Virtual Reality for Inspection, Maintenance, Operation, and Repair of Nuclear Power Plants

(VRIMOR)

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# TABLE OF CONTENTS

1 EXECUTIVE SUMMARY

2 DETAILED FINAL REPORT

2.1 Objective and Strategic Aspects

2.2 Scientific and Technical Description of the Results

2.2.1 User Requirements and Functional Specification
2.2.2 Human Modelling Interfaces
  2.2.2.1 Voice Activated Control
  2.2.2.2 Mouse Activated Control
2.2.3 ALARA Assessment Tools
  2.2.3.1 Radiological modelling
  2.2.3.2 HUMAN MODELLING ANALYSIS
  2.2.3.3 Body Part Trajectory Analysis
2.2.4 Environmental Scanning and Data Manipulation
  2.2.4.1 Laser Scanning and Data Presentation
  2.2.4.2 Gamma Scanning and Analysis
2.2.5 Project Evaluation Exercise

2.3 Assessment of Results and Conclusions

2.4 Acknowledgements

2.5 References

3 MANAGEMENT FINAL REPORT

3.1 List of Deliverables

3.2 Comparison of Initially Planned Activities and Work Actually Accomplished

3.3 Management and Co-ordination Aspects

4 SUMMARY OF FINAL REPORT

4.1 Objectives

4.2 Research Performed and Methods Adopted

4.3 Main Achievements

4.4 Exploitation and Dissemination
1 EXECUTIVE SUMMARY

The main objective of the VRIMOR Project was to develop a methodology and demonstrate the viability of minimising occupational exposure, reducing safety risks, and minimising costs associated with manual maintenance and other activities on operational nuclear power plant. The Project involved the development of computer simulation and radiological dose analysis tools together with their human computer interfaces. It also included the enhancement of existing radiometric and geometric scanning facilities that provided data for a comprehensive virtual environment in which to develop, rehearse and assess manual intervention tasks. The Project involved the integration of these technologies to satisfy an operator’s need to plan these tasks with greater ease and confidence than was presently available. The degree of success was measured during the application of the integrated system to a regular maintenance task at the Almaraz NPP in Spain towards the end of the Project programme. A characteristic of the developments was that there was a series of parallel streams, which allowed cross-comparison of techniques and provided a degree of interchange-ability for the subsequent exploitation of the developments.

As the successful integration and demonstration of the technologies was key to meeting the Project objective, considerable effort was expended by the Partners in designing the interfaces and planning the test intervention. This resulted in a top-level design document that reflected all the systems involved and the data interfaces to be adopted. All these interfaces were successfully tested. With respect to the intervention tasks, several iterations occurred in order to ensure that the evaluation exercise was achievable, meaningful and had the potential to provide measurable benefits. One of the critical developments was the gamma scanner system that was used in its prototype form to demonstrate the data gathering, conversion and sharing aspects of the project under laboratory-controlled conditions. This proved valuable in determining required improvements, calibration issues and demonstrating the data exchange process. The human computer interface development programme resulted in the successful demonstration of mannequin control via voice recognition and a six-degree-of-freedom mouse. All these demonstrations were completed in the first half of the Project programme and provided a high degree of confidence for the successful development of the final integrated system.

The second half of the Project programme involved the completion of the individual tool developments, the application of the scanning technologies to the candidate test site at Almaraz NPP, the manipulation of the resulting data and preparation of the virtual scenarios, the presentation to and training of NPP staff in the application of the tools, and the gathering and analysis of user feedback. Although the opportunity to interface with NPP staff was limited by their availability, they exhibited significant enthusiasm and provided very positive feedback on the suite of tools developed. There were some difficulties with the prototype tools but these have either been overcome or future developments identified to solve them. A conservative cost-benefit analysis has demonstrated a potential payback period of less than two years making the overall system very attractive to NPP operators.

Although the Project aim was to develop and demonstrate the integration of technologies from different Partners, each development is re-usable and has the potential be combined with other technologies or to be used in isolation. For example, the development of intuitive mannequin controls for human modelling programmes can be used for applications in all industries. To assist with this subsequent exploitation, open standards have been used where possible for the data exchange interfaces. The system has been developed to satisfy a perceived need at NPP and has been successful in that context. The feedback received from the evaluation exercise has identified
improvements that can be made and helped to identify the best opportunities for future exploitation in nuclear power and other industries.
2 DETAILED FINAL REPORT

2.1 Objective and Strategic Aspects

The VRIMOR project is very clearly focused on NPP inspection, maintenance and repair teams and subcontracted staff. Although some of the equipment will be provided and used by consortium partners, computer-modelling tools will be provisioned for use by NPP staff at the candidate test site. The successful demonstration and acceptance by these workers of the technologies developed here is the key to the further exploitation of the work. This includes not only the use of the combined technologies to provide an improved method of task planning, but also the effectiveness of the human computer interfaces (HCIs) developed for their use.

The objective to achieve standards for data exchange within the project remains an important aim. The software developments undertaken in the Project are demonstrating the feasibility of providing user interfaces for non-expert users to encourage the uptake of the potentially powerful human modelling techniques available commercially. The VRIMOR Project vision also remains that these tools should be available at low cost on desktop computers within 3-4 years of project commencement.

It is similar for the scanning facilities that are being developed and interfaced within the project. The core technologies associated with these facilities are continually being developed such that their costs and performance should result in purchase and rental prices that are within reach of NPPs or utility companies within a short period after project completion. Already, within the first part of the Project, the next generation of laser scanner has been constructed and the gamma-scanning prototype has been improved significantly. The establishment of interfaces using the facilities available within this project will shorten the time to market and contribute to the development and marketing of the technologies ahead of their potential commercialisation.

It is anticipated that technological developments arising from the project will be published in the scientific press subject to approval by the consortium and the Commission. The Project has been presented at the FISA 2001 Conference, is referenced on Partners websites, and it is intended to be presented at a forthcoming ALARA conference.

Having identified the end users and the project aims, it is clear to see that the competitiveness of EU nuclear utilities will be improved from the adoption of technologies developed within this project. Productivity should increase as a result of reducing outages through the effective use of these technologies. As a consequence, costs will be reduced through more efficient working and the removal of project risk while safety and human reliability will be increased as a result of improved planning and training of staff. These measures will be addressed during the evaluation exercise at the Almaraz NPP and results incorporated into the final report.

Although directed towards NPP inspection, maintenance and repair applications, which provide a significant market, it is also applicable to decommissioning applications, which provides a substantial growth market. Other related industries such as fuel reprocessing and manufacture will also have potential use for the technologies being developed here.

The overall social aims of the VRIMOR project are to improve the working conditions for staff associated with activities in radiological controlled areas. This will be achieved through a
combination of aspects that will result in the nuclear industry becoming a more attractive place of employment.

The developmental aims of the project are to deliver tools that the mission team can use directly without the need for additional expertise. This contributes to the improvement of working conditions by facilitating technologies directly to those that can benefit from it without having to invest in extensive retraining and skill development programmes. Indeed, the training programme for the evaluation exercise has been explicitly kept short to demonstrate this aspect. Because the information is captured digitally it can be easily moved around the Community to gain knowledge and opinion from other areas of expertise if required. Equally, the optimised mission sequences can be submitted to other NPPs for them to use in addressing similar mission requirements.

Overall, the VRIMOR project aims to demonstrate that better assessments of worker operations in radioactive areas can be carried out leading to improvement in working conditions. This could be a leading initiative to standardise and regulate improvements of this nature throughout the Community.

Many of the current operating facilities in Europe were designed or built during the 1970s or earlier. The majority of information about these facilities is therefore only available in formats that were available at that time. Furthermore, the provisions for safety and the proposed working practices are a reflection of the technologies and regulatory requirements at that time. Repeatedly plant operators today are frustrated by this situation and have to carefully balance safety and cost on an ad hoc basis. The VRIMOR project aims to facilitate a suite of technologies that can help plant operators overcome this dilemma in a cost-effective manner.

In particular, the project aims to develop tools that will facilitate the use of modern advanced technologies to plant operators in order that they can improve the safety and reduce the costs of their inspection, maintenance and repair operations. This complies with the Community’s overall policy of striving to maintain and improve the competitiveness of the Industry within Europe. In view of the reusability of computer models the application of these technologies will also assist in the maintenance of competences in the industry by providing effective training material. In addition, the VR tools that are being developed can be used to assist with public awareness and the enhancement of public acceptance of nuclear energy.

### 2.2 Scientific and Technical Description of the Results

#### 2.2.1 User Requirements and Functional Specification

**THE POTENTIAL VRIMOR CONTRIBUTION TO THE PROCESS IMPROVEMENT**

The prediction of the expected doses, the evaluation of the physical viability of the task, and the schedule of the training in specific tasks, are currently conventionally performed, using a variety of separated methods (approximated calculations, visual inspections, operative experience, mock-ups…). Taking this into account, an integrated and automated environment can provide many operative and economic advantages. If besides of this, the methodology has enough capability of generalisation, the additional advantage is the availability of a data exchange format and experiences between specialists, not available at the moment. This capability allows that for a
specific operative situation, this can be evaluated and solved in a co-operative way, not just counting with the Plant personnel.

VRIMOR methodology gives the possibility of simulating a specific task in a virtual reality environment, which represents the area where the real job is going to be carried out. The system also provides the area dose information, which allows obtaining the approximate dose received by the workers during the task performance and above all, to compare different options.

Based on the information gathered during the project, it is thought that this application can provide the following improvements to a typical work methodology in any NPP:

- The system can help the Radio Protection Service to improve the accuracy of the predicted doses taken by the workers.
- It can be also used to test the feasibility and effectiveness of candidate mitigation strategies, such as to see how doses can decrease adding a shield or changing the suitable geometry of the area.
- The system can be used to test maintenance strategies. The application of the virtual reality technology can help the Maintenance Service to see if the equipment can be moved easily inside the area.
- It also can improve the maintenance training, showing to the work team the correct task performance, how to manipulate the tools, where to spend the waiting minutes, the time needed to carry out the task, etc.
- If the simulated area has constant or predictable radiological levels, then this system can save doses for the radiological protection technicians, who would not have to enter so many times to take radiological measures.
- The system can also save doses for those people who would enter in the area previously to the task performance to visualise the environment distribution, to check if there is enough room, to train in a specific task, etc.

USER REQUIREMENTS

Under the final user perspective, a methodology similar to the proposed one, has to consider the following aspects:

- **Versatility**- This means that this methodology must be able to accommodate different operative plant situations (different areas, different dose levels and different tasks).
- **Quick response capability**- The time spent using this methodology should not be higher than the time spent following the current practices.
- **Affordable Cost**- VRIMOR methodology should have a justified cost compared with the current situation. This cost must be assumable by the Plant, based on its utilisation, and the savings both in dose and time must be taken into account.
- **Reasonable Realism**- This methodology should be able to represent the reality as faithfully as possible in all the following aspects: geometry of the area, radiological parameters, components, and tools.
- **Portability**- This application should run preferably in a PC.
Ergonomics- The interaction of the user with the application should be ergonomic.

Licensing issues (if any) - The application of this methodology does not require any kind of Regulatory License nor to be supervised by the Regulatory Body.

Validation capability- VRIMOR methodology should be able to be validated against some evaluation criteria.

Documentation- A well structured and simple user manual is required.

Low Maintenance Cost- The maintenance of the applications must not imply an excessive cost. VRIMOR methodology should try to minimise the use of external software licenses, which versions can change outside the project control. Software stability must be guaranteed for a reasonably period of time.

Training needed- The use of the applications should not require a very complex training either a long one. It must be easy to use.

EVALUATION CRITERIA

These are the evaluation criteria related to the formerly defined user requirements:

1. The application of the methodology to be developed should imply an improvement compared to the current practices in terms of total doses received during the whole process, an improvement in cost terms and in safety.

2. The application of the methodology to be developed should imply an improvement compared to the current practices in terms of cost.

