussed above, the TNA should also address those issues worthy of consideration by future submarine and submersible designers that will enhance the performance of pilots of manned or remote systems during the DISSUB RVM, thereby easing their training requirements as well. For example, many of the complications that arise during underwater operations involving manned and remotely operated submersibles do so because many items of subsea equipment were more often than not designed for human (diver) operation, as opposed to operation mediated by manipulator, or some other limited function tool. Another example is submarine deck marking and/or fin lighting (RVM cues). The current situation is far from satisfactory, yet with appropriate attention, relatively simple systems could ease the workload of the NSRS operators, just as basic lighting displays assist commercial pilots to bring their aircraft on-stand.

### 12.1. HFI Issues

Again, given the fact that NSRS does not yet exist, and given the potential for innovation in a future system solution, the evolution of training methods and TBT solutions must occur in parallel with human factors design criteria. However, it is highly likely that the contents of the DEFSTAN 00-25 chapters, as they currently stand, will be inadequate with regard to some of the human interface design requirements of NSRS. Whilst DEFSTAN 00-25 presents useful data with regard to such basic ergonomic issues as anthropometry, conventional display and control issues, systems approaches to HFI and the like, the series does not adequately address training in the context of special applications (such as UKSRS/NSRS). The standard does also not cope well with applications demanding the introduction of very recent HSI devices, such as advanced displays, multi-function, multi-axis joysticks and so on. In the context of HFI, it is also recommended that due consideration is given to ISO 13407, *Human-Centred Design Processes for Interactive Systems* (1999).

## 13. A DISTRIBUTED NSRS TRAINING/SYNTHETIC EXERCISE CONCEPT

For a general review of distributed synthetic environment technologies and processes, please refer to Appendix 1.

To design and implement a Europe-wide NSRS synthetic "exercise" system will require further in-depth study to define fully the requirements and hardware/software specifications for each participating country. Only a superficial overview of the concept can be presented here. Nevertheless, the potential for obtaining significant annual cost savings (when compared to typical exercise costs) is, has been demonstrated elsewhere in the networked simulation industry, enormous.

Appendix 1 describes the main elements of a DIS-based network (Distributed Interactive Simulation) as would probably feature in a distributed NSRS synthetic exercise system. Many of the communication bandwidth/real-time performance trade-offs normally experienced by network developers may well become insignificant in the case of NSRS, due to the relatively small number of active nodes one might expect. Even future extensions of the network, to accommodate other countries wishing to become part of NSRS, would not subject the network to the latencies and communications overheads witnessed with other, more publicly accessible systems. Consequently, it is likely that all the international standard and best practice aspects of DIS can be implemented within a reasonably homogeneous SIMNET-like network provided to the international NSRS community.

Figure 3, then shows a simplified distribution of NSRS nodes throughout a wide area European network, based on the RORV/SRV options described earlier. In this Figure, one might envisage a scenario whereby a synthetic exercise is organised with MoD Abbey Wood in the overall exercise coordination role (CRF) with France supplying Rescue Assets Management and the virtual MOSHIP system with medical support. Norway or the Clyde region base might provide the rescue vehicle component of the exercise or even access to a *real* land-based decompression facility (see below). In the example shown, Turkey might act as the DISSUB nation of origin, bringing its class of virtual submarine to the exercise with which the rescue vehicle would ultimately mate. Granted, this is an unlikely scenario, but the beauty of distributed simulation is that different nations and participants can play out whatever role is required of them during a particular exercise – something that may not happen in the real world where financial, personnel/hardware resource and safety limitations would dictate otherwise.

Each major national node in this network would consist of one or more Windows-based computers capable of generating quite high-fidelity interactive 3D graphics, yet providing its users with a real-time connection to the other synthetic exercise participants. In performing a coordination role, MoD Abbey Wood will have set up and distributed the virtual "theatre of campaign" – the seascape (and state), weather, subsea conditions and seabed profile – prior to exercise start (as illustrated by the dotted red line in Figure 3). **Note that, from a financial perspective, the Royal Navy has already procured virtual seascape, weather modules and vessel models, developed in an international standard software architecture and capable of running on a conventional PC.**

Connected to each national node would be other nodes, typically on a LAN within the same NSRS facility but possibly distributed throughout a country-wide WAN, depending on the availability of resources at the time of the synthetic exercise and the role the country was playing in that exercise.

For example, the Norwegian wide area node would itself spawn a limited number of Intranet nodes, some of which would be totally SE-based, others of which would be linked to actual physical assets, such as medical facilities or hyperbaric chambers. Indeed, for the purposes of synthetic exercise, there is no reason why actual assets need to be tied up. Rather, low-cost physical mock-ups, together with volunteers, actors or medical mannequins, could be brought into use on receipt of a computerised message.

