Haptic Feedback:
A Potted History, From Telepresence to Virtual Reality

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ABSTRACT
This paper presents a short review of the history surrounding the development of haptic feedback systems, from early manipulators and telerobots, used in the nuclear and subsea industries, to today's impressive desktop devices, used to support real-time interaction with 3D visual simulations, or *Virtual Reality*. Four examples of recent VR projects are described, illustrating the use of haptic feedback in ceramics, aerospace, surgical and defence applications. These examples serve to illustrate the premise that haptic feedback systems have evolved much faster than their visual display counterparts and are, today, delivering impressive peripheral devices that are truly usable by non-specialist users of computing technology.

Keywords
Haptics, Virtual Reality, telepresence, human factors, ceramics, surgery, aerospace, defence.

INTRODUCTION
Some of the early developments relating to physical methods of generating haptic feedback for human-system design purposes have been well covered in historical publications by (for example) Corliss & Johnson (1968), Mosher (1964), Stone (1992), Thring (1983) and, more recently, in an excellent book by Burdea (1996). However, it is only quite recently that haptic technologies have appeared that are capable of delivering believable sensory stimuli at a reasonable cost, using human interface devices of a practical size.

This has opened up a wealth of opportunities for academic research and commercial developments, from haptic feedback systems to aid blind persons' exploration of virtual environments, through applications in aerospace and surgery, to a revitalisation of the ceramics industry. This brief paper cannot catalogue all relevant developments, but attempts to provide a potted review the history of haptic feedback from the early days of teleoperation or telerobotics to present-day developments in Virtual Reality (VR) and simulation.

Turning first to the robotics arena, most researchers now accept the definitions put forward by Sheridan when considering the systems aspects of controlling remote robotic vehicles and manipulators (eg. Sheridan 1987, 1989). Until the mid-1990s, terms such as teleoperation, telepresence, robotics, telerobotics and supervisory control had been used interchangeably.

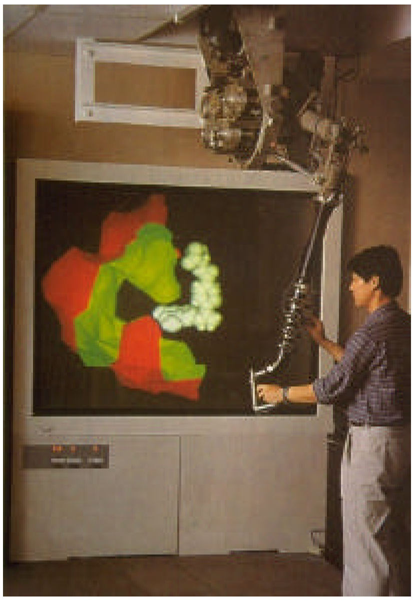
Two of relevance to the emergence of haptic feedback developments are *teleoperation* – the extension of a person's sensing and manipulation capability to a remote location and *telepresence* – the **ideal** of sensing sufficient information about the teleoperator and task environment, and communicating this to the human operator in a sufficiently natural way, that the operator feels physically present at the remote site. The "Holy Grail" of telepresence also provided the motivation behind some of the early human-system interface efforts underpinning NASA's Virtual Environment Workstation, *VIEW* (eg. Fisher *et al*., 1988, which included investigations of basic glove-mounted vibrotactile feedback transducers), and the commercial VR aspirations of the late VPL Inc with its flagship product, the *DataGlove*.


New Electronic Glove Will Let You Move Robot Hand Like It's Your Own — From Miles Away!
— And You'll Even Be Able to Feel Things The Robot Picked Up
ENQUIRER

The remote handling communities serving nuclear, subsea, space and military markets had hoped that telepresence would become the natural successor to the many remote handling systems in evidence in the 1950s. Unfortunately, even today, creating the illusion that a human operator is still present in a remote hazardous worksite or is fully immersed within a computer-generated world remains the “Holy Grail”.