3. The proposed methodology should be flexible enough as to allow its use in several plant areas and tasks.

4. The simulated results should be in a reasonably agreement with the real ones.

5. The application of the proposed methodology should not result in unacceptable contamination levels of the involved equipment.

6. The time needed to apply the proposed methodology should be as a maximum the current one.

7. The proposed methodology should ensure the Software portability.

8. The proposed methodology should be Ergonomic.

9. The proposed methodology should be well documented.

10. The proposed methodology should have a low maintenance cost.

11. The proposed methodology should need a little training.
FUNCTIONAL SPECIFICATIONS

VRIMOR system consists of 5 interconnected subsystems each of one having a particular set of functionalities. The 5 subsystems are the following ones:

1. Geometrical data capture subsystem (S1) (Z+F, UK)
2. Radiological data capture and dose map generation subsystem (S2) (CIEMAT)
3. Task planning and dose estimation subsystem. (S3) (NNC)
4. Task planning and trajectory generation subsystem. (S4) (UPM).
5. Dose estimation subsystem (S5) (SCK)

Subsystem S1 captures the geometrical environment using a laser device that generates a digital image in XYZim format that is read by advanced software called Light Form Modeller (LFM). With the aid of this tool it is performed a post-processing in order to create a 3D CAD model. The model is exported in two formats: VRML surface model format (to be used by S2, S3, S4 and S5) and 3D simplified model –solid primitives-, in a MDB format (to be read by S5). Once a full 3D model is obtained by using LFM, the VRML file is generated whereas the simplified 3D model has to be created by the end user taking into account the relevant present objects (sources, shielding, etc). The VRML model also contains the S2 raw data (measured energies/isotopes and scanning positions). The end user may visualize the virtual world, the associated radiological data and the selected 3D simplified geometry.

Subsystem S2 is integrated by 2 subcomponents. The first one, by using a radiation detector EDR, captures the environmental radiological information and produces a file in the format (X,Y,Z, energy spectrum) for each scanning position that is then normalized using the ANSI Standard Energy Index (divided into 25 energy bands), which is called S2 ANSI rad data. These radiological data are fed into LFM (S1) and is also used by the second subcomponent which makes a post processing of this radiological information together with the geometrical one (using the VRML 3D surface model generated by S1), in order to estimate the sources originating the radiation field with the assumption of superficial sources. Based on this and using additional algorithms, a dose rate map (dose grid) in the complete modelled area is generated to be compared to the one created by S5 (see bellow VISIPLAN).

Subsystem S5 consists of two parts: the first part, VISIGAMMA, uses both the ANSI rad files and the VRML 3D surface model in order to make a first source estimation (equivalent source approach) and to calculate dose rate maps in the area viewed by each S2 scan. The second part, VISIPLAN, is one of the three end-user packages and reads data from VISIGAMMA (dose rate map in the area viewed by each S2 scan), LFM (3D simplified model in MDB format) and the end user (materials information) in the same MDB format. As output data, it provides a MDB file (shared with S1) containing the final estimation of sources associated to objects and the dose rate map (dose grid) of the environment in the same format as S2.

The end user functionalities are: dose assessment given a trajectory and a dose grid size (base case, using trajectories generated by S4 or S3) and sensitivity analysis on the base case (geometry, sources, shielding and dose rate variations)

Subsystem S3 is the second of the three end-user packages. Receives the VRML 3D model from S1 together with the file containing the dose rate map (dose grid) generated by S5 or S2. Using the information provided by the plant related to the task to be performed, the mannequin(s) is manipulated by the end user through a 6 degree of freedom (d.o.f.) user interface device and a
mouse. Programming speed is enhanced by the use of a stereo viewing system which will provide
the user with depth perception. The system facilitates storage and retrieval of the mannequin
simulation and also calculates the doses received by the mannequin(s) for the task and alternatively
the trajectory.

Finally, Subsystem S4 is the last of the three end-user packages. It reads the same information as
S3: namely the VRML 3D model from S1 together with the file containing the dose rate map (dose
grid) generated by S5 or S2. In this case, the mannequin(s) is manipulated using an integrated UGI
and voice driven user interface and, contrarily to S3, it does not provide directly the dose estimation
but only the trajectory generated by the mannequin during the task execution which, in turn, is used
by S5 to estimate the doses received during the simulation.

2.2.2 Human Modelling Interfaces

Dose assessment and task planning have traditionally been carried out using two-dimensional
layouts with discrete calculations used to estimate the operator dose at a number of key locations in
which the operator will be working. The objective is to establish the most effective way to carry out
a task while achieving the lowest practical dose level.

There is scope to improve this planning and assessment process through the use of modern human
modelling software programmes. However, these tools are in general complex and require
significant training and continuous use to maintain adequate user competence. The VRIMOR
Human Modelling work packages were designed to provide improved control for some of these
programmes in order that non-expert users could produce human activity simulations quickly with a
minimal level of training. Two independent systems have been developed; a voice-controlled
interface that provides a library of commands to move the human model, and a joystick or mouse
driven interface. These are described in the following sections.

2.2.2.1 VOICE ACTIVATED CONTROL

General Description

UPM has developed a planning and simulation tool, called HESPI, based on a combination of a
graphical user interface and a voice interface. The goal of HESPI in the VRIMOR project is to help
the personnel of a nuclear power plant in the design of an intervention. The expected users of the
tool are the specialist in maintenance in the nuclear power plant and, secondarily, the specialist in
radiological protection.

The design of an intervention implies making decisions about how many operators will participate
in the intervention, the actions to be performed by all of them, the paths to be followed by each of
them through the controlled environment, the time required for each action and the necessary
interaction among operators.

HESPI takes as input a geometrical model of the environment where the intervention is going to
take place. This geometrical model, in VRIMOR, has been produced with the laser scanner
provided by Z+F but, in general, any model in the VRML language can be imported into HESPI.

The tool provides the designer of an intervention with a humanoid 3D model or mannequin that can
be loaded into the desired environment and will be used by the designer as if he was manipulating a
puppet. The 3D humanoid model that is used by the HeSPI tool is called Jack, and is commercially distributed by EDS. Jack is a very complex and powerful mannequin, with many degrees of freedom, inverse kinematics, and ergonomic constraints. However, it requires a long training to be able to design simulations by using the tool provided with Jack. The main challenge of HeSPI was to encapsulate Jack into an easy to learn user interface, taking into account that the intended users are not expected to have experience in the usage of three-dimensional applications, and they are not willing to spend a long time learning to use tools such as Jack. Our hypothesis was that a combination of a graphical user interface (GUI) and a voice recognition system would offer good enough interaction possibilities for the success in the objectives of the project.

In the design of an intervention it is also important to minimize exposure to radiation, both to individual operators and collectively. This goal is achieved by exporting from HESPI the trajectories that have been followed by each of the virtual operators in the simulation of the designed operation. These trajectories can then be imported into the VISIPLAN tool, provided by SCK CEN, that allows the analysis of the designed intervention from the radiological point of view. Test trajectories have been successfully exported to and analyzed by the VISIPLAN tool.

**Design Approach**

The design of the HeSPI human modelling tool was strongly oriented towards the requirements and characteristics of the final user of this tool. Our previous experiences in the development of systems based on the use of virtual environments for this kind of users (we had already developed some training applications for NPP personnel using 3D environments) indicated that NPP personnel are not used to interact with computer programs in general, and most of them have never used a 3D interface before.

Therefore, usability became our main design criterion and success measure. We have followed a usability-oriented development process in which a usability expert was deeply involved and supervised the technical developments at each stage of the process. Feedback from real users would have been desirable but the availability of NPP personnel in this project was limited to the final evaluation session.

Simplification of the user interaction with the mannequin is mainly achieved in HeSPI through two mechanisms:

- a voice recognition package
- a pre-defined set of generic and configurable mannequin actions from which the user can select the desired ones.

**Voice recognition**

In the design of HeSPI we considered that issuing voice commands was a natural way of composing a new intervention. We thought of the scenario as if it was a kind of theatre stage and the mannequins were virtual actors. In this setting, the maintenance specialist would act as the director, indicating each actor what to do at every moment. Voice then arises as very intuitive way of interacting with those virtual actors.

To enforce this idea, we decided to restrict the use of voice to the composition of the operation. The rest of the user interface is a conventional graphical user interface based on windows, buttons, etc. We also decided that the voice recognition could be activated or de-activated at wish by the operators. We have assumed in our design that the user who activates the voice recognition seeks
for simplicity, and is willing to sacrifice some of the flexibility provided by the tool. Therefore, when using voice recognition, some of the parameters available for the configuration of the subtasks are set automatically to the default value. The result is that the use of the tool is simpler and the design of the operation is quicker, but the precision in the execution of some subtasks by the human mannequin can be lower. Our hypothesis was that for most of the applications of this tool, the required precision would not be too high. The results of the evaluation seem to confirm that our intuition was correct. The Almaraz operators clearly preferred simplicity over precision.

Predefined generic and configurable actions

The selection of this mechanism was based on the hypothesis that most of the actions that maintenance operators have to perform in different scenarios are similar. Therefore, by incorporating into the tool an extensive set of these pre-defined actions, the design of a new intervention will consist mainly on the selection, configuration and sequencing of the appropriate pre-defined actions. Only a small number of actions will have to be built from scratch. Our internal evaluation has shown that considerable reductions in modelling time can be achieved through this mechanism.

The particular tasks that need to be modelled in a nuclear power plant have been studied in different interventions and we have abstracted from them the set of general actions that are currently pre-defined in HESPI.

Building actions from scratch is also possible in the HeSPI tool by using the facilities provided for the definition of new postures. The capability of Jack to automatically animate the mannequin from one posture to another one in a realistic way is then used for the construction of a new action as the transition from one posture to another one.

The definition of new postures in HeSPI is one of its most complex functionalities, and it is performed through a graphical user interface provided by Jack. We have experimented with the use of voice recognition for the implementation of this functionality but the results were not satisfactory, so we decided to maintain Jack’s interface, which is quite intuitive.

New predefined actions can be added to the HESPI tool. Therefore, if the tool is applied on a regular basis for the planning of interventions and the new required actions are being added to the tool, the percentage of actions to be designed from scratch will be decreasing over time and the user efficiency in the use of the tool will be increasing. This advantage of the tool has not been directly evaluated on the evaluation session in Almaraz, but we believe that it would be one very much appreciated by a regular user of the tool.

The main difficulty in the HeSPI pre-defined actions that was revealed by the observational study was that the mechanism designed to allow for the manipulation of the three-dimensional objects in the environment by the human mannequin was too complex. This mechanism is what we call “the cubes”.

The mechanism has its roots in our search for flexibility combined with easiness of use. Our solution is to add to each object in the environment with which the mannequin will have to interact, a set of 10 small cubes. 6 of these cubes will act as handles, so that the mannequin will have the built-in capability to hold the object by any of these cubes. The remaining 4 cubes will act as position markers, so that the mannequin will have the built-in capability to walk to the object and stop in front of it on the position marked by the cube. This allows the user to issue commands of the type “walk to the box”, or “grasp the box”, without having to go into a low level and detailed design of how the animation of the mannequin should be, but nevertheless obtaining a quite precise
animation. For example, when the operator issues the command “grasp the box”, the mannequin can automatically grasp the object with one hand using the closest handle cube. The attachment of the 10 cubes to the objects of the environment is performed automatically by the tool during the pre-processing step.

**Evaluation**

The evaluation of the HeSPI tool has adopted two forms:

- a technical evaluation of the correctness, reliability, efficiency and robustness quality factors of the tool has been performed by the UPM’s staff prior to the user evaluation at Almaraz
- a user evaluation at Almaraz mainly centred on the usability quality factor.

The results of the evaluation of HeSPI at Almaraz have been quite satisfactory. We can conclude that the required functionality has been successfully incorporated into the tool and that real users are able to plan and design quite complex interventions easily and quickly.

