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3-D TV SYSTEMS FOR REMOTE OPERATIONS: DEVELOPMENT AND APPLICATIONS

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ABSTRACT

This paper describes a development of 3-D television systems at Harwell and a comparison of a 3-D system with conventional TV. 3-D TV has been proven to be a useful remote handling tool which gives operators improved perception of the remote scene and so enables them to perform tasks more accurately and quickly. The paper describes trials at Chalk River Nuclear Laboratories with a Harwell 3-D TV system. This trial involved the performance of a navigation task via a remote manipulator which showed a significant benefit for three-dimensional television. This adds to the existing knowledge of TV systems performance for remote tasks which enables cost-benefit assessments to be made for new applications. A recently developed radiation tolerant 3-D camera is also described.

INTRODUCTION

The Remote Handling and Robotics Department of AEA Technology based at Harwell Laboratory carries out research, development, and applications engineering on remote television systems for remote handling and inspection, primarily for nuclear environments. The work includes the development and application of stereoscopic or three dimensional (3-D) TV. Chalk River Nuclear Laboratories (CRNL) of AECL undertakes applications engineering for remote systems in CANDU reactors and other nuclear facilities (Charles Kittmer to change if required). The purpose of 3-D TV in remote handling is to improve the operators perception of the remote scene and thus to improve his performance of a wide range of tasks. Early development work on 3-D TV at Harwell concentrated on producing basic design rules to ensure that stereoscopic pictures presented to the operator are both comfortable to view and give useful depth information. This development and evaluation work has been reported elsewhere [1,2]. The guidelines produced relate to the electronic and optical matching of the two picture channels, as determined by the optical design of the stereoscopic camera and display, and to the accuracy of depth reproduction.

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The purpose of this paper is to describe recent developments in technology and experiences in applications trials of 3-D TV systems designed and built at Harwell Laboratory. The main developments reported are associated with the design and manufacture of an advanced radiation tolerant 3-D camera, improved display systems, and video tape recording techniques. The trials reported here were carried out at Chalk River Nuclear Laboratories in connection with the application of 3-D TV in CANDU stations.

EVALUATIONS AT CRNL

Summary Remarks

A wide range of evaluations of the Harwell Stereoscopic Television System, and conventional two dimensional television systems have been carried out recently at Chalk River Nuclear Laboratories. The purpose of the evaluations has been to provide information for designers and users of remote-handling systems in order that the specification of cost effective television viewing equipment can be readily made.

The main results of the evaluations are in line with those reported earlier by AEA Technology, Harwell. The results showed that the high quality stereoscopic television system gave performance benefits in terms of accuracy and speeds of operation for most remote handling and inspection operations. The benefits were more marked for the following types of operation:

- Tasks involving scene indentification or object recognition.
- Tasks involving complex manipulation.
- Tasks where there is a lighting or visibility difficulty.
- Tasks where multi degree-of-freedom alignment is required.

In addition it was found that the positioning requirements of the Harwell 3-D TV camera were less exacting than the requirements for the other systems.

One of the Chalk River trials is particularly worthy of reporting here because it gives new results for a previously unreported task type; ie navigation through a cluttered environment. This task was included in the evaluations at CRNL because of potential applications in navigating within the calandria of CANDU reactors.

Experimental Set-Up

Four camera set-ups were used for each experiment:

- o Set-up A (2-D, level): A Harwell stereoscopic CCTV System operating in 2-D mode with its camera faced 46 centimetres above the floor and approximately 3 metres from the task site.

- o Set-up B (3-D level): A Harwell stereoscopic CCTV System operating in stereo mode with its camera in a position identical to that of Set-up A.

- o Set-up C (orthogonal 2-D): Two separate 2-D cameras placed 46 cm above the floor and position such that their optical axis intersected at the task site orthogonally. The position of the reference camera was similar to the camera position used in Set-ups A and B above.