NUCLEAR INDUSTRY & EARLY BILATERAL MANIPULATORS

Bilateral Master-Slave Manipulators (MSMs) – functionally no different from today’s desktop haptic feedback systems – have been prevalent in the international nuclear industry for over half a decade, permitting safe, remote handling of irradiated material under direct human control and supported by direct (lead-window) and indirect (closed-circuit TV) vision. A master control arm is typically a mechanical reproduction of a remote slave arm (the slave gripper being replaced at the master by a scissor, pistol, or similar control grip device), the two components being linked by means of chains, cables or some other electromechanical motion system. “Mini-masters”, such as that proposed in the 1980s for the original NASA Flight Telerobotic Servicer and other remotely controlled space, subsea and land vehicles are, as the name suggests, small master controllers. These may or may not be kinematically similar to the remote slave device and have met with mixed levels of success when applied to laboratory or field demonstrators.



By far the most publicised use of master control arms for Virtual Reality applications has been for molecular modelling (the well-known “GROPE IIIb” Project) and haptic interaction with electrostatic molecule-substrate force simulations and nano-level surfaces (generated from Scanning Tunnelling Microscope data) at the University of North Carolina at Chapel Hill (eg. Brooks ,1988; Brooks *et al.*, 1990).

Early work at UNC utilised an Argonne Remote Manipulator (ARM) system, one of two donated from the Argonne National Laboratory, and a field sequential computer screen (based on liquid crystal shutter glasses). Later, the screen was replaced with a projection display, with users of the ARM interacting with 3D images produced using polarised projection display lenses and spectacles.

Servomanipulators

Compared with mechanical MSMs, servomanipulators have the advantages of being mobile (cable linkages) and possessing large load-carrying capacities. The early servomanipulators were designed to incorporate ac-driven servos, connected back-to-back, to provide force reflection.

These were later replaced with dc servos, integrated within the manipulator arm, leading to a more compact form of remote handling device. One of the most popular servomanipulators - the MA-23M – was designed in a modular fashion to aid repair and maintenance, as well as provide an upgrading path for introducing automation (Vertut, 1976). Selectable force feedback (also known as “force boost”) ratios - 1/2, 1/4, 1/8 - were included as standard, the bilateral positioning system being provided by means of potentiometers which determined the relative positions of master and slave arms.

Exoskeletons

Exoskeletons originated partly as “Man Amplifiers”, capable, through direct human slaving, of lifting and moving heavy loads. The early “Handyman” controller, described in Mosher (1964) and Corliss & Johnson (1968), was an example of a forearm-and-hand exoskeleton possessing two 10-degree-of-freedom (dof) electrohydraulic arms; the General Electric “Hardiman” was a whole-body exoskeletal frame (Thring, 1983).

Until quite recently, the exoskeleton concept had been unpopular, due to limitations in the functional anatomy of the human arm. Also, force-reflecting actuators had to be mounted on the outside of the exoskeletal framework to accommodate the users’ arm. Furthermore, there were concerns with such devices’ small operating volume, possible safety hazards (associated with toppling and locking) and electro-mechanical inefficiency (see also Wilson, 1975; Salisbury, 1979). Nevertheless, thanks in part to the emergence of a range of lightweight, low-cost body systems developed under the VR banner, the exoskeleton received renewed interest as a means of registering body movement in a virtual environment and, importantly, as a technique for feeding haptic data back to the immersed user (eg. Bergamasco, 1992). However, even to this day, exoskeletons have been confined to academic research labs and noticeably absent from commercial catalogues. Witness the fate of the pioneering US company Exos, sold to Microsoft in 1996, having developed such exoskeletal haptic demonstrators as *SAFiRE* (Sensing And Force Reflecting Exoskeleton) and the *HEHD* (Hand Exoskeleton Haptic Display).

OTHER HAPTIC FEEDBACK ATTEMPTS

As hinted earlier, there have been many attempts to recreate tactile and force sensations at the finger, hand, arm and whole body level – far more than can be covered here. However, a wealth of data on historical and contemporary devices has been compiled under the excellent Haptics Community Web Page (http://haptic.mech.northwestern.edu/database/).