An illustration of this would be in the case of Turkey in the Figure 3 example. Depending on the level to which Turkey had funded their own additional in-country content development (as discussed earlier), their NSRS team might be able to simulate DISSUB evacuation times by running a program that involves virtual humans (or "avatars") entering the escape chamber and climbing into the rescue vehicle. Alternatively (and as a cheaper option), Turkey could enlist the help of a small number of volunteers who would be "cycled" through a simplified mock-up of the chamber, in order to generate realistic evacuation timings that were then experienced by all participants in the distributed exercise. Another example might be the distribution of DISSUB casualties throughout layered MOSHIP decompression modules. As the rescued submariners were brought to the surface in the synthetic exercise environment, so real actors could be moved around the physical mock-ups, thereby simulating decompression, treatment and habitability schedules.

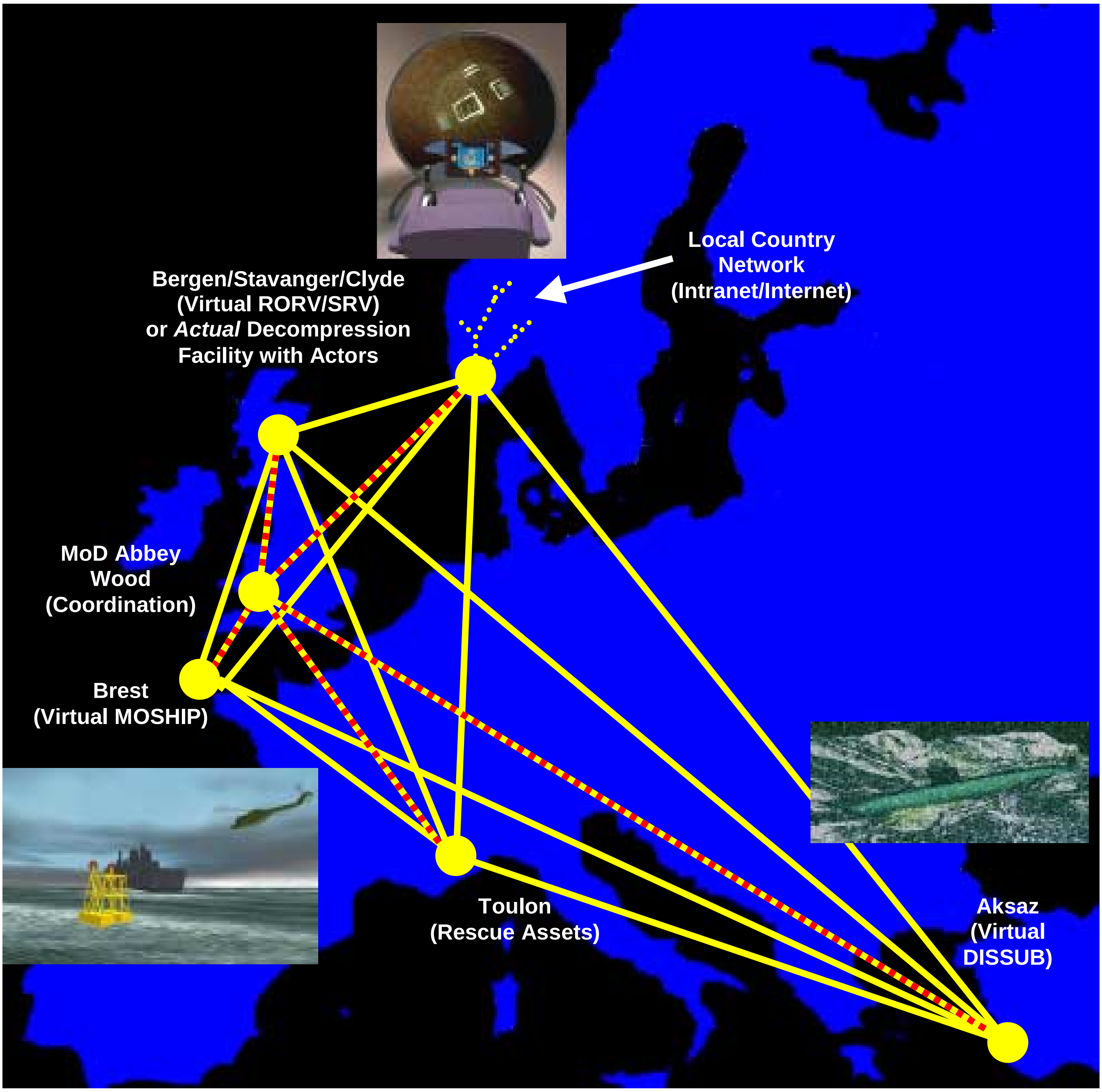


**Figure 3: Simplified Illustration of NSRS Distributed Simulated Exercise Architecture (Concept)**
**(based on point-to-point communications architecture – yellow links and centralised coordination and resource distribution – dotted red links).**

## 14. CONCLUSIONS

The NATO Submarine Rescue System, NSRS, is a potential future MoD DISSUB rescue asset, based on an as-yet undefined configuration of vehicle(s), manned or unmanned.