Most of the comments of the operators were quite positive, showing their interest on the methodology and recognizing its usefulness. The most remarkable drawback noted by the operators was the complexity of the applications. This, in a way, confirms the validity of the motivation of the project to build simplified interfaces to allow the use of three dimensional human simulation tools by NPP operators. These simulation tools (such as Jack or Ergo) are too complex to be used and require a high level of training and skills. We have invested our efforts in the design of simpler interfaces, and we can say that, although the complexity perceived by the operators is high, they in fact were able to design not-so-simple operations in only a few hours of training and use. Moreover the operators remarked that the voice controlled interface provided by HeSPI was especially easy to use.

**Applicability**

There are two main areas of application of the human simulation tools developed in Vrimor (specifically HeSPI) within the context of maintenance interventions in a NPP:

- Planning of the intervention
- Training of the operators that will perform the intervention

The evaluation at Almaraz centred on the planning of the intervention, and it demonstrated that one of our hypotheses (that the amount of detail required in the animations of the human mannequin for this task is not very high) was correct. The evaluators felt comfortable with the precision of the pre-defined actions provided by HeSPI.

A conclusion of our analysis is that the approach of HeSPI seems to be more suitable for applications in which the set of possible actions has been delimited and they have been incorporated into the tool as pre-defined actions, while ERGODOSE would be more suitable in applications in which the ratio of new actions over pre-defined actions to be used in the planning of a new operation is higher.

On the other hand the use of HeSPI and ERGODOSE for training has not been evaluated with real users, although the evaluators commented on the clear usefulness of these tools for this task. The amount of details required in the animations to be useful for training is still to be determined. A balance among the effort required on the part of the designer and the quality and precision of the result has to be found. Training is one of the application areas that UPM plans to pursue for the
future exploitation of HeSPI, and we intend to study how this effort-precision trade-off can be managed and incorporated into the design of HeSPI.

The NPP personnel stated that if they had the set of technologies provided by Vrimor they would use them, without any doubt, because they consider them useful. This is the most important conclusion that can be drawn from the evaluation session regarding the applicability of these tools. However, there is an issue that could stop NPPs from acquiring and applying them: the cost of the software licences. The acquisition of HeSPI requires the acquisition of a licence of the human modelling tool Jack, which is quite expensive. In order to maximise the applicability of HeSPI, the UPM’s team plans, as a future development, to substitute the human mannequin provided by Jack by our own mannequin. We already have other 3D mannequins that we have developed for other applications. We are currently implementing some of the pre-defined animations with those mannequins. What we do not have yet are the capabilities for interactive design of physically realistic animations provided by Jack.

Another extension that would improve the applicability of HeSPI would be the possibility to display radiological information (dose grid and radiation sources) to allow for a more informed design of the intervention. Now it is necessary to complete the design, generate the trajectories and analyse them with VISIPLAN, and then go back to HeSPI to make any necessary changes and repeat all the process again. We do not intend to reproduce all the functionality of VISIPLAN, but at least the visualization of the dose grid would allow the designer to know in advance the areas to avoid and to get a better design from the beginning.

2.2.2.2 MOUSE-ACTIVATED CONTROL

INTRODUCTION

The Mouse Activated System is part of a development produced by NNC and known as “ERGODOSE”. It is based on the commercial human modelling programme from Delmia Inc. known as ENVISION ERGO. An example of an ERGO human model with its joints degrees of freedom that are controllable by the user is shown in Figure 1. As positioning the human model in its 3D virtual environment can be confusing, the research undertaken included evaluating the benefits of low cost stereo glasses as well as developing an intuitive interface for controlling the complex human model.

The Mouse Concept

The human modelling concept involved taking the commercial ergonomics package, Delmia ENVISION with the ERGO option, and interfacing a hardware control device in order to simplify the creation of a simulation so that a non-expert user could easily create a virtual maintenance task.

Various hardware devices were reviewed at the beginning of the project with low cost and ease-of-use the selection drivers. Many devices were considered ranging from games controllers to specialist virtual reality interface devices. The device selected was the Magellan SpaceMouse from Logitech, which was also favoured by several organisations.

![Figure 1: Human mannequin with degrees of motion shown](image)
in the computer graphics community. This device is a proportional joystick that allows movement in all axes giving control to six degrees of freedom. This would allow the mannequin movements to be linked with logical movements of the SpaceMouse in the direction of intended travel.

The joystick is an ideal control device for driving the human modelling application but when using it in the VRIMOR application additional inputs are required. This functionality has been achieved through the development of a graphical user interface (GUI). The GUI has also been designed to be easier to use than the current software interface within ENVISION, which requires extensive training and is of a non-standard design.

During the user requirement stage of the project it was identified that at all stages of the task design and analysis it would be necessary to have a task breakdown so that individual parts of the simulation could be identified. This included planning the sequence of tasks before the simulation construction began and was required at all stages of the modelling process. This has been integrated into the application as a workflow complementing the joystick device.

**Design**

**SPACE MOUSE INTEGRATION**

The space mouse driver is used to drive two parts of the system, camera navigation and the mannequin or its parts. The camera has five degrees of movement allowing translation in all axes plus pan and tilt. The SpaceMouse control is orientated to the screen, i.e. a pan to the right is achieved by a clockwise rotation of the mouse puck. The SpaceMouse movement is linked to the mannequin in such a way that a movement left will cause the mannequin to move to his left.

**USER INTERFACE DESIGN**

The user interface has been developed as a three-stage workflow. It starts with the planning mode followed by the creation mode, which allows the simulation to be developed, and finally the analysis mode, which allows the simulation to be run and other options to be used. The following sections describe the functionality of these modes.

**PLANNING MODE**

The planning mode forms the first stage of the workflow within the ERGODOSE application and has been designed to capture information to help the creation stage and to document the analysis stage of the simulation.

The planning mode requires the production of a plan in the form of a storyboard dope sheet prior to any simulation construction. The storyboard breaks the task into small subtasks with timing and notes presented as a table. This dope sheet process is taken from the animation industry where it was developed to aid the planning and coordination of hand painted animation cells but it translates very well into computer based animation and simulation industries. It is important as an aid to non-expert users to avoid becoming lost in a simulation over the period of its production.

In addition to the dope sheet a gannt chart has been added to the application to give a graphical representation of the subtask durations. This is also helpful when setting the radiological conditions of the environment, which is modelled as discrete radiological states. (Section 2.2.3.2)
CREATION MODE

The GUI for the creation mode can be seen in Figure 2. This mode is where the user will spend most of their time while constructing a simulation. In this mode the user interface combines a GUI with the space mouse for controlling the 3D world.

The SpaceMouse allows the mannequins to be posed and animated and the camera to be moved. The different modes in which the SpaceMouse operates can be changed through the buttons on the device or through the GUI.

![Figure 2: Creation mode](image)

The GUI makes us of a large tool pallet down the right hand side of the screen. This is divided into two parts. The top provides the tool pallet for changing the SpaceMouse modes such as switching between moving the mannequin and the camera. The bottom half lists the subtasks that make up the task to be simulated and these are used to switch between mannequins and guide the development of the simulation based on information entered in the previous planning mode.

ANALYSIS MODE

This mode allows the simulation to be reviewed as well as providing the outputs for the dose assessment options, which are enabled through menu options.

The interface follows the same format as the creation mode with a large tool pallet down the right hand side of the screen. In this mode only a list of the subtasks is displayed and this is used to display results from the real-time dose assessment model when in this mode. It is also possible to output this data in the form of a CSV file that can be read into a spreadsheet for further analysis.
Implementation

DEVELOPMENT LANGUAGES AND APIS

ENVISION provides a number of APIs to allow additional modules to be developed and to interact with the software that allow the mannequins and other parts of the software to be manipulated using the C programming language. The API to allow the use of the Joystick was also provided as libraries to be used with the C programming language. Although these were designed for the C language it was preferable to use C++ for the development because of its object orientated development properties. Fortunately the close lineage of the two languages made it a trivial task to convert the language bindings to work with the C++ compiler enabling all the module code to be written using modern flexible programming techniques and give more scope to for future development.

The user interface has been developed using the Windows Win32 SDK because of its low level support for the operating system. This was a requirement because ENVISION has very little support for adding additional user interface functionality.

SOFTWARE ARCHITECTURE

The system has been developed using object-orientated development in C++. Two main interfacing issues have constrained the design. These were the limitations of ENVISION's user API, Axxess and the lack of support for adding interface components to the Windows version of ENVISION (all functionality for this is designed for using Motif).

The user interface was added to the system by constructing wrapper classes around the Win32 API, used to develop all the interface components. These were designed to add functionality to the existing message handlers of Envison so that additional components could be to piggybacked onto the application controlling it through the Axxess API.

SIMULATION DATA

The 3D environment data is supplied to the system as VRML files which are well supported in ENVISION and required no additional manipulation.

The ENVISION application stores all its application data in a library database with geometry stored independently of simulation data. The software does not have a single file that can be moved between systems whereas ERGODOSE needed to store additional information such as subtask details and real world timings. Although the ENVISION application provides a way to create a call-back function for loading and saving additional information, a better approach was identified using the XML standard. This allowed the additional information to be saved to any location with a reference to the library file where the simulation data was stored. This had the benefit that with the addition of an XSLT file, which could process the contents of the file, it allowed the results of the simulation to be displayed as a printable file on any PC equipped with an Internet browser.

SIMULATION TIMING

The management of time within ERGODOSE presented a number of problems. Early on in the requirements stage of the project it was identified that time would need to be represented as real
world time for conducting dose assessment but this mean that either simulation time be managed separately or all aspects of the task animated with the correct speed and timing.

For the latter option full animations would be needed of tasks such as removing nuts and bolts and the timings created accurately which would be very time consuming and difficult. For this reason a separate timing system was implemented which allowed task time to be specified independently of simulation time allowing a task to be simulated in quickly then scaled to the correct task time for the dose assessment. This proved very successful and had the added benefit of allowing the task times to be changed to investigate different time scenarios without the need to edit the simulation.

INTEGRATION WITH DOSE ASSESSMENT MODULE

As described in section 2.2.3.2 the dose assessment modules were developed as separate components designed using the COM component architecture so that their reuse could be maximised in future developments. The code to use these components was also greatly simplified because all components exposed the same interface removing duplicate code.

2.2.3 ALARA Assessment Tools

2.2.3.1 RADIOLOGICAL MODELLING

- The optimisation of radiological protection of the workers in nuclear industry is an important part of the safety culture. However the application of the ALARA concept (As low as reasonably Achievable) is not always straightforward. The first part of ALARA, the “As Low As” part, concerns the reduction of the dose. In order to investigate this part the analyst must be able to predict the dose in the work area and must also be able to investigate the effects of geometry, material or source changes.
- Therefore SCK•CEN developed the VISIPLAN 3D ALARA planning tool a radio-geometrical tool allowing a dose assessment in a 3D environment taking into account geometry, materials and sources.
- However before any calculations can start the analyst first needs to build the radio-geometrical model. This process can be very tedious when information needs to be derived from paper plans and $4\pi$ dose measurements on site.
- Therefore we developed in the VRIMOR project the interfacing of VISIPLAN with the geometry modelling tool LFM (Z+F Ltd.) and the EDR gamma scanning equipment (CIEMAT) in order to accelerate the geometric and radiological model building process.
- In the next sections we describe the different developments and their applicability in an industrial environment.

VISIPLAN 3D ALARA Planning Tool

The VISPLAN 3D ALARA planning tool is a fully operational radio-geometrical code used by different SCK•CEN clients in the nuclear sector of Europe.

The dose calculations in the programme are based on a 3D model of the work place including geometry, material and source information. All calculations are based on the point-kernel
calculation technique using an infinite media build-up correction. This technique has proven to be a valid method in the field of radiation protection involving external exposure to gamma radiation.

A set of model building tools is provided to define the geometrical and materials model of the work area by using primitive volumes such as boxes, spheres, cylinders and tubes. The material information is associated to these primitive volumes and is based on standard materials such as concrete, water, iron. The density of the materials can be changed according to the model needs. Mixtures of materials can also be defined and attributed to a volume in order to simulate the attenuation by complex internal structures (i.e. the simulation of a steam generator). The radiological modelling of a site involves source position, strength, geometry and composition. Source geometries available to the user are point, line, box, sphere and cylinder. The source spectrum can be selected from an isotope list or can be defined directly by the user at standard photon energies.

