Large scale real time multi-user virtual reality
CASE FOR SUPPORT

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Industrial Collaborators: British Telecommunication PLC *and* Silicon Graphics Ltd

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Part 1: Previous research and track record

University of Reading

Dr. Paul Sharkey

The principal investigator for this project is Dr. Paul Sharkey, Head of the Virtual Reality and Robotics Research Groups at the Department of Cybernetics. Dr Sharkey has published extensively in the area of dynamic systems and robotics, including stability of systems with delays, bandwidth considerations, two-time scale modelling, robot design and control, systerm architectures and active vision systems. He was appointed as a Lecturer Grade B at the Department in Sept 1993, after 6 years postdoctoral research at the University of Oxford. He was co-principal investigator on an EPSRC project (GR/J44049) “An Active Visual Sensor for Telepresence” with Dr. D.W. Murray of the University of Oxford. Currently he is a co-investigator on a c.£500k LINK project “Reliability of High Speed Machinery” with Prof. Kevin Warwick as principal investigator. He also holds a number of smaller grants for postgraduate research.

Prof. Kevin Warwick

Prof. Kevin Warwick is widely published in the areas of control, robotics, artificial intelligence and signal processing. Since 1992 he has been the principal investigator on seven EPSRC, two NERCO and fourteen Industrially funded projects totalling an investment of £1,820,649 over three years.

Virtual Reality Research Group

The Department of Cybernetics’ Virtual Reality Research Group (VRRG) has been investigating some of the fundamental issues of large scale multi-user virtual reality systems over the past three years. We have identified six areas of particular importance which, when combined, will provide a strong underlying structure for effective and efficient real time multi-user environments. These are: 1) time related object behaviour; 2) collision prediction; 3) consistency control through ownership requirement prediction; 4) estimation of communication delays; 5) communication protocols; and 6) task distribution. They complement other related work in particular: the restriction of object communication via spatial modelling (Benford, 1993[1]); mapping such restrictions to multicast groups (Macedonia *et al*, 1995); the dynamic spawning of servers, suggested by West (1992); and dead reckoning of object movement (McDonough, 1992).

PaRADE

Reading has combined these six concepts in a prototype Predictive Real-time Architecture for Distribute Virtual Environments (PaRADE). PaRADE facilitates the controlled interaction of many users, hosted on

[1] see Appendix II for a list of supporting references.

machines of differing performance, connected over local and wide area networks (Roberts *et al*, 1995). Users are able to pick up, place and pass objects while maintaining consistency control without the usual associated synchronisation delays. The specially developed communication protocol combines fast response time with low bandwidth requirements and guaranteed reception. The guarantee method has been shown to limit the increase in bandwidth usage of a single machine by only 37% compared to a 605% increase incurred by the conventional DIS heartbeat approach. Distribution of generic tasks to other machines allows fast and predictable response times for local user input and output, regardless of the number of users.

The PaRADE system has been designed and developed as part of a doctorial research in distributed virtual reality systems by David Roberts who wishes to continue his research in this project. Further contributions to PaRADE have been made by two other postgraduate students in VRRG on collision prediction and the continuous evolution of virtual environments with non-deterministic user input. The PaRADE project was supervised by Dr Paul Sharkey.

Recent Relevant Publications

D Roberts, "Distributed Virtual Reality Systems", Thesis Submitted for PhD, Department of Cybernetics, University of Reading, 1995.

D Roberts, P Sharkey and P Sandoz, "A Real-Time Predictive Architecture for Distributed Virtual Reality", Proceedings of the first ACM Siggraph Workshop on Simulation and Interaction in Virtual Environments, Iowa City, USA, July 1995

P Sharkey, "Bandwidth Issues for Active Vision Systems", Second International Conference on Mechatronics and Machine Vision in Practice, Hong Kong, Sept. 1995

D W Murray, I D Reid, P F McLauchlan, P M Sharkey, K J Bradshaw, and S M Fairley, "Active Exploration of Dynamic and Static Scenes", REAL-TIME COMPUTER VISION, eds C Brown & D Terzopoulos, 1994

P Sandoz and P Sharkey, "Collision Prediction in Multi-User Artificial Worlds", European IEEE Workshop CMP'94, Czech Republic, 1994

P Sharkey and A Kumar, "Virtual Time for Virtual Environments", SPIE International Symposium on Telemanipulation and Telepresence II, Philadelphia, USA, Oct. 1995