The civilian operators of the UKSRS system, based on the manned submersible *LR5(X)* and the *Scorpio* ROV system are highly experienced, "hands-on" submersible personnel. However, this has meant that training policies for commercial operations and UKSRS have evolved through practice and experience in the field.

Few, if any studies of the training requirements of manned and remotely operated vehicles in a DISSUB configuration have been undertaken and published. The unique nature of the DISSUB operation and the limited opportunities to take part in NATO trials have all contributed to the absence of relevant material.

This report has addressed the scope of training needs for 3 alternative system options:

- Manned submersible only (SRV)
- Manned Submersible with Remotely Operated Submersible Support (SRV + ROV)
- Remotely Operated Submersible Single/Limited Number Crew (RORV)

The main conclusion drawn from a high-level analysis of these options (personnel and equipment) indicates that a good proportion of the basic engineering and support tasks associated with a future DISSUB rescue submersible system can be trained in a cost effective way by exposing students/trainees to actual equipment in a dry (dockside/storage facility) or wet (limited trial dives) context, using actual equipment.

However, there are certain tasks that cannot be fully trained using real equipment or in real subsea settings. In particular those missions that involve operations in and around a submarine and/or exposure to variable subsea environments may negate the deployment of real assets due to safety, even cost limitations. These tasks lend themselves extremely well to simulation or Virtual Environment implementation in that they demand the real-time participation and skills execution on the part of the trainee.

In the case of simulation-based training, once a computer-generated model or environment has been built, certain basic engineering and support tasks previously best performed using real equipment, might be performed more effectively by using the same models. Adapting these models to fulfil these additional training roles not only makes sense in terms of maximising one's initial investment for quite modest additional outlay, but should serve to reduce significantly the number of times trainees need to monopolise real NSRS equipment.

Given parallel efforts in the use of advanced training technologies such as VR for various aspects of submarine training in the UK (SMQ(D) for *Trafalgar*/*Astute* SSN and *Vanguard* SSBN) that training policy should ensure, where possible, the integration of TBT for **both DISSUB rescuers *and* evacuees**. Thus, future training systems developed for submarines should seriously consider the added value of integrating developments with those under way for NSRS training and *vice versa*.

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# APPENDIX 1

## DISTRIBUTED INTERACTIVE SIMULATION: A SIMPLIFIED DESCRIPTION

The ability to link disparate simulation users for the purposes of interaction within a shared virtual or synthetic environment in real time ("interoperability") – be they in the same room or building, even geographically remote – has been steadily developing since the 1980s. Today, it is commonplace for domestic PC and video console users to be able to log into shared first-person gaming environments and join forces or compete with others via standard modems and the global Internet. The growth of business using the same digital environment and the recent obsession with *e-learning* has exposed the Internet as a potential method of accelerating the MoD's moves toward smart procurement, CALS and distributed training. Within the Virtual Environment community, shared virtual workspaces have been under development for some time, from the early VPL Inc *RB2* system ("Reality Built for Two") to the multi-gigabit fibre optic networks assembled by the DIVE community (Distributed Interactive Virtual Environment), notably in Sweden.

### A1.1 SIMNET

Perhaps the best-known efforts in the defence community evolved from an initiative started in 1983 when the US Defense Advanced Research Projects Agency (DARPA) sponsored a programme known as SIMNET (SIMulation NETworking). SIMNET was designed to create the technologies necessary to expand single task trainers into a network of team trainers, all existing within the same virtual world. There is no doubt that SIMNET was successful, with some 300 simulators becoming networked during the programme.

However, what SIMNET had actually achieved can be described as an example of *homogeneous* interoperability, with all the simulators having been manufactured by the same computer vendor! This was fine for those SIMNET participants who possessed (or, indeed could afford) the particular type of computing system in question. However, for those with non-conforming computers, whilst they could (with some effort) connect to SIMNET, it was quite likely that the specification of their device put them at a distinct disadvantage when trying to interact or undertake combat with other network users.

### A1.2 DIS

This fundamental limitation of SIMNET, coupled with the growth of the Internet (supporting a vast array of dissimilar computers), led to the emergence of the Distributed Interactive Simulation (DIS) concept. DIS has been designed to support autonomous computer "nodes", each node comprising a single computer (similar, or dissimilar in specification to its network counterparts). Each node is responsible for hosting and maintaining the electronic description – 3D model, behaviour, and so on – of a "unit" within the overall DIS environment, be that a virtual vessel, a small flotilla, even a single human combatant or actor ("avatar" in SE parlance). Consequently, each node should:

- Update the state of the unit it hosts, for example "move vessel forward *x* nautical miles at increased speed of *y* knots", as demanded by the unit's simulation user.
- Register and update a local digital representation of the shared virtual environment, including the state all other nodes and *non-node entities* (for example a randomly changing model of the sea or weather hosted on a separate computer)
- Display this representation to the node computer user in a meaningful and consistent way, taking into consideration the media capabilities of the computer.