- o Set-up D (2-D, elevated): A Harwell stereoscopic CCTV System operating in 2-D mode placed 1.7 metres off the floor and aimed down at the task site, approximately 3 metres away.

Ten AECL employees participated as subjects in the assessment programme. Each was tested for depth perception prior to the experiment using a Bausch and Lomb vision tester. All subjects have previous remote handling experience. In order to remove the effect of learning from the results, the camera set-ups were presented to each subject in pseudo-random order.

The test, termed the Maze Test, was designed to simulate a visually complex task site and involved manoeuvring a vertical rod through an arrangement of 13 tubes in a pre-determined order and placing it in a specified tube. The camera and task arrangements are shown in Figure 1. The tubes ranged in height from 25 to 91 cm and in diameter from 3 to 7.6 cm. Before testing began, subjects were run through the course viewing it directly in order to establish a control time for each operator. For each camera set-up a subject's time, number of hits (inadvertent contact with tubes) and number of attempts to complete the task (manoeuvering as well as insertion) were recorded.

Results and Conclusions, Maze Test

When performing this complex task the 3-D level camera set-up was found to be superior to other set-ups in both speed and accuracy. The other set-ups, 2-D orthogonal, and 2-D elevated were similar to one another in terms of accuracy and speed but fell far short of the performance of the 3-D level, requiring over 2.5 times the task duration and incurring 3 times the number of hits. It was observed that subjects operating with the 2-D orthogonal were very confused when performing complex tasks, one subject was unable to complete the task using this set-up. The other set-up, 2-D level, yielded the poorest results both in terms of speed an accuracy. The speed and accuracy results for the four camera set-ups are shown in Table 1 below:

Table 1 - Results for Maze Test at CRNL

Camera Set-Up	Mean Number of Hits Incurred	Ratio and Mean Time Taken to Perform Task
A: 2-D, level	3.7	4.23
B: 3-D, level	0.6	1.00
C: 2-D, orthogonal	2.6	2.87
D: 2-D, elevated	2.9	2.18

Subjects Comments

Subjects were asked to make general comments on the tasks and television set-ups. Subjects found set-up B, 3-D level, to be superior to all other set-ups tested in that it provided strong and unambiguous depth information. Subjects reported that this enabled them to perform the tasks with more confidence and speed. Subjects also reported that the 2-D orthogonal set-up was the most difficult system to use, even though it did not produce the worst results. The most prevalent complaint was the confusion that the subjects had in co-ordinating the two images in order to interpret the scene. This confusion was a strong factor in highly complex tasks.

Trial Conclusions

The results for the Maze Test given above provide useful additional information to data already accumulated from previous experiments using 3-D and 2-D television systems [3]. The information now held on trials of television systems provides valuable information which may be used to assess the cost-benefit of applying a given television system for new applications. The factors which should be taken into account when making a cost-benefit analysis for television systems include the following:

- Fewer cameras might be required for 3-D systems.
- Fewer camera deployment systems required for 3-D systems.
- Impact of chosen television system on project completion time.
- Impact of television system on errors, collisions, and consequent damage to remote handling equipment and plant.

In addition to the tangible and measurable benefits of 3-D TV, it is likely that there are additional benefits. These arise both from the reduced work-load place on the operator when using 3-D TV systems and from the improved ability to recover from unexpected event. This improved ability to recover from an unexpected event is due to the improved scene interpretation capability provided by high quality three-dimensional TV systems.

CAMERA DEVELOPMENTS

The ultimate aim of the development work on 3-D TV systems is to provide systems which can be used for a variety of nuclear applications including: inspection of power reactors; post-irradiation examination; fuel processing applications; and decommissioning of a wide range of facilities. The specification for a camera to work in these environments was produced by consultation with experts on remote viewing systems within the UK nuclear industry and by analysis of requirements for decommissioning of the Windscale Advanced Gas Cooled Reactor (WAGR). The specification included the temperature requirement to 150°C with chilled air cooling, on board lighting requirements, materials and mechanical constraints. Some aspects of the camera specification and design are discussed below.