K Warwick, J Gray and D Roberts, "Virtual Reality in Engineering", IEE, ISBN 0 85296 803 5, 1993

D Roberts and M Griffin, "LOKI-2 An Architecture for Distributed Virtual Reality", IEE Computer and Control Division Colloquium: Distributed Virtual Reality, London, UK, 1993

D Roberts and K Warwick, "An overview of Virtual Reality", Virtual Reality in Engineering, IEE, ISBN 0 85296 803 5, 1993

P M Sharkey and D W Murray, "Coping with Delays for Real-time Gaze Control (The Fall and Rise of the Smith Regulator)", Proc. SPIE Conf. on Sensor Fusion, Boston, pp. 292–304, Sept 1993

M Griffin and D Roberts, "Distributed Virtual Reality Systems", EPSRC and ACME Symposium, Virtual Reality for Design and Manufacture, Coventry University, UK, 1992

Miscellaneous

The Department of Cybernetics has considerable research expertise in audio and video technology which will be available to the project on an informal basis. The Department hosted an IEE Workshop on VR in Engineering in Sept 1993 (organised by David Roberts and Kevin Warwick) a Workshop on VR and Disability in November 1994 (David Roberts, Paul Sharkey), and is currently organising the first European Conference on Disability, Virtual Reality and Associated Technologies (Paul Sharkey, Chairman of Programme Comittee).

University of Nottingham

Dr Steven D. Benford

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Dr Benford's research interests combine Virtual Reality, Computer Supported Cooperative Work and Distributed Systems. The main focus of his recent work has been on the development of *Collaborative Virtual Environments* (CVEs); multi-user distributed virtual reality systems that support cooperative work. Much of this work has involved mapping out what is a new research area and early results have been published in a variety of sources. A general overview of this work can be found in a recent Computer Journal paper (Benford, Bowers, Fahlén, Mariani and Rodden, 1994). More specific examples include:

- The development of the Spatial Model of Interaction where inhabitants of shared virtual worlds manage real-time communication using the mechanisms of *aura*, *focus* and *nimbus*. This has been implemented in the MASSIVE system as described in a forthcoming paper in ACM Transactions on Computer Human Interaction (ACM TOCHI) (Greenhalgh and Benford, in press, 1995).
- The definition and exploration of user-embodiment issues (i.e. how to represent participants in CVEs to one another). This work has recently been presented at ACM CHI'95 (Benford, Bowers, Fahlén, Greenhalgh and Snowdon, 1995).
- The development of techniques for multi-user information visualisation, resulting in the concept of Populated Information Terrains (PITS). This work will appear in a forthcoming paper in the MIT Press journal *Presence* (Benford, Bowers, Fahlén, Mariani and Rodden, in press, 1995).
- The development of distributed architectures for CVEs. A paper describing key distributed systems techniques (e.g. spatial trading) has just been presented at the 15th IEEE Conference on Distributed Computing Systems (ICDCS'95) (Greenhalgh and Benford, 1995)

Notable research projects which act as the technical baseline for this project include:-

COMIC

COMIC was a multi-disciplinary Esprit III Basic Research Action into CSCW (project 6225). One aspect of this work has involved the development of spatial techniques to support cooperative work and the construction of shared virtual environments.

VIRTUOSI

The largest of the projects in the UK's EPSRC/DTI JFIT programme on CSCW, this project is examining the use of space as a means of supporting cooperative work. The project involves three universities working in close co-operation with a number of companies (including BT, GPT, GEC Hirst Research Centre, Division Ltd. and BICC) to construct and pilot industrial examples of CVEs.

DEVRL

This EPSRC funded project (under the ROPA scheme) focuses on the development of a wide area virtual reality laboratory. As part of this work, virtual meetings have taken place over SuperJANET at regular intervals. These have recently been extended to include sites from continental Europe.

VISAGE

A feasibility study funded by the ESRC into the use of CVEs combined with Geographical Information Systems to support the process of collaborative environmental planning and consultation with the public. This project provides a concrete example of an end-user application of CVEs and has provided an opportunity for interaction with potential end-users of such technology.

COVEN

A new project, starting in October 1995, funded under the EC IV Framework ACTS programme. COVEN will construct a European wide demonstrator of a CVE to support both business users and citizens in travel shopping, planning and rehearsal.