Once the model is defined tools become available to calculate and analyse the dose rate field and to calculate doses on work trajectories with the aim to optimise the work approach according to the ALARA principle. A screen interface of the VISIPLAN tool is given in figure 1.

The ability to edit the 3D environment; to introduce shielding or to change the geometry or sources, is a great asset of the tool (fig.2). The geometry can be simulated "as is" at the beginning of the simulation but also in different consecutive geometry changing steps during the maintenance or intervention simulation enabling a dose prediction for every phase of the work. A complete dose assessment can be done in the pre-job study enabling the analyst to explore "what if" questions and reduce errors. The analyst is then able to select the best approach to perform the work in reality.

3D Dose Grid Interface

Dose rate calculations on 2D grids where available in the VISIPLAN software allowing a quick dose evaluation in order to examine and evaluate the radiation risk in the work area. The dose rate grid calculations were extended in the VRIMOR project in order to provide the ErgoDose tool with dose information on a 3D dose rate grid. A calculation interface was developed to define, calculate and display the dose rate on a 3D grid and export the results to the ErgoDose human motion simulation tool enabling an on line dose assessment in the latter.
Figure 1: VISIPLAN screen interface with a geometry, captured and modelled with the LFM tool, ready to perform dose rate calculation on grids and trajectories.

Figure 2: Example of a sequence of geometry's derived from the "as is" situation in order to simulate a filter replacement activity. The radiological conditions for each situation can be evaluated based on the source strength on the filter (red) determined in the "as is" situation, through standard radiation measurement or gamma scanning, before the maintenance starts.

VISIGAMMA Tools

A set of new tools, developed during the VRIMOR project, has been introduced to the VISIPLAN software and is called VISIGAMMA. The tools enable the user to import and analyse gamma scans measured with the EDR gamma scanner of CIEMAT using a visualisation and a source-fitting interface.

The visualisation tools allow a plot of the gamma scans in a 3D view or a pan and tilt view enabling the user to relate the radiation intensity picture to the measured geometry. This analysis together
with technical information available from the site leads to a geometry model for the sources. The source composition is determined from the EDR gamma spectra or from other supporting measurements.

The source strengths are assessed using the source strength estimation tool once the source geometry and composition are fixed. The source strength estimation tool takes full advantage of both a precise characterisation of the EDR gamma scanner and the modelling capabilities of VISIPLAN and allows a source strength determination with an accuracy that is adequate for radiation protection studies.

The method was tested in a calibrated environment and applied with success in an industrial environment. An example of a scan in a, industrial environment is given below. It concerns an area in the Nuclear Power Plant at Almaraz, Spain (Fig. 3). The source strengths that where determined allowed a dose rate prediction that agreed within 20% with the dose rate measurements in the area using standard dose meters. The dose rate pattern calculated form the model is shown in Figure 4.

**Figure 3:** Gamma scan of an area at Almaraz NPP shown with a VISIGAMMA 3D top view and a pan and tilt plot
Figure 4: 2D dose rate grid calculated using the VISIPLAN tool based on the source strengths determined, using the VISIGAMMA source fitting tools and the EDR gamma scans

Geometry and Materials Data

As described earlier geometry building can be very tedious when information has to be derived from paper or 2D plans and added to the VISIPLAN geometry and material database. In order to speed up the process of creating the geometric model an interface is created between LFM (Z+F Ltd.) and VISIPLAN. This interface enables the extraction of a set of volumes describing a simplified geometric model of the site in the VISIPLAN geometry and materials format. A detailed geometry model is first established in LFM adapted to also store materials data. The transfer of the solid object to VISIPLAN is one to one except for bends in the piping. Bends are simplified to a set of tube segments (Fig. 5).

The interface allows also the transfer of the data from VISIPLAN to LFM in order to transfer fitted source information (position, geometry and strength) to the LFM database. This in turn enables LFM to provide a source model in VRML that can be used in the human motion simulation tools increasing the awareness of the simulator with respect to the risks in the simulated area.

Figure 5: Example of an LFM model (left) transferred to the VISIPLAN tool (right) for dose calculation
CONCLUSION

The VISIPLAN 3D dose assessment tool has shown to be a flexible dose assessment environment and is now equipped with interfaces allowing a faster geometry and radiological model-building phase.

The VISIPLAN 3D dose assessment tool now interfaces with the LFM (Z+F Ltd.) geometry scanning and model building tool allowing a fast geometric definition of the work environment.

The interface between VISIPLAN and the EDR gamma-scanning tool (CIEMAT) allows a faster and more rigorous analysis of the radiological conditions of the site leading to a faster source model definition.

The source fitting and modelling methodology was tested with success both in an experimental environment and in-situ in an industrial environment. Experience is gained on the interpretation and reliability of the source fitting results that can be applied in future workplace characterisations.

The radiological modelling methodology developed here, based on the combined approach of geometry scanning, gamma scanning and a 3D dose assessment tool, has shown to be a valuable technique in the characterisation of a radioactive site for radiation protection studies and ALARA evaluations.

2.2.3.2 HUMAN MODELLING ANALYSIS

Introduction

The real-time dose assessment module forms part of the ERGODOSE human modelling tool (section 2.2.2.2), enabling a task designer to use pre-calculated dose fields to carry out quick design-time dose assessments while designing a complex task.

The research in this area has looked how to use a pre-calculated 3D grid representing the dose field in an area so that it can be interrogated in real-time. A Module has also been produced to support XML trajectory files so that mannequin paths can be exported to offline dose assessment tools such as VISIPLAN.

Concept

By integrating a pre-calculated dose field into the human modelling component of the application, tasks can be designed and optimised simultaneously and different solutions evaluated without conducting lengthy offline assessments. This also allowed validation to be conducted against the previously validated VISIPLAN tool.

The most important tool for allowing this is the ability to conduct a quick dose calculation at any stage during the design process. As an additional aid to the task designer the dose field can also be queried at any location in the environment while developing the simulation.
Design

The real-time dose assessment module is designed to use a pre-calculated 3D data grid containing the dose field for the entire maintenance area for which the dose assessment is to be conducted. This can be taken from a tool such as VISIPLAN or directly from devices such as the EDR scanner depending on the type of task. For example, data could be taken directly from the EDR scanner if the dose field is not likely to change markedly during a maintenance operation whereas if strong sources were being moved or shielding were changed the VISIPLAN tool could be used to generate dose fields for the different scenarios.

As detailed in Section 2.2.2.2, a task planning system was developed in ERGODOSE allowing the task to be broken down into small subtasks. One of the drivers for this development was to create a meaningful breakdown of the simulation task for documenting dose estimates. This has enabled dose calculations to be made for each operator in the simulation and to show how this breaks down over the duration of the maintenance operation.

To allow the dose field to be queried a number of options were looked at. The final solution used a movable object that could be placed at any location in the virtual environment and the dose field value returned. In ERGODOSE this is done be moving a static mannequin about in the world with the benefit that dose rates can be returned for the head and chest at the same time. This also gives the operator a good comparator of scale in the environment. Other options were considered for displaying the field strength such as 2D texture plans, which would allow a slice through the dose grid to be shown on a plan with colours showing the field strength. This was rejected because ENVISION did not have the correct functionality. Similarly representing the dose grid as lots of individual points was considered but these could only be represented as geometric objects by envision and would have placed too large a processing burden on the system.

An initial assumption was made that using the nearest dose grid data point for the field strength when working with a half-meter resolution grid would produce a reasonable dose estimate. As the research progressed it became apparent that although, for discreet readings of the dose field this proved to be sufficiently accurate, over time errors built up and large inaccuracies propagated through the results. To counteract this, 3D interpolation algorithms were investigated and proved a good solution to this problem.

3D Interpolation algorithm

The ‘nearest point’ method originally used to approximate the dose rate at a specified location was found to result in excessively inaccurate cumulative doses during dose assessment calculations. In order to improve the dose rate approximations a number of interpolation methods (including linear interpolation and B-spline interpolation) were considered. The aim in using interpolation was to base a dose rate approximation on the eight surrounding dose grid values.

<table>
<thead>
<tr>
<th>Coordinate</th>
<th>Dose Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>$d_1$</td>
</tr>
<tr>
<td>b</td>
<td>$d_2$</td>
</tr>
<tr>
<td>c</td>
<td>$d_3$</td>
</tr>
<tr>
<td>d</td>
<td>$d_4$</td>
</tr>
<tr>
<td>e</td>
<td>$d_5$</td>
</tr>
<tr>
<td>f</td>
<td>$d_6$</td>
</tr>
<tr>
<td>g</td>
<td>$d_7$</td>
</tr>
<tr>
<td>h</td>
<td>$d_8$</td>
</tr>
</tbody>
</table>
Linear interpolation is the simplest interpolation method, and assumes a continuous, linear progression between two known values:

\[
\text{Dose rate at } x = d_1 + \frac{(d_2 - d_1)x}{s}
\]

To achieve an approximation based on all eight surrounding dose grid values, a series of seven linear interpolations is performed. The method employed is as follows:

1. Perform a linear interpolation between the dose rates at e and f, based on the x co-ordinate.
2. Perform a linear interpolation between the dose rates at g and h, based on the x co-ordinate.
3. Perform a linear interpolation between the dose rate approximations achieved in steps 1 and 2, based on the z co-ordinate.
4. Perform a linear interpolation between the dose rates at a and b, based on the x co-ordinate.
5. Perform a linear interpolation between the dose rates at c and d, based on the x co-ordinate.
6. Perform a linear interpolation between the dose rate approximations achieved in steps 4 and 5, based on the z co-ordinate.
7. Perform a linear interpolation between the dose rate approximations achieved in steps 3 and 6, based on the y co-ordinate.

These interpolations were resolved into a single equation. This equation is used during the dose assessment calculations to obtain an approximation for the dose rate at a specified point.

It is accepted that there are more accurate interpolation methods (such as the 3D B-spline interpolation) for making approximations between 2 or more points in 3D space. However, the method above has proved to be sufficiently accurate during testing, and any further increases in accuracy offered by the B-spline method are outweighed by the increased complexity of the method.

**Implementation**

The implementation of the dose assessment module compared to the ERGODOSE tool was relatively straightforward because it was entirely bespoke with no dependency on other programs or code libraries.

The module was developed as two COM components, one for exporting trajectory data and one for the dose grid assessment. These choices were made to maximise the reuse of the tool in future application development. The analysis of the data required by each component revealed that they both needed the same information and could be controlled through a standard interface. This made integrating them with ERGODOSE much simpler, requiring only one set of methods for both analysis routes.
2.2.3.3 BODY PART TRAJECTORY ANALYSIS

Overview

The trajectory dose analysis is an important tool for the ALARA analyst, not only in order to assess the total dose for a task under consideration but also to make an in depth analysis regarding the dose contribution of specific subtasks or the dose contribution of specific sources. The availability and accessibility of this data provides the analyst with a means to perform a quantitative analysis on which to base his shielding strategy or suggest another approach to perform the proposed task. The effectiveness of a strategy change can thus be evaluated in detail.

In the VRIMOR project we have combined the flexibility of the human motion modelling tools with the strength of the dose assessment and analysis tools of VISIPLAN 3D ALARA planning tool. This was achieved through the development of the Trajectory Input Interface enabling a fast and flexible transfer of trajectories simulated in virtual reality with the human simulation tools to the VISIPLAN tool for a detailed dose assessment.

The method was tested for a human motion simulation of a filter replacement task at Almaraz Nuclear Power station. In the next sections we describe the interface, the dose assessment and the dose analysis tool and the application to the dose evaluation of a filter replacement task.

Trajectory input interface

The trajectory input and dose calculation tool is designed to transfer the trajectories from a human motion modelling and task simulation tool to the VISIPLAN 3D ALARA planning tool enabling an automated dose assessment on the trajectories based on the radio-geometrical model of the work environment established earlier.