Choice of Lens

The survey of requirements indicated that the camera should have more than one angle of view. This presented problems in the design. A zoom lens is a desirable feature in advanced stereoscopic cameras. Operators are used to using zoom lenses and may feel restricted by a single or multiple fixed angles-of-view. However, on the timescale required for the development of this camera it was not possible to overcome the difficulties of incorporating commercially available radiation tolerant zoom lenses. The precise requirements of image matching apply equally well to the imaging lenses as they do to the processing electronics and display systems. The available radiation tolerant zoom lenses were surveyed and it was found that none had suitable characteristics for incorporation to a versatile stereoscopic camera. The principal problems with existing zoom lenses were either the size of the lens which restricts the necessary small camera inter-axis distance, or the repeatability of positioning of the lens elements. Lack of repeatability causes off-sets either in image size or position. If these exceed the limits previously discussed [2], then the lens will be unsuitable for use in the stereoscopic camera. In order to provide two angles of view without the use of zoom lenses, it was decided to incorporate two sets of lenses for wide and narrow angles of view on a high accuracy turret mechanism. The high accuracy mechanism ensures that the stringent requirements for matching in stereoscopic pictures are met.

Although no commercially available zoom lens could be found to suit this camera. There is no fundamental difficulty in using zoom lenses in stereoscopic pictures and excellent results have been achieved on laboratory prototype cameras at Harwell. It is preferable to design the lens specifically for stereoscopic use and a project to produce such a lens is currently underway at Harwell Laboratory [5].

It should be emphasized in the selection of stereoscopic cameras that zoom or multiple focal length cameras should not be specified without considerable thought. Either option of multiple angle of view or zoom lens adds considerably to the complexity of the stereo camera and therefore to the cost of the installation. In many circumstances it is necessary to specify multiple angles of view but in some cases it will be possible to avoid this, possibly by use of a more versatile deployment system, which would allow operators to make full use of a single, fixed, angle of view.

Camera Electronics

The requirements for camera electronics in a radiation tolerant stereoscopic camera include requirements for accurate matching of the two pictures. This is achieved by increasing the amount of control over the scan wave-forms and video processing circuits. Because the camera is radiation tolerant, it is necessary to use camera pick-up tubes rather than more modern solid-state camera sensors. Choice of a high quality camera tube enables excellent radiation-tolerance performance combined with very high picture quality. These tubes require electronic signals to achieve the scanning of the electron beam within the pick-up tube. The scan circuits must allow sufficient adjustment to cope with any non-linearities in the tube focusing and deflection arrangement. The adjustments to scan wave-forms are achieved by addition of supplementary wave-forms to the main scanning saw-tooth. Such circuits are not normally encountered in radiation tolerant television cameras and were designed specially for the Harwell stereoscopic camera.

Computer Control System

Accurate picture matching also calls for computer control of sensor and lens adjustments during normal operations. These adjustments are necessary to change the focus and convergence distance of the camera. Additionally the incorporation the camera design of two angles of view means that the sensor and lens adjustments need to be altered when the angle of view is changed by movement of the lens turret. When the lens change command is selected at the console, the computer demands the unlocking, rotation, and re-locking of the lens turret, at the same time the new positions for lens and sensors are calculated and the motors are driven to their new positions. During this time the video output of the camera is blanked (for approximately 0.5 seconds) so the operator does not see a confused picture while the lens is being changed and the picture re-focused. The re-calculation of lens and sensor position ensures that the camera is focused and converged on the same position in the object scene before and after the lens change operation. As in earlier cameras developed by Harwell, the link between focus and convergence is retained. This reduces the number of controls which the operator needs to use, thus simplifying his task. In this camera the link is made by calculation in software; as a focus change is demanded, so the position of the focus lens is monitored and the position requirements for correct convergence are maintained during the focus operation. It is envisaged that as operators become more skilled in the use of stereoscopic cameras they will occasionally want to overrule the software link between focus and convergence. This might arise when, for example, an operator wants to maintain his view of an overall manipulation scene but to improve focus towards the rear of the scene. In this case he would be allowed to leave the camera converged at the front of the scene but to change focus to the rear of the scene. However, for most operators best results will be achieved by having a fixed link between focus and convergence distance.