As each node is responsible for maintaining its own model of the synthetic environment, problems may arise if there are significant inconsistencies are allowed to exist between these separate world views, resulting in unrealistic simulation results or negative training, and a corresponding degradation of interoperability in a DIS network.

In the case of shared, real-time synthetic environments running over the Internet, any technique capable of reducing time delays over the network, also referred to as system "latency" is crucial. As will be seen later, DIS boasts a number of features that contribute towards latency reduction.

### A1.3 Internet Communication Protocols

In the current context, a communication protocol can be defined as a widely accepted format for transmitting data between two or more devices. Communication protocols define the method of data error checking to be used, the method of data compression and how the sending and receiving nodes (computers) will indicate that a message has been sent and received, respectively.

#### A1.3.1 TCP/IP

The Internet is based on communication protocols generally referred to as TCP/IP (Transmission Control Protocol/Internet Protocol). Both TCP and IP were developed from DoD research in the 1980s – ARPAnet – to allow cooperating computers (nodes as described above) to share resources across a network. In essence, the low-level Internet Protocols deal with addressing and routeing. This is the layer that is common to all Internet applications. Packets of IP data can be sent over a variety of communications links, from telephone lines and Ethernet to radio and fibre optic connections.

The higher-level TC Protocols handle the flow of data packets between systems and provide such services as data reliability (error checking and correction), the speed of data sent, the avoidance of network congestion, full-duplex operations (send and receive), and data multiplexing (in order to pass data between the network layer and the correct application – the bare minimum any transport protocol should do). Unfortunately, the very fact that TCP supports all of these services means that the network latency can suffer. Nevertheless, TCP guarantees the delivery of data and also guarantees that packets will be delivered in the same order in which they were sent.

### A1.3.2 UDP/IP

An often-quoted alternative protocol to TCP is UDP or "User Datagram Protocol". UDP is a thin layer on top of the IP that provides a way to distinguish among multiple programs running on a single machine. UDP is a packet-based, connectionless service that provides no control over congestion. In other words, data packets are simply placed on a network in the hope that they will eventually reach the intended receiver. It is also up to the application to split data into packets, and provide any necessary error checking, prior to send. However, because of this, UDP allows the fastest and most simple way of transmitting data to the receiver. UDP has been used with Internet games and multimedia applications, such as Voice-Over IP (VoIP), real-time video conferencing, and streaming of stored audio and video, where reliable data transfer is not absolutely necessary.

**Nevertheless, and despite some of its shortcomings, it is TCP/IP that has, on the basis of early uptake and dissemination, "won out" as the *de facto* Internet Protocol.**

## A1.4 Reducing Latency in DIS Over the Internet

In a DIS environment operating over the Internet, for example, the state of one's own node and that of others is communicated by means of small packets of data called Protocol Data Units (PDUs). A PDU might, for example, contain data relevant to vessel location, speed and acceleration. Once transmitted, a remote node on the DIS network would be able to use these data to calculate (via dead reckoning) the vessel's latest position before the next PDU arrives. In this way, the amount of data transmitted can be kept to a minimum – 250 bytes per second or better – thereby reducing the load on communications networks.

In addition to this, DIS does **not** require a central server. All data can be passed to all nodes and may be accepted or rejected by each node on the basis of pre-programmed computer settings or other filters (see multicasting, below). This "point-to-point" feature helps to keep system latency, to a minimum, and is especially important given that each node is supervised by a human operator who is extremely intolerant of input-display lags in simulation[1].

Another useful and lag-reducing characteristic of DIS is that of "multicasting" (which is supported by UDP/IP **and not TCP/IP**). Rather than sending every state message to every node, nodes can become members of multicast groups, each group having its own IP address. If one node "broadcasts" a state message to a multicast group, only the group members are informed. This further improves network performance by relieving the communications load on the sending and receiving nodes.

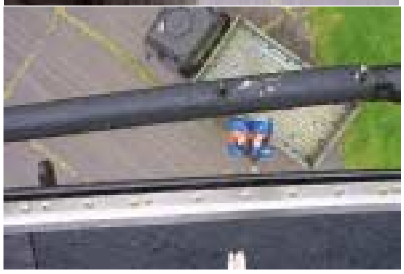
[1] IEEE 1278.2 (1995) – *IEEE Standard for Distributed Interactive Simulation -- Communication Services and Profiles* – indicates that the underlying communications structure should provide 100 ms or less latency for packet exchange for "closely coupled interactions between simulated entities". This figure has, it is claimed, been based on reaction time averages from human performance studies.