Two human motion modelling and task simulation tools were developed in the VRIMOR project i.e. HeSPI (fig. 1.) developed by UPM and ErgoDose (Fig. 2) developed by NNC. Both human motion and simulation systems enable the creation of a set of trajectories that can be imported into VISIPLAN at the end of the simulation.

- A file format was established to enable the data transfer between the different applications. The data exported from the human motion simulation tools contain the task name, the operator names and the subtask the operators perform in the virtual environment. For each of these subtasks the duration is given together with the time interval spent at the different work positions. Information is provided on the spatial position of the head, chest, left hand and right hand of the mannequin and can be used for dose evaluations at these positions.

- The dose rate evaluation is performed in a pre-established radio-geometrical model taking into account the sources, materials and geometry of the environment. Simulations involving changing radio-geometrical situations like a movement of a source during the tasks require a split of the trajectory in separate trajectory files each containing the actions performed in the specific radio-geometrical model describing the situation. The dose is then evaluated on each trajectory file using the specific radio-geometrical model in VISIPLAN. At the end of the calculations the results of the different subtask trajectories are brought together in a scenario result file containing all the actions taken by the different operators in the simulation with a dose evaluation for every subtask. This
information can be printed in a form or can be examined with the dose result analysis tools of VISIPLAN.

![Figure 1: A trajectory simulation with the HeSPI tool](image1.png)

![Figure 2: A trajectory simulation with the ErgoDose tool](image2.png)

**Dose result analysis tools**

The calculated dose results can be analysed using different tools provided in VISIPLAN. The dose uptake for a work simulation is first examined with the Scenario result tool in order to evaluate the total dose and establish a general overview of the dose uptake during the different subtasks on the different trajectories. A graph of the dose rate per subtask trajectory helps the user to find and evaluate the most dose intensive subtask trajectory. The dose distribution in the work force can also be evaluated graphically enabling a quick detection of large dose uptake of specific operators.
More detailed information on a subtask trajectory can be evaluated using the trajectory or subtask result tool enabling to identify the contribution of the different sources at the different worker positions of the subtask. The sources with the greatest impact on the dose uptake can be easily detected and acted upon if possible during the ALARA optimisation process.

Examining the dose data using these tools helps the ALARA analyst to get a better picture of the dose uptake throughout the simulated task and helps to formulate shielding solutions or alternatives for some actions. This leads to the creation of a new scenario that then can be compared quantitatively with the previous one by using the scenario comparison tool.

The strength of this method lies in the comparison and optimization of the simulations. The trajectories can be re-evaluated in other shielding conditions to evaluate the shielding effectiveness or other trajectories can be simulated in the human motion simulation tool taking into account the lesson learned through the dose uptake analysis of the previous simulations.
Application

The integration of the human modelling tool with the dose assessment tool was tested and applied in the simulation of a filter replacement task at Almaraz power station.

A human motion simulation of a task was performed by UPM and NNC using their specific human motion simulation. The trajectories described the replacement of a contaminated filter. The filter is positioned on a platform that is accessed by ladder. An example of a subtask trajectory simulated in a human motion simulation and imported in VISIPLAN is given in Figure 4.

Figure 4: Display of a selected trajectory subtask imported in VISIPLAN geometry describing the action of an operator entering the area and going to the platform to perform the maintenance (see also Fig. 1 and 2)

The filter replacement task was simulated in a sequence of five geometries of which four are described in Figure 2. A fifth geometry considers the situation when the contaminated filter is removed from the site and a new filter is installed.

UPM and NNC delivered trajectory grouped per geometric condition. The files where loaded in VISIPLAN and integrated. The result of the dose assessment is given in Table 2.

<table>
<thead>
<tr>
<th>2.2.3.4 HESPI TRAJECTORY</th>
<th>2.2.3.5 ERGODOSE TRAJECTORY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time (man-h)</td>
<td>Collective dose (man-mSv)</td>
</tr>
<tr>
<td>Geometry 1</td>
<td>0.59</td>
</tr>
<tr>
<td>Geometry 2</td>
<td>0.09</td>
</tr>
<tr>
<td>Geometry 3</td>
<td>(*)</td>
</tr>
<tr>
<td>Geometry 4</td>
<td>0.16</td>
</tr>
<tr>
<td>Geometry 5</td>
<td>0.84</td>
</tr>
<tr>
<td>2.2.3.6 TOTAL</td>
<td>1.68</td>
</tr>
</tbody>
</table>

Table 2: Comparison of the integrated dose using respectively the HeSPI and ErgoDose trajectories ((*) integrated in geometry 3, (**) negligible dose after the removal of the filter)
Both trajectories were developed independently and resulted in a different dose uptake for the same general description of the activities. The detailed dose analysis with the VISIPLAN tools enabled a quick detection of the reason causing the dose uptake difference. Closer examination of the trajectories with the VISIPLAN analysis tools showed that this is due to the positions chosen during the most dose intensive task namely the unbolting of the filter housing. This again shows the strength of the detailed trajectory dose analysis tools available to the analyst.
Conclusion

The trajectory interface developed in the VRIMOR project to transfer human simulation modeling trajectories from ErgoDose(NNC) and HeSPI tool(UPM) to VISIPLAN is fully operational and has shown to be an efficient coupling between the flexibility of the human motion simulation tools and the dose assessment and analysis capabilities of VISIPLAN. The combined approach allows the dose integration on complex trajectory files involving different operators performing different tasks in a radiological environment. The dose assessment can be performed at the position of four different body parts; chest, head, left hand and right hand. The results of the trajectory dose assessment allow the evaluation of the collective and individual dose for the work simulated in a virtual environment.

This tool is especially valuable to the ALARA analyst who is now able to analyse a complex task prepared by the technical people in a human motion simulation tool in a realistic representation of the radioactive environment. The dose assessment and analysis tools of VISIPLAN help the ALARA analyst to propose other approaches for executing the tasks based on quantitative data. The combined tools allows the analyst to explore the effects of shielding, geometry changes, source strength changes and trajectory changes on the dose uptake with the aim to reduce the dose as low as reasonably achievable.

2.2.4 Environmental Scanning and Data Manipulation

2.2.4.1 LASER SCANNING AND DATA PRESENTATION

Overview

The ability to scan and model a radiological hazardous working environment and to then produce as-built CAD models can bring enormous benefit to the what-if questions which arise during repair and maintenance work. Laser scanning and modelling is now a well established approach, however adding the radiological dimension to this model is entirely new and so it pushes the what-if type questions into a new realm, not only can a user plan, simulate and practice tasks in a simulated (but mapped from reality) world, they also have access to precise radiological dose uptake predications for the that task. The end users of this technology will clearly be in the nuclear maintenance and cleanup sectors and they will benefit from a more define and predictably lower does uptake during task which have been fully simulated in advance to ensure a minimal does uptake.

Laser scanning and modelling is a technology that has only become a mainstream methodology within the last two years and so it is still relatively new. Laser cameras are now small, light and portable with fast image acquisition times (< 90 seconds) and wide field-of-views with long operating ranges (50 metres range with 1mm resolution). In the VRIMOR project, an additional level of functionality has been added: this being the additional of radiological mapping to augment the geometrical data from the laser scanner.

The techniques of scanning and modelling process like environments are well understood. Constructing useful models for end users should be considered as a layered process. Where a plant had never used the methodology before, there is a requirement to fully scan the areas concerned using both laser and radiological sensors and following this, the whole geometrical modelling and radiological modelling process. For subsequent use, the methodology is much simpler and
providing that the plant is still the same from a geometrical perspective, the only the radiological mapping need be carried out and the dose model calculated. The geometric situation of most process plants can be static for many years, however the radiological state of the plant can change on a daily basis. With this in mind, for an end user to benefit from this approach, the geometrical (laser) scanning need only be done each time there is a major change in the plant, for example during a refit. The radiological data gathering would be done on a more regular basis; before some intervention process for example.

**Laser Scanner Description**

The Image 5000 series of laser measuring instruments provide a rapid, non-contact, geometric measurement of almost any environment. Control of the camera is by FireWire port of a suitable laptop computer. The camera system uses a mechanical deflection unit to drive a laser beam in different directions. For each measurement, a range and intensity value is measured and an entire scan results in a corresponding range and intensity image. The range images represent the geometry of the environment whereas the intensity images render a visual representation. Both images correspond at each pixel and are independent of ambient light due to the active illumination with laser light.

![Imager 5003 Laser Camera](image)

Laser measurement system

The measurement system is based on the principle of phase difference measurement (AMCW). The transmitted laser light is intensity modulated, i.e. the intensity of the laser light is varied from dark to light in a sinusoidal fashion, up to 96 million times per second. The laser light scattered back from an object is received by a photo diode. Thus two sinusoidal intensity signals are obtained: the transmitted laser light and the back scattered light received by the photo diode. Owing to the time of flight of the laser light to the object and back, both sinusoidal signals are shifted in time with respect to each other which in turn results in a phase shift. This phase shift is directly proportional to the range of a measured object and is obtained by special processing electronics. The amplitude of the back-scattered light corresponds to the intensity value and depends on the reflectivity and distance of the measured object. This is similar to the brightness of a black and white picture.

Deflection System

The laser beam is deflected in two dimensions with this system. The vertical deflection of the laser beam is achieved by a mirror, rotating about a horizontal axis at up to 900 rev/min and covering a
field of view of 270 degrees vertically, including the overhead area. (The shadowing of 90 degrees in the floor area occurs due to the mounting of the system on a tripod.) The horizontal deflection of the beam is achieved by a pan-motion of the entire measurement system, covering a horizontal field of view of up to 360 degrees. The acquired images contain up to 15,000 pixels in the vertical (Elevation) and up to 36,000 pixels in the horizontal (Azimuth).

**Image Format**
Every pixel contains a range and an intensity value, as well as two angle measurements. Therefore the corresponding XYZ-coordinates in space can be computed for each pixel. While the laser beam is deflected in a continuous motion, the laser measurement system typically acquires 125,000 data pixels per second and stores them on the hard drive of a connected PC. A maximum data rate of 625,000 pixels/second is possible. A typical 360 degrees omni-directional image consists of 4,500 pixels horizontally and 3,750 pixels vertically, altogether 16.9 million picture points, which is significantly more than any digital camera could capture nowadays. The total scan time is only
approximately 140 seconds. A maximum resolution of up to 270 million pixels is possible. Depending on the application, the field of view, resolution, as well as measurement data rate (pixels per second) can be adjusted. It is thus possible to survey different regions using optimal adjustments.

**Light Form Modeller Overview (LFM)**

Light Form Modeller (LFM) has been developed specifically to convert 3-D points data into 3-D CAD models. The resultant models can then be seamlessly exported to a wide range of popular CAD systems. Conversion from point data to CAD objects is achieved by the application of powerful analysis algorithms that have been developed to facilitate swift points-to-primitives translation. The approach used in the model building process enables an operator to construct a 3-D model in an incremental, intuitive and interactive way and to rapidly produce a ground-up CAD model of a specific region of interest or to validate-update existing 3-D CAD models.

Modelling of small and large structures alike dictates that significant numbers of scan images need to be taken from a number of different viewpoints, and consequently building a 3-D CAD model can quickly become a very complex undertaking. For this reason, LFM provides seamless support to the operator to allow rapid registration of multiple images from multiple viewpoints in order to compose the 3-D CAD model.

Conversion from 3-D point data into CAD objects is facilitated using a range of specially developed fitting algorithms that have been developed to be both robust and accurate. The conversion process is done with the aid of an operator who selects specific groups of points that, for example, belong to the surface of a pipe, and then directs the system to automatically find the best-fit CAD representation of a pipe. This approach leads to very swift construction of the model even for operators new to the system.

Modelling a section of 3-D space into a 3-D CAD representation is a task which requires extremely good support in: 3-D fly through, 3-D points editing, inter image registration (i.e. positioning of multiple models within a whole), and the ability to view and manipulate multiple 3-D and 2-D images in the same workspace simultaneously. These facilities, and much more, are provided by LFM to aid the user through the modelling process.