The presence of computer control in the camera system allows other advanced features to be incorporated in the camera. An important one of these for remote handling operations is a read-out of convergence distance at the control panel. It is a feature of accurately engineered stereoscopic cameras that the camera and display can be used for a range-finding. The camera operator views the display and adjusts the convergence control until the two images (left and right) of the object of interest merge together on the screen. At this point the camera is converged at that distance and feedback from the convergence position motors can be translated into a distance from the front of the camera. This information is valuable for planning remote handling operations and enables accurate sizing of items within the field of view. Computer control also allows the read-out of camera temperature, coolant flow and lens setting of wide or narrow angle-of-view.

The camera controller computer is located on the cold side of the active facility with the rest of the camera control unit and display electronics. Cabling is minimised by the use of final drive circuits and buffers for the sense in potentiometers in radiation tolerant designs located in the camera head.

Camera Features

The main features of the newly developed camera are summarised in Table 2. The camera can work with cable lengths in excess of 100 metres. The target design figure for radiation tolerance is a total dose 10^6 Gy (= 10^8 rad) with dose rates up to 10^4 Gy/Hr (= 10^6 rad/Hr). The camera has automatic iris function and also allows manual iris control.

DISPLAY DEVELOPMENTS

The basic design of displays has not been altered since the original design was produced in 1986. This design has been found to work extremely well and the displays produced have worked reliably in a number of applications since 1986. Each display comprises two monitors and an optical arrangement which combines the two pictures by a semi-reflective mirror and allows separation of them at the eyes using lightweight polarising spectacles. It is important that the pictures are well matched both electronically and optically. In recent designs of the monitor electronic matching is achieved by additional custom-built circuitry within each monitor. This is preferable to the earlier method of alignment of the pictures using magnets placed within the monitor around the display tube. Electronic adjustment is easier to achieve than magnetic adjustment and has proved extremely reliable during operation.

The original monitor sizes were 15" diagonal for black and white and 16" diagonal for colour. In order to achieve a more compact and more portable display a smaller version which incorporates many of the advanced features of the larger displays has been produced. The first prototype of a 12" black-and-white display is now complete and a similarly sized 14" colour display is being considered.

VIDEO TAPE RECORDING OF 3-D TV PICTURES

3-D pictures can be recorded in a number of ways. The usual way used with the systems developed at Harwell is to record the left and right fields alternately to the odd and even fields of the video tape. The tape is then played back via two frame stores which repeat fields to ensure that the picture as played back does not flicker. For example, the left field is repeated once while the right field is being read from the tape to the right monitor and to its respective frame store. This method has a slight disadvantage in that the left and right pictures as recorded on the tape are not taken at the same instant in time. If it is necessary to have simultaneous information from both cameras, for example if measurements of a moving object are to be taken from the video tape, it is necessary to use an alternative technique. One such technique is the use of two high quality tape recorders synchronised together. This method gives very good results but it is expensive and requires some skill on the part of the operator in recording and playback. An alternative technique for recording simultaneous left and right pictures uses the multiplexing of the two pictures onto a single line of video information so that the time difference between pictures is limited to 30μS. This technique together with the other techniques mentioned is described more fully elsewhere [4].

CONCLUDING REMARKS

The trials and equipment developments described here show that 3-D TV can provide a useful tool in remote handling and inspection operations. Development is already at a stage where 3-D TV systems can be usefully employed to enable operators to carry out remote operations more quickly and accurately than with conventional television.

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