Between them, these projects demonstrate a range of activities from basic research through to pre-competitive industrial research. In particular, Dr Benford 's research has involved funded collaboration with a number of companies including:

- *British Telecom* - collaboration includes Virtuosi, supervision of part time PhD students, running networked trials of CVEs between Nottingham and BT Labs at Martlesham Heath and a new BT directly funded project under the BT/JISC Research Collaboration Programme.
- *Division* - collaboration includes the Virtuosi and COVEN projects.
- *BICC* - collaboration via the Virtuosi project.
- *GPT* - collaboration via the Virtuosi project.
- *British Gas* - collaboration via a British Gas funded PhD studentship.
- *Thomson CSF* - collaboration via COVEN.
- *KPN* (Dutch Telecom) - collaboration via COVEN.
- *TNO* (Dutch research company) - collaboration via COVEN.

Dr Benford also collaborates with several international research laboratories including:

- *The Swedish Institute of Computer Science (Sweden)* via the COMIC and COVEN projects.
- *GMD (Bonn, Germany)* via the COMIC project.
- *EPFL/University of Geneva (Switzerland)* via the COVEN project.

The primary contribution of Dr Benford's previous research to the UK's competitiveness has been:

1. Helping UK VR manufacturers with new techniques and mechanisms for extending current products towards increased support for networking and cooperative work.
2. Helping companies in the telecommunications arena (i.e. BT and GPT) gain an understanding of future telecommunications applications and the demands.
2. Helping end user companies such as BICC and British Gas understand the improvements in work practices and efficiency that might be gained through the future application of CVEs.

Contributions to improving the quality of life for UK citizens include the VISAGE project which aims to enhance public understanding and consultation for environmental planning issues and also the use of CVEs to support tele-shopping as will explored in the COVEN project. In a more general sense, it could be argued that by focusing on support for social interaction, Dr Benford's work is also striving to enhance the usability and enjoyablilty of tele-communications applications for the general citizen.

Research expertise within Dr Benford's laboratory includes the development of VR applications, distributed systems and networks, multi-media and HCI. In particular, several current researchers, especially David Snowdon and Chris Greenhalgh, have already established research reputations of their own and will be able to contribute to the project.

Part 2: Description of the proposed research and its context

A. Introduction

Many applications including interactive home entertainment and battle field simulation are set to drive the development of very large scale distributed virtual reality systems. For these applications to be successful they must be responsive, allowing participants to interact with their surroundings and peers in a natural manner. An issue of prime importance in the usability of a virtual reality system is that of local latency which causes disorientation and in some cases may result in nausea (Regan and Price, 1993). Considerable investment has been made to reduce the latency on single user machines, but as the transfer of information is ultimately constrained by the speed of light, communication between physically remote peers will inevitably incur much higher, unacceptable delays.

This proposal focuses on the development of a unified kernel, based on an underlying time parameterised environment model incorporating time based reasoning, which reduces latency by anticipation and advance communication of events. This kernel will be designed with the emphasis on providing manageable and scaleable services for a very large number of users, interacting in real time. The kernel will be validated by comparing its performance and usability against that of an industry standard approach. A test group consisting of sites in both the UK and USA will be set up for long distance multi-user testing.

Large multi-user virtual reality systems offer a considerable economic generation potential from applications such as interactive home entertainment but can only be realised when the issues of overcoming network induced latency are addressed.

B. Scientific/Technological Relevance

Large multi-player systems such as the DIS based NPSNET (Macedonia, 1994) are not temporally based. The replicated database relies on events being communicated to each replication. Delays in this communication cause the event to be reproduced out of synchronisation, resulting in moving objects appearing in different position to various users. This makes close user interaction, such as passing an object, unworkable. Consistency control has been incorporated in the DIVE system (Carlson, 1992) but relies on centralised control making it unscaleable and, as no prediction algorithm is employed, results in excessive latency.

A distributed virtual reality system should be scaleable, responsive and consistent. Current systems exhibit some of these criteria but the philosophy of their design precludes them from meeting all three. Latency caused by communication delays may, in many cases, be eliminated by predicting events and communicating them in advance. This theory may also be applied to consistency control through anticipating ownership requirements, allowing virtual objects to be smoothly exchanged between users. This project aims to promote the combination of these techniques with scaleable communication protocols and group interaction abstractions in the design of a responsive and consistent multi-user systems. It is hoped that this project will redirect other research away from the current state-based philosophy and, through key industrial and academic links, will provide important direction in the creation of standards, feeding technical information to industry.

The time of commencement of this project is of paramount importance as a peak in expenditure in the development of multi-player systems is expected and no standards are in place which adequately address the issues of network induced latency.