## A1.5 Communications Security

Network security will represent a major concern should a distributed NSRS synthetic exercise go ahead based on the Internet and Internet Protocols. Any attempts to breach security, not only from an information-gathering point of view, but also in the case of more malicious activities (eg. virus posting, real-time exercise disruption, etc.), must be combated. Unfortunately, the Internet is actually a shared network of networks and, in its most common form, is not suitable for secure transactions. However recently there has been an emergence of a technology capable of achieving Internet security over and above that provided by an organisation’s existing firewalls. This technology is known collectively as *Virtual Private Networks* (VPNs) and treats the Internet as if it were a secure private network. In essence a VPN creates a “tunnel” for encrypted packets of data between users with the ends of the tunnel governed by software processes that initiate, terminate and authenticate the VPN. This tunnel is routed through a number of Internet Service Providers (“ISPs”).

Another method of achieving network and transmission security in the case of NSRS might be possible by exploiting NATO’s Wide Area Network CRONOS (Crisis Response Operations in NATO Operating Systems). CRONOS was implemented by NATO’s Consultation, Command, and Control Agency (NC3A) in 1995, in response to the requirement to transmit tactical data throughout the chain of command between forces deployed throughout Bosnia and SHAPE. CRONOS was based at the time on Microsoft Windows NT Server 4.0. More recently, NC3A planned to replace 11 of the original CRONOS servers with more up-to-date Pentium clusters. In addition, NC3A and SHAPE plan to explore, develop, and support advanced capabilities including the CRONOS Wide Web, a Virtual Command Centre, and integrated data-voice-video over TCP/IP.

# RAF Helicopter Voice Marshalling
# Virtual Environments Trainer



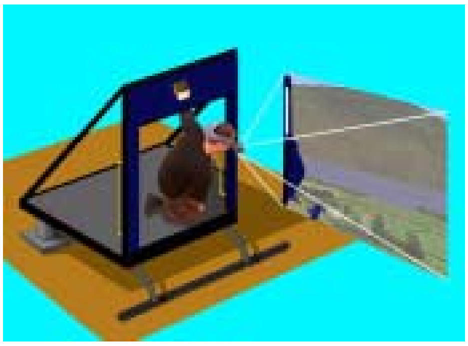
The past 2 years have witnessed a steady increase in the number of search and rescue missions flown by RAF helicopter crews. To quote but one example, in 2000, the Anglesey (NW Wales)-based Search and Rescue Training Unit (SARTU) of the Defence Helicopter Flying School (DHFS) at RAF Valley had carried out 231 rescue missions, ranging from injured mountaineers and air crash survivors to the airlifting of ferry passengers and the transfer of road traffic accident victims to hospital. As of the end of 2001 the total stood at over 200.

Central to the success of these missions is the role played by the helicopter voice marshalling aircrew. Working out of the open rear doors of the RAF's *Griffin* HT1 (Bell 412) helicopters, voice-marshalling aircrew verbally relay important flight commands to the pilot in order to guarantee the accuracy and safety of the aircraft's approach to a landing site or target object. Looking across the spectrum of RAF activities, voice marshalling plays a vital role, not only in search and rescue missions, but in the delivery of military and survival resources to remote areas, often confined by natural features such as forests and mountains.

Training aircrew on the ground to support RAF helicopter pilots to fly into increasingly hazardous and confined environments is becoming more and more difficult. To improve upon the current situation, in November of 2001 the RAF commissioned VP Defence to develop a VR Voice Marshalling simulator in order to foster improved training techniques and to minimise the need for costly "remedial" training, both on the ground and in the air. The project began by conducting a human factors and training needs analysis, performed with the support of RAF subject matter experts from the Central Flying School (CFS) and DHFS. These analyses involved ground exercises and flight trials at RAF Shawbury and Valley and set out to define:

- the primary Voice Marshalling task elements (open-field, open-sea and confined area approaches),
- features of the *Griffin* demanding graphical reproduction (in particular those items mounted on or around the door, skid and outer skin used to generate parallax cues with external environmental features), and
- the specification of the sources of (predominantly monocular) visual cues, utilised during reconnaissance and final approach (for both land and sea operations).