The commercial haptics arena is also changing on a regular basis (witness Immersion Corporation's recent acquisition of Haptech Technologies and Virtual Technologies – home of the CyberGlove, CyberTouch and CyberGrasp). The next 5 years promise some quite exciting developments in this field, with systems becoming more widespread as costs come down and software and applications support is improved. Just a small selection of those devices with which the author's team has been involved will be covered here, before looking at a number of emerging applications fields.

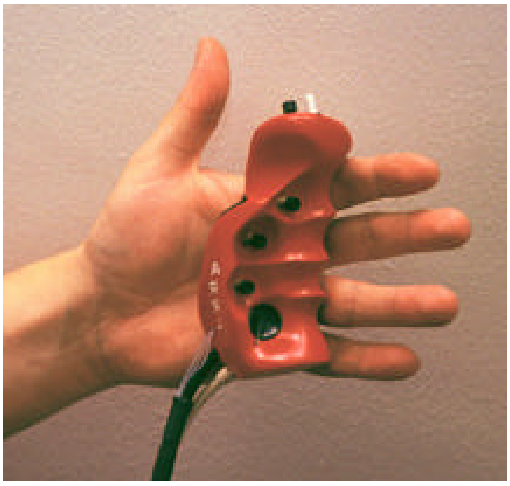
Teletact I, II and Teletact *Commander*

Teletact was conceived in November of 1989, during one of the generic research programmes within the UK's National Advanced Robotics Research Centre in Salford. The concept of using pneumatics to provide feedback to the fingers of an operator controlling a robot originated in the 1960s, courtesy of research efforts at Northrop Grumman (Jones & Thousand, 1966).

Co-developed with Airmuscle Ltd of Cranfield, the first prototype glove, employing 20 small air pockets was produced in September of 1990, and appeared on the BBC's *Tomorrow's World* TV Programme later that year, with a selection of vegetables and an Angoran rabbit as the tactile subject!

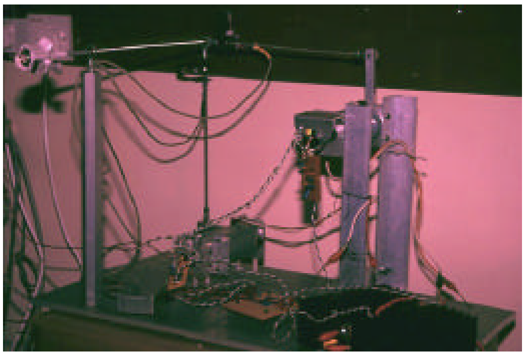
This prototype glove was of an analogue design, supplying up to 13lb psi of air pressure per pocket (proportional control, later with inflation *and* deflation). The author recalls a period of intense legal activity in the early 1990s when, having visited Airmuscle, the developers of what was then W Industries' (later Virtuality) *Space Glove* produced a prototype tactile feedback version using remarkably similar pneumatics technology to that integrated within *Teletact*!

A more sophisticated glove - Teletact II - was specified in May of 1991. This device featured a greater density of air pockets, 30 in all, with two pressure ranges. The majority of the pockets (29) were limited to 15lb psi. However, a new palmar force feedback pad was developed, receiving a maximum pressure of 30lb psi. A vacuum system was also devised to increase the step response of the glove whilst deflating.



In contrast to the glove, the Teletact *Commander* was a simple multifunction hand controller equipped with embedded Polhemus or Ascension tracking sensors. Three Teletact-like air pockets were attached to the outer surface of the hand controller to provide simple tactile cues when the user's virtual hand or cursor made contact with a virtual object. These pockets were controlled either by compressor or by a single solenoid-actuated piston.

Other haptic developments at the ARRC included a prototype minimally invasive surgery haptic feedback system, funded by the Department of Health and Wolfson Foundation. This device actually pre-dated the Immersion Corporation *Impulse Engine* and used basic strain gauge, potentiometer and servomotor devices to provide position sensing and feedback to a laparoscopic instrument in 3 translational degrees of freedom, with grip/forceps actuation.