C. Relevance to Beneficiaries

Multi-user virtual reality has the potential to generate a huge market in areas such as home entertainment, computer supported co-operative working, teleconferencing and large scale simulations. Virtual reality is also thought to have the potential to reduce product lead times by allowing designers and engineers to work with the same model (Warwick *et al*, 1993). Such a system would be particularly useful if the engineers and designers could work as a group on the model. This can only be realised if the issues of low latency consistency control are tackled.

The UK is presently in a strong position in the VR industry, being home to three of the most successful VR companies, a world leading telecommunications company and a number of good academic research groups working in the area. By combining the VR and telecommunications expertise with that of academic research, the UK has the potential to become a world leader in the multi-user market. To achieve this, it is vital that the UK should have input to the creation of standards. Current standards do not adequately address the issue of communication delays and therefore a key aim is to influence applicable standards such as the Distributed Simulation Standard (ANSI/IEEE1278-1993 - DIS) and the Virtual Reality Mark-up

Language (VRML). This will also reduce the development costs of companies who might otherwise expend great time and effort trying to implement unsuitable standards.

This project is strongly supported by BT and Silicon Graphics. BT are providing equipment, software and maintenance at a list price cost of £61,178, and over the duration of the project will provide five days per year use of their reality centre costed at £15,000, management input of one man day per month costed at £12,600 and travelling expenses for meetings and annual extended stays at their reality centre costed at £1,150. BT are investigating the possibility of purchasing immersive equipment at an approximate cost of £30,000, which may be loaned to the project. Silicon graphics are providing 20 days per year access to their reality centre and one day per month management input costed at £90,000. Written statements from both industrial collaborators are given in Appendix I.

D. Dissemination and Exploitation

Quarterly formal meetings will be held between all participants, to which an EPSRC representative will be invited. Reports to all collaborators will be provided by Reading and Nottingham at key milestones, as shown in part 3. Silicon Graphics will establish key links into standards committees, which will be exploited by Reading, Nottingham and BT. BT are presently investigating strategies for influencing VR related standards and intend to use these to disseminate information from this project. Results will be propagated through international journals and conferences.

Exploitation is presently under negotiation between the four parties.

E. The Programme

The primary objective of this project is to promote the importance of predictive, real-time philosophy in the design of distributed, multi-user virtual reality systems. It will then be shown how this can be combined with group interaction and scaleable protocols to produce a responsive, consistent and expandable system. A secondary objective is to influence standards including DIS and VRML. The aims are to develop a unified real-time kernel based on these principles, formulate a test group consisting of sites in the UK and USA and compare the performance and usability of the kernel with that of a system based on current standards. A suitable test application will be developed to demonstrate the key issues and assess the two kernels.

The Silicon Graphics Reality Centre represents a £2 million pound investment focused on the development and demonstration of leading edge computer graphics techniques. With its three channel wraparound display, it is the most advanced facility of its kind in Europe. BT are currently commissioning their own Reality Centre at Ipswich. The principles developed within the project will be used to link the BT and Silicon Graphics Reality Centres and later, it is hoped, incorporated in commercial applications produced by both companies.

The workload will be split between the Universities of Reading and Nottingham with the project management being undertaken at Reading.

E.1 Goals

The real-time kernel will exhibit the following features:

1. Regardless of communication delays, the position of a moving object will be presented consistently to all the users once that object’s last change in velocity has reached each user’s machine.
2. The effect of latency induced by distributed consistency control will, in most interaction scenarios, be significantly reduced when compared to non-predictive methods and in many cases eliminated.
3. Perceived latency to be consiedrably less dependent on communication bandwidth (over current systems, e.g. DIS).
4. Provision for the expansion of the number of users without adversely affecting perceived latency.

E.2 Assessment Criteria

1. Consistency of position of objects presented to each user compared to the DIS kernel.
2. Latency incurred by consistency control compared to DIVE.

3. Scaleability in terms of bandwidth requirements, reliability and time taken for communication compared to DIS kernel.
4. Usability of the system for close user interaction compared to DIS kernel and DIVE.

E.3 Project Outline

Requirements Analysis

A brief review of current and future applications will be undertaken with an aim to finding general application requirements of a generic multi-user virtual reality system. A more thorough analysis will then be made of the test application, both in terms of its own functionality and of the requirements it places on the supporting kernel. Current multi-user systems will be investigated to quantify their strengths and weaknesses. Network testing will be carried out between participating sites to find the limits over which the kernel is expected to work. Finally, from the above findings, a detailed requirements analysis will be generated for the kernel.