The results of these trials were collated into a single user requirements document that became the baseline reference for the "construction" of the virtual world. The simulator development period was limited by the in-service training needs of the RAF and took place between November, 2001 and February, 2002. In brief, the main elements of the delivered simulators include:



**VM Student's workstation.** A simple wooden framework representing part of the rear door area of the *Griffin* helicopter has been constructed to provide a suitable minimum metallic framework for the immersive VR equipment (ie. the Polhemus *Fastrak* tracking system for the Kaiser *ProView* XL-50 head-mounted display) and to provide aircrew students with safe and representative handholds, together with a robust attachment point for a standard RAF harness;

**VM Trainer's workstation.** A single Pentium IV PC (Windows 2000) with dual graphics cards drives both the real-time rendering engine for the VM student (duplicating the student's HMD view on one of two trainer displays) and the *scenario control interface* used by the trainer to set up, run and replay/debrief scenarios;

**Virtual landscape scenarios.** In order to facilitate subsequent transfer of training assessments, it was decided to construct a virtual landscape representative of the RAF Shawbury site. Digital terrain elevation data and aerial photographs were used to generate the base topography, with the airfield occupying some 3km by 4km (at high fidelity) and the surrounding environment out to 10km by 10 km represented at a lower resolution. Target objects, from military trucks to barrels can be positioned within the virtual landscape by the VM trainer. Other landscape features, such as copses, dead trees, small lakes and ponds, electricity/radar pylons, hangars and other man-made features are included to ensure sufficient visual details to support a range of VM activities;

**Virtual seascape scenarios.** The majority of the effort necessary for delivering a virtual seascape had already been expended, courtesy of a previous project designed to deliver immersive VR trainers for Royal Navy close-range weapons systems. Target objects, from survival dinghies to a motor launch can be positioned within the virtual seascape by the VM trainer. Sea states 1 through 6 are available and, for both the sea and land environments, variable levels of fog and precipitation can be selected, together with and time of day effects.

The in-service date for this simulator is scheduled for March 2002, after which a short study will be conducted to review the process of how well the VR system has been integrated with existing training techniques and to appraise the success (or otherwise) of its adoption by trainers and students alike. Another early goal, to be conducted with SMEs from the RAF, is to carry out an investigation of the transfer of training from the simulator setting to the real-world environment.

# MoD Contract No. ICS1B/114552:

# Supply of Virtual Reality Voice Marshalling Training System at RAF Shawbury and RAF Valley

## User Requirements Document

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**Date of this Issue:**
**December, 2001 (F01)**

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# VERSION CONTROL

## Draft

| ISSUE No. | Changes | Page Nos. | Date | Author |
|---|---|---|---|---|
| D01 | - | - | 28 November, 2001 | R J STONE |

## Final

| ISSUE No. | Changes | Page Nos. | Date | Author |
|---|---|---|---|---|
| F01 | As requested at 28 October Progress Meeting | Numerous | 10 December, 2001 | R J STONE |
| F | | | | |
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# 1 Introduction

This User Requirements Document (URD) has been written to fulfil the early tasks of MoD Contract No. ICS1B/114552 – *Supply of Virtual Reality Voice Marshalling Training System at RAF Shawbury and RAF Valley*. In the absence of a Training Needs Analysis and associated Human Factors Task Description, the URD sets out to summarise those aspects of the real Voice Marshalling tasks that will directly influence the **content and quality** of the VR simulator. The contents of this document were, therefore used to brief the VP technical team prior to the data collection exercise. In addition, this document will be referred to later during system integration and in the drawing up of the final acceptance schedule.

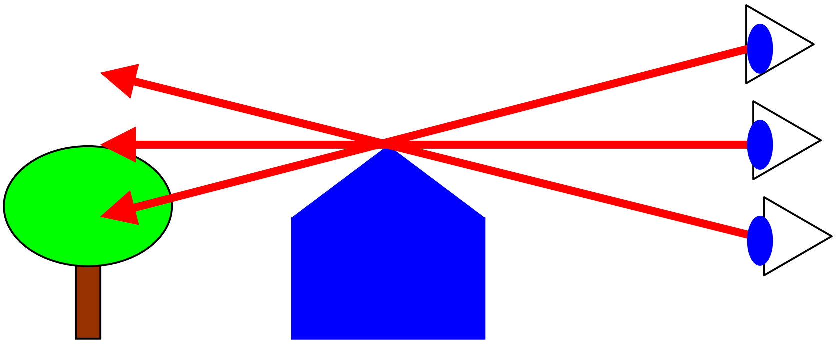
The document has been divided into 2 sections, dealing with each of the user requirements visits to RAF Shawbury and Valley. Each section provides brief details of the flights undertaken and lists the features to be considered and implemented during the VR software development process. An appendix (Appendix 1) details the dimensions and layout of the rear door area for reference.

# 2 RAF Shawbury

The Griffin flight from RAF Shawbury lasted approximately 1 hour. The initial environment was cross-country, culminating in the vicinity of a small but fairly dense copse (see image below) to perform a reconnaissance of and approach into a clearing within the copse. Subsequent to the confined area landing, the crew returned to Shawbury for load collection and depositing on an isolated Bedford truck, followed by a basic Voice Marshalling (VM) approach over the airfield's sloping area.