A simple wire frame cube provided the test environment, hosted on a 486 PC and allowing users to explore the inside of the cube using haptic feedback, whilst and invoking and varying such parameters such as in-cube viscosity, wall elasticity, dynamic "beating" effects and back wall "tissue" grasp and pull.

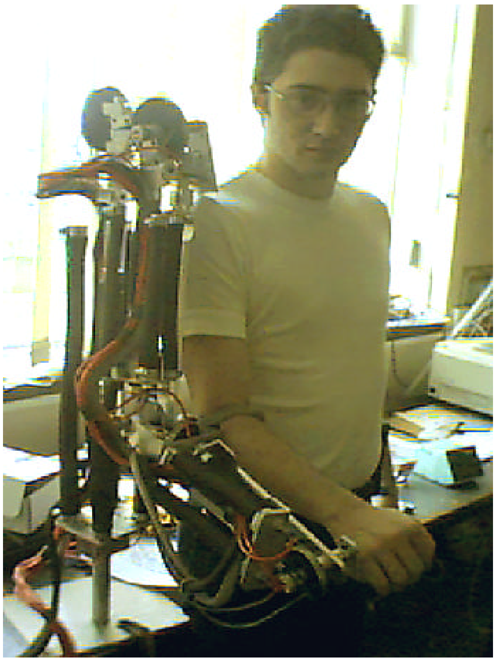
A piezo tactile feedback demonstrator system was also developed by the ARRC, in collaboration with the Electronic & Electrical Engineering Department of the University of Salford, for the Defence Research Agency (Chertsey).

Called the *TactGlove*, it consisted of a 3-digit sensory glove assembly (thumb, index and middle finger) equipped with a Polhemus Fastrak tracker and PZT piezo "sounders" to provide variable frequency tactile input. A simple VR control panel - was developed using Superscape Limited's Virtual Reality Toolkit (VRT).

Users could view the virtual control panel using either a standard monitor, or via a Virtual I-O *i-Glasses* headset (stereo or biocular modes) and could control the 3D position of a schematic "hand" (a simple 3-cylinder cursor).

On making contact between the "hand" and one of three virtual controls (a rotary knob, push-button and toggle switch), the appropriate "collision" signal was transmitted to the glove sensors, either singly or in combination. Actuating the control produced a perceptible change in the frequency of stimulation or in the case of the push-button and toggle switch, a build-up of frequency, followed by a rapid drop, to simulate breakout forces.

Recognition of Salford University's ongoing efforts in haptic technologies should be made here, under the leadership of Darwin Caldwell, Professor of Advanced Robotics. Caldwell's team has been involved in the design, construction and testing in a virtual world of an "Integrated Haptic Experience", comprising a 7-dof arm tracking and force reflection pMA exoskeleton, a 15-dof hand/finger tracker and a 5-dof force reflection hand master, together with a cutaneous tactile feedback glove providing pressure, textural, shape, frictional and thermal feedback.



FOUR CASE STUDIES FROM THE VR COMMUNITY

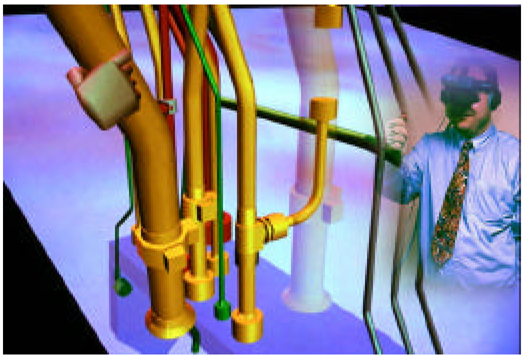
Ceramics

Recent developments in the British economy have prompted certain "heritage" industries to look very closely at their businesses and the prospects for improved productivity and growth in the early part of this new century. Companies such as Wedgwood and Royal Doulton, famous international, historical names in the production of quality crockery and figurines are turning to Virtual Reality 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.

The importance of experiments like these, however, lies not only with the results but moreso 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 Sensable Technologies Inc's *PHANToM* Desktop 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.