At the core of LFM is embodied the high performance ACIS 3-D CAD modelling kernel. Because there is such a bewildering choice of CAD systems on the market today, cross-compatibility between CAD systems is a serious issue. By using the popular ACIS kernel however, LFM can provide the user with the ability to export to and import from virtually any CAD package, either directly using the SAT file format or indirectly through the use of optional off the shelf translators. Extensive CAD manipulation and editing facilities are provided by LFM to augment the model quality after the fitting stages have been completed. This allows the user to: extend, intersect and manipulate the model to the stage where they are satisfied that the modelling objectives have been reached. An on-line history mechanism provides roll back, roll forward, and "what if?" scenarios to be explored without worry of permanently affecting the model.

**Applicability**

LFM has been used extensively in the processing, building, automotive, chemical and nuclear industries. It can be used whenever there is a need to quickly produce a 3-D CAD model of an
existing environment. The reasons for requiring "as-built" models are diverse, but are typically driven by modification, simulation, maintenance, safety, or plant life management requirements.

System Overview within the VRIMOR Project
Shortly after the project inception, the overall system design (WP4) focussed its effort towards ensuring that both the work package definitions and the interfaces between the work packages (who were in themselves widely distributed) were clearly defined and, where possible, using standard interfaces. As a result of this effort, only two interchange formats are used throughout the entire project. All information interchange is file-base and, at present, there is no live linking of modules.

VRML Link
The primary interchange format for the models between partners is VRML. Since the end users of the model need the data for simulation work, VRML is a near ideal format that is readily understood by many packages. Most importantly, VRML based models can be readily viewed using Internet based web browsers, which means that finished models can be viewed with tools which already exist on most computer systems.

MDB Link
Unlike the VRML link, the mdb link is proprietary. It has been developed within the VRIMOR programme as a mechanism to enable two-way transfer of solid model data between LFM and VisiPlan (see diagram). The mdb link is a file-based database which can transfer the solid object...
data into VisiPlan from which to calculate the overall dose model. For the purpose of dose calculation, the geometric model can be rather too complex and for this reason, at export to the mdb database, the primitives go through a simplification process where, for example, items of pipe work go through without modification, but elbows are simplified to two short (straight) pieces of pipe at 45 degrees to each other.

The techniques of scanning and modelling process like environments are well understood. Constructing useful models for end users should be considered as a layered process. Where a plant had never used the methodology before, there is a requirement to fully scan the areas concerned using both laser and radiological sensors and following this, the whole geometrical modelling and radiological modelling process. For subsequent use, the methodology is much simpler and providing that the plant is still the same from a geometrical perspective, the only the radiological mapping need be carried out and the dose model calculated. The geometric situation of most process plants can be static for many years, however the radiological state of the plant can change on a daily basis. With this in mind, for an end user to benefit from this approach, the geometrical (laser) scanning need only be done each time there is a major change in the plant, for example during a refit. The radiological data gathering would be done on a more regular basis; before some intervention process for example.

2.2.4.2 GAMMA SCANNING AND ANALYSIS

Introduction

CIEMAT activities in VRIMOR project has been focused on five main areas:

1. Development of a pre-industrial version of the CIEMAT gamma scanner prototype, named EDR. CIEMAT contribution to the project was based on an existing gamma scanner experimental prototype. One of the project goals was its modification in order to have ready a reliable prototype for applications in nuclear industry. The umbilical connection to the control computer was deeply modified in order to increase the scanner-control maximum distance and reduce complexity in the connection.

2. Development of a computer code for generating dose rate maps from the radiometric information obtained by making use of the gamma scanner considered in the project. This code becomes an alternative to the work carried out by SCK-CEN in the same area. A comparison of the functionality of both dose rate calculation methods is one of the project results.

3. Performing a detailed characterization of the EDR gamma scanner directional response. The integration in VISIPLAN of data reported in a preliminary directional response study at CIEMAT showed that low uncertainty levels could be achieved in the identification of radioactive sources as long as precise angular response would be included in the code. A new experiment in a CIEMAT facility was scheduled during Brussels meeting.

4. Radiometric and geometric measurements in a controlled facility were acquired, with the aim of generating a set of files representative of a real scenario. These files must be readable and processed by all the other groups. Standard formats for file interchange were tested with these experimental data. They become the first test bench for verifying compatibility and operating capability of all partners’ contributions.
5. Scanning at Almaraz Nuclear Power Plant. Scanning of AE51 facility in Almaraz was scheduled the first week in June, but it was postponed to the end of this month. Measurements were acquired during the days June 25 to 27.

In the next sections the works described above are further commented.

**Software — Dose Map Calculation**

A radiological model to be used by CIEMAT for dose rate map computing has been implemented on a computer code. It is based on the Point kernel method for computing photon flux and dose rate in a particular position due to radioactive sources in the presence of other non-emitting materials acting as shielding. The radioactive volumes are modelled as emitting surfaces. Point sources are distributed in the centre of each three vertex faces that generate the volume contour. The build-up factors are considered to account for the radiation scattering effects, using the Geometric Progression as a fitting function. The geometry is generated by making use of a CAD tool such as Autocad, 3Dstudio or SolidWorks. The created geometry is exported to a DXF file format. In a second step, each volume is loaded with material and radiological attributes. The code results have been verified by comparing with other packages based on the same calculation method, such as PUTZ. This file is used by the dose calculation code, developed in ANSI C, using the LabWindows CVI graphic libraries.

*Dose Map Computing (Dose Rate Calculation in a Position)*

The algorithm considered for the dose rate calculation makes use of the expression for the photon flux in a position due to a single point source:

\[
\Phi(E) = N(E) \frac{e^{-\mu(E)R}}{4 \cdot \pi \cdot R^2} \cdot B(\mu(E) \cdot R)
\]

- \( \Phi(E) \) = Flux (photons /s·cm\(^2\))
- \( N(E) \) = Emission (photons/s)
- \( \mu(E) \) = Mass attenuation coefficient (cm\(^2\)/g)
- \( R \) = Distance from location P to source S (cm)
- \( B(\mu(E) \cdot R) \) = Build-up
- \( E \) = Energy (keV)

The build-up factor considered in this formula corresponds to an empirical correction for scattered photons. This factor must be considered for achieving realistic results in non-trivial geometrical situations. Different expressions can be found in the literature for this factor. We have decided to implement the build-up formula known as Geometrical Progression (GP). This formula has demonstrated better results than other algorithms such as Taylor formula.

*Spectrum Format*

A standard format for sharing spectrometric information has been defined. The scanner generates classical 1024 channel spectra, while other partners’ software tools require ANSI spectra. The code of the tool has been adapted for generating this format as well.
Hardware — New Gamma Scanner Prototype

A second version of the gamma scanner has been constructed. Fig. 2.2.4.2.1 a view of the equipment. It has been designed to be more reliable, decontaminable and more accurate. On the other hand, a better alignment of different systems axis (laser, video camera, collimated detector) can be achieved.

Figure 2.2.4.2.1: General view of the new version gamma scanner

Umbilical connections were modified from the previous version during this period. A thick connection composed of several coaxial, series and power cables, has been replaced by a RJ45 link cable. This implied to partially modify the hardware in the scanner body and the software.

The current version permits the hardware control via TCP/IP connection, thus avoiding constraints due to distance and limitation of cumbersome cabling from the control site to the scanner.

Directional Response Characterization

In order to obtain accurate information about the shielding capability of the radiation collimator in the scanner, directional studies were defined with point sources. The basic idea is to know the detector response for a radiation field with negligible background and a single point source located at different azimuthal $\phi$ and zenithal $\theta$ angles relative to the detector $z$ axis. Scans of an area with a fixed point source would be valid for having this information. Whereas $4\pi$ scanning with a very narrow step ($>0.5^\circ$) both in horizontal and vertical directions would be ideal, acquisition times limited the resolution. Measurement times should be compatible with working time periods of the facility used for these tests. Two levels were selected:

1. The range $[-6, +6]$ degrees, both horizontal and vertical, would be scanned with $0.5^\circ$ angular step.
2. A larger angular step, $10^\circ$, would be used for the range $[-80^\circ, +260^\circ]$ horizontal, $[-45^\circ, +80^\circ]$ vertical, $10.0^\circ$ step.

These two scans would be done by considering two isotopes: $^{137}$Cs and $^{60}$Co. All these results were sent to SCK for their process and integration with the VISIPLAN tool.

**Tests in a Controlled Facility**

The Project initial intent was that an early scan of the candidate area in Almaraz Nuclear Power Plant be carried out to provide realistic data upon which to carry out development trials. This task could not be performed. A complementary strategy was developed with the intention of providing data sets and models that could be validated and distributed among the partners for re-use within their own development activities. With this aim, the possibility of performing an experimental scenario in a controlled facility was proposed. CIEMAT offered the IR14 laboratory for this. An experimental scenario including a tube with a simulated hot spot and a huge collimated point source was built. Scans from two reference locations were acquired. Geometrical (laser) and radiometric measurements were distributed to SCK-CEN. This partner processed the data and shared files and results with the others. Calculations and graphics presented in Brussels Meeting (February 20-22, 2002) by SCK-CEN showed good results. Additional comments about further characterization measurements were suggested.

**Scanning at Almaraz NPP**

Tests with the gamma scanner in Almaraz Nuclear Power Plant were performed. The scanner was transported to EA facility ground -5 by the Health Physics Department of the Plant making use of a crane and a mobile platform. The hardware was assembled and tested at the EA51 entrance and was displaced to the facility when the scanner was ready to operate. Working conditions at this level of the EA building was severe relating temperature and humidity. Conditions were even worse at EA51 (environmental temperature close to $40^\circ$ C and higher humidity). Background radiation levels were $\sim 5$ mR/h at EA51 and ten times lower at EA ground -5 close to EA51 entrance.

Hand measurements performed with GM rate meter previously to the scan revealed that the dose rate in contact in the filter area was only ten times higher than the background level. At the moment of the measurements, relevant activity concentrations were not found at this point, showing values similar to other parts of the pipes. The radiological situation of the facility at the date of scanning was not optimum for a remote survey, neither with a scanner nor with any other remote equipment such as a gamma camera. Scans confirmed this result.

Other measurements were performed at this facility out of the EA51. The corridor at EA ground 5 near the entrance to EA51 presented a lower background level. On the other pipes transporting radioactive materials were disposed at this site together with non-active ones. There was a pipe located throughout the corridor ceiling particularly active. It was shielded with lead cylinders all along but in an elbow, this just protected with a lead blanket. Contact dose rate at this point was 60-80 mR/h. Background dose date was $\sim 0.5$ mR/h and 1-2 mR/h in contact to the pipe shielding far away the elbow. A scan of this area revealed a hot spot in the elbow (see Fig. 2.2.4.2). The scan was repeated from other positions and different conditions, confirming the presence of the hot spot. These measurements concluded that the EDR gamma scanner was fully operative.
Conclusions

All the proposed tasks in the project have successfully achieved. A pre-industrial gamma scanner is fully operative and its directional sensitivity characterized. Tests in industrial facilities have been performed. The scanner in its current version is compatible with VISIPLAN, what increases its capabilities.

The generated code has demonstrated to be useful and can be an interesting alternative to VISIPLAN algorithms in some particular cases in which time is more important than accuracy. The comparison with VISIPLAN revealed that results were always close, although the code is less accurate for measurements near source surfaces. This is due to the consideration of surface sources instead of volumetric ones.

2.2.5 Project Evaluation Exercise

Technological Evaluation Plan

There are two different sources of information to perform the VRIMOR evaluation. The first one is the evaluation session performed in Almaraz NPP., where during two days, members of the Almaraz staff were trained in the two different applications: UPM-based on Jack and NNC-based on Ergo.

The second source is the evaluation of the tool based on the feedback provided by the developers and other end users.
Regarding the Almaraz evaluation, to get these results, the relevant simulation equipment have been transported to Almaraz NPP and some operators have been trained in the different applications developed by the project.