## 2.1 Reconnaissance

The helicopter pilot carries out one or more circular sweeps of target area, primarily to allow the helicopter crewman to select appropriate markers. The crewman and pilot agree on the "5S" reconnaissance information – **Size**, **Shape**, **Surround**, **Surface** and **Slope**. They then identify markers for final approach (man-made or natural) - perspective, parallax ("backdrop" = parallax in height – see below; also parallax horizontally), size and shape constancies are all-important.



Markers include **(and should feature in the VR Simulation)**:

- Telegraph poles
- Isolated trees and bushes (40' Standard NATO Tree)
- Dead trees within woods/copses
- Small ponds
- House features - 10' to top of typical house first floor window, 20' to top of second storey window
- Hangars – 30' to top of door, 40' to top of hangar
- ATC Tower (35' to top)
- Runway square markers (40 units) separation)

### 2.2 Helicopter Near-Door/Rotor Features (see also Appendix 1)

It was apparent from comments from aircrew and observation of head movements that instructors and students use helicopter physical features to line up with (or obtain parallax cues from) features in the scene. These include (**and should feature in the detail of the VR Griffin model**):

- Doorframe lugs and outer shell features
- Skid
- Skid rivets
- Rotor blade tip colour (dark contrast band – see above)

### 2.3 Rotor Downdraft

- Provides a useful cue (especially in confined areas)

- Influenced by wind (10-15 knot wind will move the downdraft effects aft of the helicopter).

### 2.4 Shadows

- Useful if over man-made surfaces (eg. high contrast shadows on tarmac/concrete, etc.)
- If the light is from right direction shadows will be used
- Shadows important (but not relied upon) for load lifting and depositing

### 2.5 Cabin Movement

One of the apparent consequences of the *pilot's* choice of approach vector markers is that both doors were open during the Shawbury flight VM exercises and the VM was observed to make rapid and regular movements between the doors. Also, the P2 cockpit window was used during VM (again, probably as a result of the pilot's choice of line-up). **However, the ability to see the external environment when looking towards the cockpit windows in the virtual Griffin is considered an important feature for the simulation**.

### 2.6 Final Approach

The key to successful VM activities is not solely the accurate estimation of distance to target. Rather, VM trainees are expected to be able to "halve" the distance repeatedly between their helicopter and target, thereby ensuring a smooth countdown (5-4-3-2-1) to the target and, thus, a steady rate of approach on the part of the pilot. Halving is not dependent on absolute range estimation (which humans are poor at performing anyway). Again, this emphasises the need for random features in the scene (as opposed to straight textures), thus allowing the students to practice the halving process.

## 3 RAF Valley

This visit involved an approximate 1-hour trip in Griffin; crossing the runway towards the golf course and scrubland to perform basic approach VM manoeuvres (20' over land, 50' over water). Following this, the flight continued on to the local harbour for flare release, drum ditch, approach and recovery, surface vessel reconnaissance, dinghy release and approach (50').

### 3.1 Markers

As far as operations over sea are concerned, there is often a paucity of natural and man-made markers. Coastal features, breakwaters, the painted bands of lighthouses, surface vessels and so on help, but cannot be guaranteed. The VM makes regular glances to the horizon, in order to avoid any descent drift that may be evident (fixating on the surface does not help in assessing changes in altitude).

Target drums and survival dinghies are very small and low-contrast targets. In calm, low-wind conditions, the rotor downdraft is directly below the helicopter and serves to push targets away prior to grapple. On these occasions, the VM instructor will more than likely abandon the exercise, as the conditions are not representative and can reduce the trainees' morale.

As noted at RAF Shawbury, in "normal" conditions (10-15+ knot wind), the downdraft moves away from the helicopter, leaving the waves to act around and on the target. Having reconnoitred the target/scene and, whilst hovering a distance away from the target, VM head movement in conjunction with occluding wave peaks/troughs are used to judge distances. The cues are also important during "halving" as described above. Other cues used by the crewman include the foam or bubbles left by a peaking wave (these can last for up to 20 seconds). The existing seascape simulation developed for the Royal Navy will be adequate for the VM simulator, although a range of targets will need to be provided so that familiarity with scale does not impinge on the training schedule (different size targets will be exposed and occluded differently under variable sea states; also, the contrast of orange/red targets will be affected by prevailing fog/precipitation conditions).

### 3.2 Helicopter Near-Door/Rotor Features

The coating on the RAF Valley Griffin skids is different to that at Shawbury – the rivets (in the main) are not available for visual reference. The flotation aids (2 on each side of the helicopter) are attached to the doorframe lugs and are also not available for visual reference. They also partially obscure the skid.