Example Application

An example application, the Virtual Arena, will be developed to compare the two kernels with regards to the assessment criteria. The Virtual Arena will be in the form of a multi-player ball game incorporating limited audience participation. The ball game will quantify the first of the above assessment criteria and the audience participation will quantify the third and fourth.

Development of DIS kernel

To act as a comparison, a kernel based on the commercial VR-Link DIS development platform will be assembled. This should, within the constraints of the toolkit, attempt to meet the kernel requirements.

Development of Real-time kernel

The real-time kernel will be based on a synchronised, real-time, distributed database. Consistency control will rely on atomic object ownership, with ownership prediction utilised to overcome network induced latency. Collision prediction for parametric object movement, combined with ownership ability, will act as a criteria for ownership prediction. Communication of state changes will be restricted to non-deterministic events, all deterministic changes such as a ball bouncing off a wall, will be calculated locally. Multicast protocols will be used to send changes simultaneously to all participants and infrequent changes backed up through a reliable protocol. To reduce latency and increase scaleability, tasks such as user to user collision detection, downloading the database to new users and backup of infrequent events will be performed remotely from the user machines.

E.4 Development Model

The development will be based on a spiral process model which reduces risk through repeated evaluation by prototyping and, verification and validation of the software engineering product. The scale of work between each evaluation increases as the project progresses. This project will develop in the following steps:

1. Requirements analysis - *Reading and Nottingham*
2. Initial prototype - *Reading and Nottingham*
3. Requirements specification - *Nottingham*
4. Requirements validation - *Investigators & BT*
5. Development plan - *Reading*
6. Risk analysis - *Investigators & BT*
7. Prototype - *Nottingham*
8. Design - *Reading*
9. Design verification - *Investigators & BT*

10. Implementation and rapid prototyping - *Reading and Nottingham*
11. Test and evaluation plan - *Reading*
12. Test and evaluation plan verification - *Investigators & BT*
13. Testing - *Reading and Nottingham*
14. Evaluation - *Reading and Nottingham*

An object oriented design methodology will be undertaken as this is particularly suited for real-time, parallel and visual systems (Jones, 1990). This methodology also lends itself well to bottom up development where aspects of the design cannot be anticipated, in other words, research. The object interfaces and functionality will be based on the requirements specification. Object oriented implementation will simplify the unification of work carried out at the two academic sites. As this project is research based, the emphasis will be on rapid prototyping.

E.5 Workplan

The project will run for three years. The workplan involves two iterations of a design, implementation and experimentation cycle. The first short iteration (one year) aims to provide rapid initial experience which will inform the second longer iteration (two years) from which final results will emerge.

Iteration 1

Work will begin with a requirements analysis involving BT which will finalise the key distributed systems techniques to be explored. A concurrent workpackage, also involving BT and SG, will design the Virtual Arena testbed application. Following this, Reading and Nottingham will each implement a version of the Virtual Arena on top of their own existing distributed VR platforms (PaRADE and MASSIVE respectively). This will be followed by an initial experimental phase which will test the performance and scaleability of the two implementations between Reading, Nottingham, BT and possibly SG and other sites over the Internet. These first experiments will serve to validate the application design, will produce some preliminary results concerning possible distribution techniques and will inform the design of more detailed experiments for the second iteration.

Iteration 2

The second iteration will begin with the design and implementation of a single real-time kernel which will combine the best aspects of PaRADE and MASSIVE with other key distribution techniques that have been identified. In parallel with the construction of the kernel, the reference DIS implementation of the application will be constructed. Once the kernels are complete, the Virtual Arena application will be ported to both, giving two available implementations, one based on DIS and one on our own kernel. In parallel with porting activity, final experiments will be designed in detail. The final six months of the project will be spent running these experiments in order to compare the two implementations and validate our proposed techniques.

These activities are reflected in the following twelve workpackages (WP) each of which produces a deliverable (D).

(Total project effort = 72 person months)

WP1: Requirements analysis (3 person months)

Producing a set of requirements for the distributed VR kernel

D1: Requirements for the distributed VR kernel (report)

WP2: Testbed application design - the Virtual Arena (3)

The design of the Virtual Arena application

D2: Application design (report)

WP3: Reading prototype application (6)

Constructing an initial application prototype using Reading's current implementation of PaRADE

D3: Reading prototype (software and report)

WP4: Nottingham prototype application (6)

Constructing an initial application prototype using Nottingham's MASSIVE system.