This evaluation includes a comparison of the different approaches developed in the project and takes into account several factors (practicality, cost, user-friendly aspects) in order to give hints to other potential users on the use of the technologies involved. Consideration is also given to aspects of commercialisation and future recommendations.

Users' feedback

One questionnaire was delivered to each trainee in order to collect their opinions about different aspects of the evaluation session. Some questions were about the general methodology, and the rest about the two specific applications: ERGO and JACK separately. Besides, two people from the project, one from TECNATOM and one form UPM, observed the development of the free exercises performed by the trainees, taking notes about incidences with the applications, comments from the trainees, problems encountered, etc. At the end of the evaluation session, during about 1 hour, all the developers, users and other attendees to the training sessions shared their opinions about the methodology and the specific applications and functionalities. The exchange of communication was very fruitful. The main conclusions are described in this section.

- They agreed that if they had this application they would use it, no doubt. They consider it very useful.
- They like the voice option. It is the most direct and faster option.
- It would be necessary to simplify the use of the tool.
- This methodology is quite useful, mainly for “critical” rooms or areas.
- Possible uses: Maintenance, Training, Radiological Protection separately and for the ALARA group jointly.
- Some of them said that a product that would be very useful by itself would be the geometrical representation of some critical areas with the radiological information associated.
- The use of the laser for geometrical representation could be very difficult to implement in some “critical” areas due to: high temperature, high radiation levels, job interference and difficult access.
- They showed interest in the possibility of changing the dose rates of the area.
- It would be very useful that Visiplan would provide the most favourable trajectory for the operator, in which he would take the smallest amount of dose.
- The dose deviation (about 40 %) is acceptable only if the final figure is used to compare between different options, not as a expected dose.
- They consider acceptable the deviation of a 10% in the dose rates.
- They consider acceptable the time invested in analysing a specific task using any of the two applications.
- Regarding the comparison between both applications, they think that both have the same objective and a similar approach. The main handicap is how to handle the different input/output devices.
- They prefer to apply the whole methodology instead just some part of it, if they could choose, in order to have a high quality product.
Developers' Perspective

The scanning at Almaraz NPP demonstrated to be a proper exercise for evaluating the capability and operation of the gamma scanner. It represented a difficult scenario for a remote survey in which the sensitivity of the scanner for locating low active sources in relative high background fields has been checked.

The ability of the tool for identifying radiation sources with contact dose rate slightly above the background level has been demonstrated. Dose rate grids generated by VISIPLAN were evaluated by comparison with hand measurements acquired with standard instrumentation by the Health Physics Department in the Plant. Results of the comparison are very positive. The exercise shows that a good dose estimate can be derived in a relatively short time using the dose integration interface developed during the VRIMOR project. The dose assessment detail depends on the detail put into the simulated trajectories.

The difference between the two simulations shows that although the comparison of simulated and calculated dose rates is within 20-30 %, that the agreement between the measured dose uptake and calculated dose uptake can be lower due to uncertainties in position and in time of the work planning. The operators will in reality not follow the exact movements of the human simulation representation.

This brings us back to the fact that the strength of the VRIMOR approach lies in the comparison and dose optimisation of the task in dose uptake, technical approach and ergonomics of the task.

The evaluation of the human modelling tools has demonstrated two different approaches to simplifying the modelling process. Both approaches have demonstrated notable success in a number of areas in addition to giving significantly more understanding of what a novice and experienced user requires in the system.

The evaluation exercise at Almaraz NPP allowed the demonstration of the combined VRIMOR approach to the radiological modelling and the dose integration on human motion trajectories.

Taking into account the novelty of this methodology (EDR, laser), involving the use of new devices (3D mouse, 3D glasses, voice activation …), the plant personnel has valuated very positively this innovation, accepting the whole methodology and showing a high interest in using it.

Evaluation Conclusions

The evaluation of VRIMOR methodology can be summarized in the following conclusions:

- The integration of the VRIMOR technologies and its potential benefits has been successfully demonstrated.
- The VRIMOR methodology facilitates group decision-making in the ALARA decision process.
- The adoption of open standards has allowed each of the VRIMOR tools to exist as standalone applications or to be integrated with others tools. This also allows the user to select the most appropriate combination of tools for the intended use.
- Each technology development has demonstrated improvements in performance, usability and flexibility.
Some of the tools require minor adaptation before significant benefits can be realised. A viable route to commercialisation has been identified. The feedback from nuclear plant operators indicates that this suite of technologies would be of significant benefit to the nuclear power community.

Final Recommendations

The analysis of the results of the VRIMOR evaluation has led to the following recommendations:

- Nuclear power stations consider the use of the VRIMOR set of technologies for station maintenance planning and training.
- Decommissioning project managers use VRIMOR technologies when multi-sources exist
- Operators consider use of the technologies for novel applications
- The VRIMOR developers increase accessibility of the technologies to the user community

2.3 Assessment of Results and Conclusions

The results from all developments have been extremely encouraging. Not least of which is the outcome of the final evaluation exercise where the target end users, the NPP staff, committed to the use of the system if it were to be made available to them. This comment was made in the context of the demonstrated system being based on prototype tools that had a number of weaknesses that would be overcome before the system was delivered to an end user as a commercialised system. That apart however, the developers could use the integrated system in order to furnish the total system service to interested parties without further development.

The use of scanning technologies has demonstrated the power of these techniques to reduce dose and provide significantly more intelligence about the environment in which operators will be expected to work. Dimensional accuracy of as-built environments enables temporary equipment to be designed with confidence and accessibility issues to be dealt with effectively. The use of the gamma scanner has been shown to be of particular benefit when there are multiple sources in an environment. The combined technologies are particularly pertinent to older power plant where information quality is often poor and for decommissioning operations where again there can be significant uncertainties.

Human modelling has been demonstrated as a tool that can be delivered to inexperienced users in an effective manner and brings with it the benefits of rehearsing and optimising operations in a safe environment. It has also been demonstrated to provide a good environment for sharing with several stakeholders associated with an operation as well as providing a training facility for operatives. When combined with the ability to assess dose burdens either directly or through the use of another tool, the human modelling tools provide a means to optimise human operational plans quickly and with confidence in line with ALARA principles. The off-line dose assessment tool provides a much more versatile capability that is able to include the effects of adding shielding or moving sources. This was demonstrated effectively in the evaluation exercise where a contaminated object was removed from the work site as part of the operation being assessed.

It is concluded that the suite of tools used and developed in the VRIMOR Project has significant potential for application in the Nuclear Industry. Being focused on human interventions the tools...
are particularly pertinent to manual inspection, repair, and dismantling. The laser scanning and human modelling tools also have potential applicability in other industries.

2.4 Acknowledgements

The partners would like to acknowledge the valuable assistance and guidance provided by the Management, Engineering, and Health Physics staff at Almaraz NPP without whose co-operation the Project would not have had the opportunity to trial the developments and get feedback on their potential application.

NNC would also like to acknowledge the support and interest provided by the UK Nuclear Industry and in particular the IMC Human Factors Technical Working Group and Nuclear Installations Inspectorate.

2.5 References


Massaut, V. 2002: The Radioprotection Optimisation applied in an actual case: the BR3 decommissioning project. 3rd European forum of ‘Radioprotectique’.


3 MANAGEMENT FINAL REPORT

3.1 List of Deliverables

The list of deliverables identified in the original project plan is given in Table 1. This also shows the date of delivery and planned date.

<table>
<thead>
<tr>
<th>Deliverable No</th>
<th>Deliverable title</th>
<th>Delivery date (planned)</th>
<th>Delivery date (achieved)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1</td>
<td>Application and user requirements and sub-system functional specifications document</td>
<td>5</td>
<td>8 (1st draft) 10 (2nd draft) 15 (3rd draft) 23 (Final)</td>
</tr>
<tr>
<td>D2.1</td>
<td>Trajectory output from simulation</td>
<td>12</td>
<td>11</td>
</tr>
<tr>
<td>D2.2</td>
<td>GUI/Voice driven simulation interface and user manuals</td>
<td>17</td>
<td>17</td>
</tr>
<tr>
<td>D2.3</td>
<td>Joystick driven stereo simulation interface and user manuals</td>
<td>17</td>
<td>17</td>
</tr>
<tr>
<td>D3.1</td>
<td>Simulation based radiological dose calculation system and user manuals</td>
<td>17</td>
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</tr>
<tr>
<td>D3.2</td>
<td>Off-line radiological dose calculation system, interface software and user manuals</td>
<td>17</td>
<td>17</td>
</tr>
<tr>
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<td>3-D dose-rate calculation and user manual</td>
<td>9</td>
<td>12</td>
</tr>
<tr>
<td>D4.2</td>
<td>Gamma camera system and operators manual</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>D4.3</td>
<td>Radiological dose/geometry integration software and user manual</td>
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<tr>
<td>D5</td>
<td>Technological and user perspective review report</td>
<td>23</td>
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</tr>
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</table>

Table 1: Schedule of deliverables

3.2 Comparison of Initially Planned Activities and Work Actually Accomplished

Deliverable D1 has been recognised as a live reference for the Project and has been subject to amendments over time as more details are revealed and the Project requirements and interfaces
become firm. The definition of the target task at the NPP enabled the final requirements to be captured but the document has been subject to further editorial changes to achieve consistency in format before its final issue.

D2.1 was achieved slightly ahead of schedule while deliverables D2.2 and D2.3 were achieved on programme to be completed in time to use the data scanned at Almaraz NPP. D 3.1 was dependent on D4.1, which was achieved later than scheduled, and was delivered to programme. Similarly, D3.2, which is based on the development of an existing software system, was available to programme. D4.2 was achieved on programme and used during the scanning window at the beginning of June 2002. The output using D4.3 was delivered behind programme and prevented pre-development of the mission scenario by one of the Partners before the evaluation exercise in October 2002. This was overcome by using a fictitious but representative scenario for the training and evaluation exercise.

The original plan for the Project is shown in Figure 1. The key issue that changed very early on was the decision to remove dependencies on plant outages. These are outside of the control of the Project and posed a major risk to a key aspect, the demonstration and evaluation of the combined technologies. The maintenance task chosen for evaluation was also planned to take place in March 2002 and would therefore provide useful validation data for the evaluation exercise later that year.

The human modelling control interfaces were developed and tested well in advance of the evaluation exercise in order that a training programme and full simulation of the task could be prepared beforehand. In addition this allowed radiological assessments to be completed before the trial at the NPP planned for October 2002. In that respect the ALARA assessment tools were developed in time for the evaluation exercise. However, as a result of some inconsistencies in timings and locations of mannequins between the two independently developed simulations, the comparison was repeated at a later date when good correlation was achieved.

The dose rate field calculation algorithm was achieved early as was the gamma scanner testing under controlled environmental conditions. As a result of these initial trials, further calibration tests were scheduled to improve the results. The gamma and laser scanners were used during the same time window in order to generate a combined geometrical and radiological model by the end of June. It was the delivery of this combined model that ran late and impacted the efforts of the simulation Partners.

Despite the delays in some aspects and some technical problems with some developments, the project has achieved its overall objectives within the contract period.
3.3 Management and Co-ordination Aspects

The VRIMOR Project has been driven by the stated need for improvement in manual intervention task planning and management at a NPP. The consortium formed to address this requirement is relatively small, only six Partners, which has helped to maintain a focused approach and good communication within the Project. That is not to say that there have not been difficulties as with any multinational project where communication is an essential ingredient for success.

Electronic communication has been the primary means of maintaining contact. With this in mind a reflector was established by UPM to manage the automatic distribution of emails and attachments within the consortium. This had a number of problems associated with file sizes resulting in several messages not being received. The Project chose subsequently to operate a combination of this system with an ftp site for larger file transfers.

Despite the small size of the consortium, meetings of the entire team have been difficult to co-ordinate in view of other business commitments. Indeed, even September 11th had an impact on the project team arrangements. However, meetings have been productive in providing opportunities to resolve some overarching technical issues as well as maintaining a good focus on the project programme. All Partners have participated fully in such meetings.