### 3.3 Cabin Movement

Not as active as that seen at Shawbury, although the VM was constantly scanning both sides of the helicopter for **fixed-wing aircraft** in the vicinity of the runway (RAF Hawks conduct circuits with low runway fly-overs and “touch and go”). Currently, fixed-wing “fly-pasts” are not included in the simulator specification.

### 3.4 Surface Vessel Reconnaissance

Pilot carries out one or more circular sweeps of vessel. VM and pilot identify deck features and possible hazards relevant to winch/recovery operations (eg. if only 3 out of 4 wires holding mast in place are visible, is the other wire free, and, therefore a hazard?).

## 4 Other Relevant Reference Images

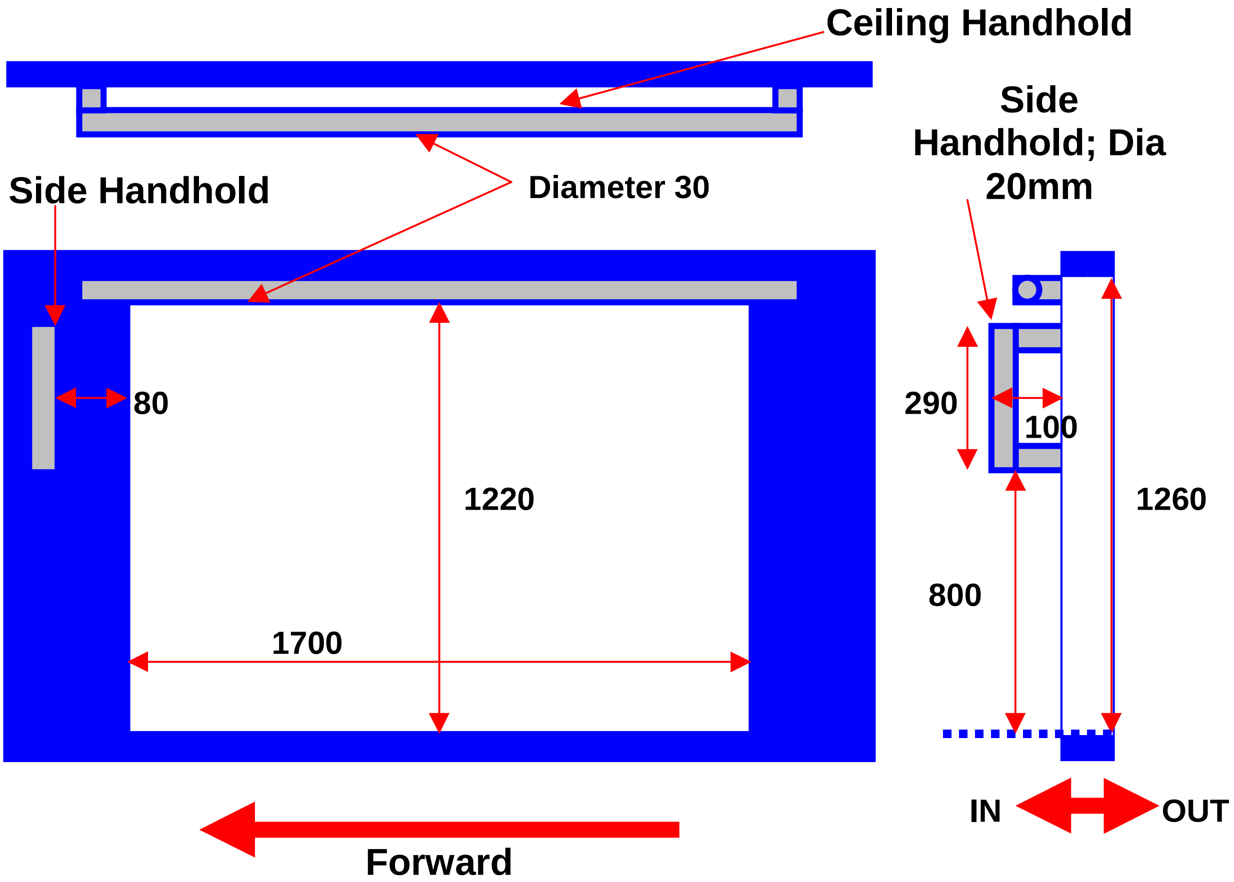
**Hangars and Airfield Buildings**

**Shawbury Sloping Ground Area With Marker**


Upper Handhold (Rear Cabin)

Harness Location Points

### APPENDIX 1: Actual Griffin Door Area Dimensions and Handhold Locations




**Side Doors and Handholds of Shawbury (left) and Valley (right) Helicopters Different**

Shawbury helicopters have a small part of the door attached just behind the cockpit; the VM handgrip is basic (forward and ceiling). In the case of the SARTU helicopters, the door is integral and slides back complete. The handgrips are more complex and shield the winch controls (forward and ceiling).