D4: Nottingham prototype (software and report)

WP5: Testing of prototypes (3)

Evaluation of the prototype applications constructed at Reading and Nottingham.

D5: Report on the prototype application performance (report)

WP6: Design of the distributed VR kernel (3)

The detailed design of an architecture for the VR kernel informed by experience with the prototype applications.

D6: Final VR kernel design (report)

WP7: Implementation of the testbed application using DIS (6)

The application designed in year one is implemented using a DIS toolkit

D6: DIS testbed application (software and report)

WP8: Implementation of the distributed VR kernel (18)

The distributed VR kernel is implemented

D6: Distributed VR kernel (software and report)

WP9: Porting the testbed application to the distributed VR kernel (9)

On completion of the distributed VR kernel, the testbed application is ported to it.

D6: Testbed application (software and report)

WP10: Design of evaluation procedures (3)

A series of final experiments are designed in order to examine the performance of the two final implementations of the testbed application.

D6: Evaluation procedure report (report)

WP11: Evaluation of DIS and VR kernel performance (9)

Performing the experiments designed in workpackage 10.

D6: Final project report (external report)

WP12: Project management (3)

Holding quarterly project meetings, co-ordinating deliverables and publicity.

E.6 Milestones

Progress will be checked against the following milestones:

M1	**Project start -** contracts have been agreed and signed; staff have been appointed.
M2	**Design ready -** prototype applications have been constructed and tested and VR kernel design is complete.
M3	**VR kernel ready -** the testbed application has been implemented and the VR kernel implementation is complete.
M4	**Project end -** evaluation complete and the final project report has been written.

F. Management and Resources

The project will be under the supervision of the principal investigator Dr Paul Sharkey and co-investigators, Dr Steve Benford and Prof Kevin Warwick. Day to day management will be carried out at each site by Dr Sharkey and Dr Benford, being responsible for the technical RA supervision. Teleconferencing facilities will be used daily to enhance co-operative working between Reading and Nottingham. Monthly meetings attended by investigators and RAs to generate and monitor short term targets. Quarterly meetings will replace each third monthly meeting and be attended by all collaborators. These quarterly meetings will include a formal presentation by each RA and produce an agreed plan of work for the next three months. The investigators will also be responsible for risk analysis and verification of requirements specification, design and test and evaluation plan. To meet the project goals in terms of building the kernel, it is necessary to employ two RAs, one at Reading (RA1A) and one at Nottingham (RA1A). The distribution of labour between the two sites will simplify testing across the Network and combine the strengths of both research groups.

The resources provided by BT and Silicon Graphics are detailed and costed in section C (Relevance to Beneficiaries).

F.1 Reading

The RA1A at Reading will be responsible for project co-ordination, which will include management of prolonged testing between at least six sites. This project extends the research carried out by David Roberts for his PhD. He has initiated this project, been influential in obtaining the industrial collaboration and has already established a potential test group. David Roberts, who has been identified as the researcher at Reading, has the technical knowledge for this project, an industrial background in project development and systems engineering and, within the department, has proven his ability for group organisation in successfully running a workshop and editing a book (Warwick *et al*, 1993) within demanding timescales. David Roberts lectures VR for the BSc and MSc Cybernetics courses at Reading and lectures the VR unit of the MSc Information Technology course at the University of Warwick. Until the appointment of Dr Sharkey, he managed the VR research group. In his spare time, he is engaged in a project to find, analyse and promote possible applications of VR for people with disabilities.

All major equipment costs at Reading are being covered by BT. Other equipment needed includes a DAT drive for backing up work costed at £700, and the cost of adding the two Silicon Graphics computers at Reading to a dedicated Mbone FDDI subnet. costed at £15,000. An allowance is also required for telephone calls to the USA sites estimated at £500. Reading University will provide access to a second Silicon Graphics workstation and a number of Sun workstations.

F.2 Nottingham

Nottingham requires a Silicon Graphics Indy workstation with extra memory to support simple graphics. Complex graphics will be tested on existing Indigo Workstations.

F.3 Travel

It is expected that there will be at least six international conference attendances, two of which will be coupled to visits to the USA test sites at a total estimated cost of £6,000. One annual extended visit to Nottingham is estimated at £900. 15 visits to the BT Reality Centre will be covered by BT. Regular visits to Silicon Graphics Reality Centre will be covered by Reading.

Part 3: Diagrammatic Project Plan