Commitment to the Project from all Partners has been good although there have been some lapses as a consequence of organisational changes. The transfer from DTN to Tecnatom caused a minor delay during the early stages of the Project while the transfer from UK Robotics to RTS Advanced Robotics and then Z&F (UK) has caused more significant disruption in progress. Z+F contributions to the project although limited in scope were pivotal to the progress of the Project and their tardiness has caused several problems. Nevertheless, with continuity of the key individuals throughout the period, the damage to the Project has been contained and the commitment sustained throughout. These organisational changes did result in significant
additional burdens for the Coordinator in unravelling differences between Partners and communications with the Commission.

To aid communication and progress, individuals were allocated responsibilities for co-ordination of work packages. This resulted in meetings and correspondence between smaller groups of Partners to resolve particular interface or other issues and undoubtedly helped to achieve satisfactory Project completion.

The high degree of motivation exhibited by all Partners was a reflection of the potential exploitation that each saw arising from the Project. The nature of the developments undertaken was that they offered two distinct results: the development of the individual Partner’s capability and the benefits of the combined technologies.
4 SUMMARY OF FINAL REPORT

4.1 Objectives

The main objective for the VRIMOR Project stemmed from the identification of difficulties associated with the planning and execution of manual interventions at Nuclear Power Plant. It had been observed that particularly during unplanned activities where there is often a degree of urgency then the information available and the processes involved in planning were inefficient and would often lead to more cost and more radiological exposure than was necessary. The VRIMOR consortium was formed with the objective of solving this problem through the delivery of a suite of integrated tools that would benefit maintenance planners and supervisors, ALARA specialists, and maintenance operators.

With such a target user community it was decided that an important element of the Project was for sample NPP staff to participate in the development programme and to evaluate the resulting suite of tools. Thus one of the key objectives of the VRIMOR programme was to develop user requirements that would direct the research and tool developments. Being a R&D programme however these requirements would be constrained by the developers to activities that were achievable within the programme, likely to be cost-effective, and that could be fully evaluated. Achieving a valuable evaluation was also a key objective in that it would provide the direction for future development and exploitation within the Nuclear Power Industry and give some guidance for other industrial applications.

The technical objectives were twofold. The first being the ability to transfer data between a suite of tools in such a way that their combination provided a system that helped to solve many of the difficulties identified with manual intervention task planning. The tools involved were a laser scanning system to capture the geometric environment, a gamma scanning device to capture the radiological environment, human modelling tools to plan the intervention tasks, and dose analysis tools for the ALARA assessment. The objective was to be able to present to the maintenance planner and ALARA assessor a virtual environment and analysis capability that would enable them to make quick and confident decisions on how to carry out an intervention most effectively. All the tools, with the exception of the gamma scanner that was a prototype, were based on commercially available software and hardware.

The second technical objective was to develop each of the tools to make them more accessible and more effective for the target applications. The laser scanning system software was to be developed to be able to import radiological data and to export geometrical and radiological data in an open standard format. The gamma scanner was to be developed to improve its accuracy, its decontaminability, and its control. The human modelling systems were to have user interfaces developed to ease their use by inexperienced modellers. Two systems were selected and voice control and joystick type control were developed to meet this objective. These systems were also to include the ability to export motion trajectories for subsequent dose analysis. Two dose analysis systems were to be developed. One was to be able to read the motion trajectories from the human modelling software; the other was to be able to compute the integrated dose within the human modelling tool.

The objective of developing some duplicate capabilities was to provide validation and cross comparison enabling the best combination of tools to be identified for a particular task. This was considered particularly important for the consideration of future exploitation in areas other than
NPPs. Indeed, one overarching objective was to make the development of each tool such that it could be re-used in isolation or with systems other than those used within the VRIMOR Project.

4.2 Research Performed and Methods Adopted

As much of the software and equipment being used within the VRIMOR Project was commercially available the Project may be considered as near to market and the extent of research to be carried out was limited with most efforts being applied to development and evaluation. The following highlights some of the research issues that arose during the development programme.

Clearly, as this Project was heavily directed towards NPP applications, considerable efforts were applied to establishing user requirements. This involved consideration of a range of potential application areas at a NPP and the nature of the problems associated with those areas. This research was achieved through close communications with NPP staff particularly at Almaraz where the evaluation exercise was planned to take place. From these communications, the project team were able to compile a schedule of success criteria against which to measure the effectiveness of the VRIMOR developments.

In developing the interface control designs for the human modelling tools, consideration was given to some prior research and further surveys carried out with NPP staff in UK and Spain. This concluded that the level of computer literacy for the target end user should not be expected to be high and that the amount of time that would be available for training would be very limited. As a consequence the modelling control interface had to be developed to be highly intuitive. Voice recognition was selected as one means of delivering the required ease of use and various systems were researched to find the best for integration with a commercial human modelling tool.

In addition, it was established that high powered and expensive computer systems were not available at NPPs and any tools had to work on moderate standard PCs. Some research was carried out on the most economical system level that would be acceptable. The most significant element was the graphics card capability, particularly if this was to support stereovision. It was concluded that satisfactory performance could be achieved with standard modern office PCs with an enhanced graphics card that would add less than 200 euro to the cost. In a similar vein a review exercise was carried out for the selection of a joystick device that was cost effective. This research involved discussions with several different end users as well as reviews of technical specifications.

Both human modelling exercises had to establish the best way to interface with commercial software programmes. This was made more difficult due to the proprietary nature of the programmes and their interfaces and prevented the respective developments being directly interchangeable between modelling tools. COM component architecture was used to maximise the level of re-use where possible. C++ was used as the favoured language for development, which required some research into how to interface with a C-based API for one application.

The radiological data manipulation was a new development and required some research into the best method of source fitting. This together with the modelling methodology was tested in both experimental and industrial environments to obtain confidence in the final technique. The dose integration technique used in the human modelling tool was based on a dose rate grid. Some iteration was carried out on the method of interpolation to minimise errors in gradient fields. However, as determined from the end user requirements research, the level of accuracy was not
required to be high in view of the uncertainties in human behaviour, which dominate the prediction error.

The gamma scanner was developed from a prototype to a pre-industrial version, which required a degree of research into the characterisation of its directional response. This was carried out using a controlled environment with known point sources and used to develop a characteristic that would be used subsequently for interpreting the data scanned in unknown fields.

4.3 Main Achievements

The first achievement was the development of a requirements document based on the potential end users perspective but with constraints identified by the VRIMOR Project Partners. This provided a sound reference document against which the respective tool developments and interfaces were completed. It was also used to establish evaluation criteria against which the success of the project deliverable would be measured. The involvement of NPP staff in the formulating of these requirements was invaluable but resulted in numerous iterations to ensure that the demonstration task for the trial at Almaraz NPP was achievable.

The capture, manipulation and data transfer of geometrical and radiological information to provide 3D visualisation models for subsequent interrogation and interaction was a major achievement. It was this principle of providing the two data types in a single environment captured using remotely operated equipment that formed the basis for the improvement to intervention planning. Once this virtual environment was available then the human modelling and other tools could be used to evaluate options for the planned intervention. Spatial considerations could be accommodated readily as could equipment requirements including access facilities. Finally, the ability to obtain immediate visual feedback on dose rate levels at any point in the virtual environment helps the planner and ALARA specialist to optimise an operational plan.

The interfaces developed for the two human modelling tools, JACK and ENVISION ERGO, were extremely powerful for both the expert and non-expert user. The voice control interface was liked by NPP staff as it was very intuitive to use. However the preparation requirements were complicated and not visible to the evaluators. In contrast, the space mouse control interface required more training to use effectively but provided a totally flexible modelling approach. It was concluded that both were viable control interfaces and that a combination may provide an optimum for some circumstances. These developments are applicable to many industries and could bring immediate benefits in efficiencies of production to users of these commercial modelling tools.

4.4 Exploitation and Dissemination

All Partners have significant experience in their own technological fields within the VRIMOR Project and are committed to the advancement of those technologies as part of their respective corporate strategies. This applies to both the commercial partners, who wish to retain a leading position in their respective fields, and the government, research and educational establishments who have similar motives. This Project has therefore provided a significant opportunity for all Partners of the consortium to develop skills and facilities directly in line with their respective corporate strategies and business objectives.
In particular, it is noteworthy that, while the Project programme was aimed toward a demonstration of the effective combination of technologies, the strategy was not to constrain the potential combination to the present Partners. The subsequent exploitation may therefore see smaller partnerships developing from within the consortium or even individual Partners using their developments alone or with others outside the present consortium. This flexibility adds significantly to the exploitation potential from this Project. Nevertheless, the achievement of a working demonstration of the combined technologies with the present consortium provided a powerful incentive for future partnerships to develop from within the Project.

One important objective has been to achieve standards for data exchange within the Project. One aim for the software developments undertaken in this project was to achieve modules readily convertible to plug-ins for the commercially available human modelling packages. The VRIMOR project vision is that these tools should be available at acceptable cost on desktop computers within 3-4 years of project commencement. While interfacing with two different modelling packages has been possible, the extent of reusable software applicable to both packages has been severely limited as a consequence of the disparity between those packages. Nevertheless, some elements of the present developments will be reusable and this will influence the future development plans for the respective tools.

It was similar for the scanning facilities that were developed and interfaced within the Project. The core technologies associated with these facilities are continually being developed such that their costs and performance should result in usage costs that are within reach of NPPs or utility companies within a short period after Project completion. The establishment of interfaces using prototype facilities within this Project has shortened the time to market and contributed to the development and marketing of the technologies ahead of their potential commercialisation. Furthermore, the successful adoption of open standards for data exchange has provided stability for the developments and opened up opportunities for further exploitation.

Having identified the end users and the project aims, it is clear to see that the competitiveness of EU nuclear utilities will be improved from the adoption of the tools developed within this Project. Productivity should increase as a result of reducing outages through the effective use of these tools. As a consequence, costs will be reduced through more efficient working and the removal of project risk while safety and human reliability will be increased as a result of improved planning and training of staff. These benefits have been quantified following the evaluation exercise and estimates have been based on conservative assumptions on utilisation at typical NPP. The results show that a relative short-term return on investment is achievable and that additional unquantifiable benefits from risk reduction can be expected from the judicious application of the tools.

The VRIMOR Project has been very clearly focused on the NPP inspection, maintenance and repair teams and subcontracted staff. Although some of the equipment will be provided and used by consortium partners, the majority has been designed for use by NPP staff. The successful demonstration and acceptance by these workers of the tools developed here has been the key to the further exploitation of the work. Since the project has utilised commercially available software and hardware in several work packages, due consideration has been given to how this will influence the potential commercialisation of the developments.

The new and novel tools developed within VRIMOR (e.g. scan, model and simulate to minimise dose uptake) are aimed at the nuclear industry. Although this market is well understood, it is constantly evolving and all hazardous work which involves dose uptake is subject to increasing
levels of restriction which, over time, should lead to increasing demand for these concepts. On a year by year basis, acceptable dose levels continue to fall and this, in turn, limits the number of intervention operations that can be performed by humans, which in turn creates an increasing requirement for VRIMOR type of tools. The successful demonstration of providing tangible benefits on a real site, in this case Almaraz NPP, will dramatically improve the acceptance and take-up of these tools at other facilities.

Looking away from the nuclear industry, it is clear that combining data from a number of different sensors to create synthetic environments, which reflect the reality of any given situation, has many potential applications. This is especially true when the resulting models can be used with 'live' mannequins to perform "what-if" type tasks in order to show a user the potential risks and gains of a given scenario. Such markets could include: military simulation, sub-sea and space. The Partners have given consideration to a range of exploitation opportunities relating to their respective business, some of which are mentioned above.

The Partners have begun their dissemination activities through a number of initiatives. Several have websites with pages and links associated with the VRIMOR project. Some have been giving briefings to their customers on the developments that will arise from the Project. The Project has presented a paper at FISA 2001 and is considering participation in a forthcoming ALARA conference. The successful completion and demonstration of the combination of VRIMOR tools together with an estimation of the potential cost benefits of their use (including dose reduction) provides an excellent basis for the dissemination of the work through publications, seminars and conferences.