Aerospace Maintenance

The use of VR to streamline design and training processes in the aerospace industry is not new (Angus & Stone, 1995). However, the absence of a credible haptic feedback mechanism has forced developers to use other sensory cues to indicate collision detection between pipes, tools, limbs and so on (eg. 3D "ghosting") within a cluttered working volume (Angus & Stone, *op cit.*).



As with other engineering applications of VR, it is only recently, that the aerospace industry has revisited VR to assess its suitability for 21st Century projects and products. The European Initiative ***ENHANCE*** (ENHanced AeroNautical Concurrent Engineering) brings together the main European civilian aeronautical companies and seeks to strengthen cooperation within the European aeronautical industry by developing common working methods which govern the European aeronautical field, defining appropriate standards and supporting concurrent engineering research. One project within *ENHANCE* concerns an advanced VR maintenance demonstrator which links a virtual mannequin with PTC/Division's MOCKUP virtual prototyping software with Sensable Technologies' *PHANToM*™ haptic feedback system. Based on a 3D model of a conceptual future large civil airliner, the VR demonstration involves controlling the mannequin during aircraft preparation and safety procedures, and in gaining access to retracted main landing gear for the purposes of wheel clearance testing.

Certain key interaction events throughout the demonstration are executed using the

PHANToM device. In order to define these stages clearly, and to identify those procedures and events warranting the application of haptic feedback, a context-specific task analysis was carried out, as recommended in the new International Standard **ISO 13407** (*Human-Centred Design Processes for Interactive Systems*).

Surgery

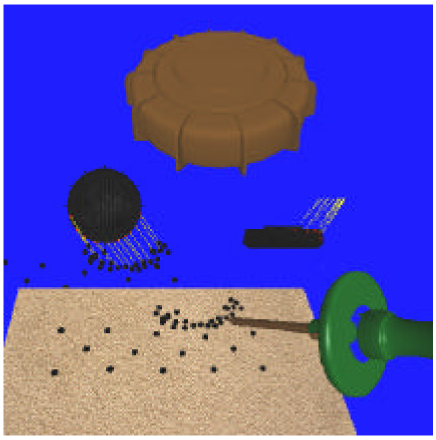
As well as the early ARRC and Immersion Corp. "keyhole" surgery haptic feedback attempts, there have been, and still are projects with significant haptic technology components. One of these projects stems from a European Union Framework V Project called ***IERAPSI***, an Integrated Environment for Rehearsal and Planning of Surgical Interventions. An early IERAPSI work package relates to the human-centred definition of surgical procedures (again based on ISO 13407), specifically focusing on surgical activities underpinning mastoidectomy, cochlear implantation and acoustic neuroma resection. The surgical procedures definition and task analyses (Stone, 2000) 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 device for irrigation and suction (possibly a *PHANToM* Desktop).

Land Mine Clearance Training

MUSE Virtual Presence's Paris-based subsidiary SimTeam has developed an immersive VR land mine detection training system for the French Army, using the *PHANToM* as the primary interaction device.

The system presents the trainee with a basic representation of the ground area to be investigated and, using a standard issue military probe attached to the *PHANToM*, he is required to locate potential mines by gently inserting a virtual representation of the probe into the "ground". Once a definite contact has been made, the trainee must continue probing until a recognisable pattern of penetrations has been made. In addition to the visual and haptic features of this trainer, a pattern recognition system is available which matches the trainee's penetrations with known land mine geometries. Once a pattern match has been made, a schematic of the most likely mine configuration is displayed.



CONCLUSIONS

The claims of early VR proponents that their immersive VR system was the "ultimate" in human-system interface technologies (to coin Ivan Sutherland's early phrase) were soon proven outlandish by those who bought and tried to use the products.

However, after nearly 15 years of development, we are now witnessing the evolution of the truly intuitive interface. Interestingly, it is not the visual modality *per se*. that won the race to deliver this interface, but the combined senses of vision, force and touch.

The history underlying the development of haptic technologies has, it must be said, benefited from more innovation, enthusiasm and excitement than that of the visual display industry and it is those qualities that have helped to produce the intuitive systems and stunning applications evident today. The best is yet to come!

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