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3-D TV: EVALUATIONS AND LESSONS LEARNED

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ABSTRACT

The paper describes the development and evaluation of 3-D Television Systems. 3-D TV had been developed with a view to proving whether it can be a useful remote handling tool which is easy to use and comfortable to view. The paper summarizes the principles of operation, the initial development, the evaluation trials at UK facilities and it reviews the developments which have subsequently taken place. 3-D TV systems have been found to give improved performance in terms of speed and accuracy of operations and to reduce the number of camera views required.

INTRODUCTION

The Engineering Sciences Division of Harwell Laboratory carries out research and development of remote television systems for remote handling in nuclear environments. The work includes equipment development and human factors experimentation; its ultimate aim is to facilitate the widespread introduction of television (TV) viewing equipment into nuclear plant.

The work includes the development of stereoscopic or three-dimensional (3-D) TV. This programme of work is nearing completion, it has been split up into the following stages:

a - Determine criteria for design of 3-D TV to be comfortable to view and useful for remote operations

b - Build engineered prototype systems

c - Evaluation of prototypes in various cold mock-up facilities

d - Build 2nd generation system, and evaluate

e - Build 3rd generation, radiation-tolerant black-and-white, system

f - Deploy camera in radio-active environments

The programme is complete up to stage (d); the third generation, radiation-tolerant camera is currently being built. The purpose of this paper is to summarize this development and evaluation programme. The work has made available 3-D TV systems which give useful improvements in depth perception for a wide range of viewing requirements and environmental conditions. The systems have proved comfortable to view, easy to use, and robust in operation.

3D TV

The purpose of the 3-D systems developed at Harwell is to give operators improved depth information about a remote scene. The 3-D systems do this by providing the viewer with binocular information which allows him to perceive a solid image from two flat pictures. The two pictures come from two cameras which are offset a small distance horizontally and whose

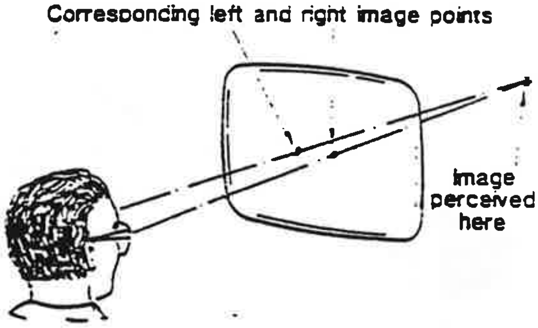


Figure 1: 3-D Image Formation

focussing targets are in the same plane. (The focussing target is equivalent to the film in a camera). The two pictures are identical except for small horizontal differences in image position. These disparities vary with the distance of the objects from the camera, so there are a range of disparities for different objects in a normal scene.

Figure 1 shows a viewer looking at a 3-D screen which allows him to see only the right image with his right eye and the left image with the left eye. Because there is a horizontal disparity between the left and right images of the same object, the viewer is tricked into perceiving the object behind the screen. A 3-D picture is built up of a large number of such points, with different horizontal disparities and therefore different distances behind or in front of the screen.

Some object points may give no horizontal disparity and so their images appear in the screen plane. They have no disparity difference because the object is in the plane in front of the 3-D camera in which the two camera axes cross, (see an earlier paper[1] for a fuller description of this and the theory of 3-D images). The control of the camera axes can thus be used to control the position of the 3-D image relative to the screen. The objects of interest are normally placed close to the screen plane, ie the cameras are converged on the objects of interest. This is important because we have found that viewers can only cope with a limited range of horizontal disparities. The limitation is because the viewer's eyes stay focussed on the screen but they change convergence around the scene to converge at distances appropriate to the image point placement. In other words we find that the viewer can accept small discrepancies between accommodation and convergence, but not large ones. We have therefore designed systems to enable the operator to keep the image acceptably close to the screen, in a truncated pyramid, as

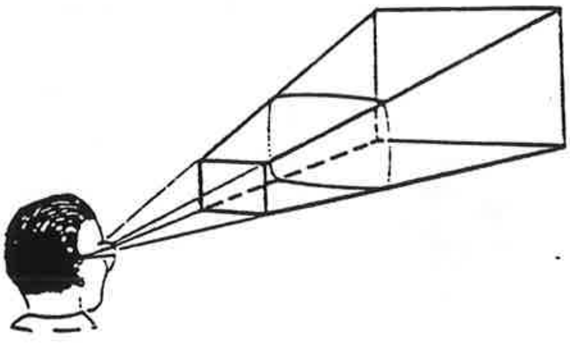


Figure 2: The Truncated Pyramid Encompassing the 3-D Image

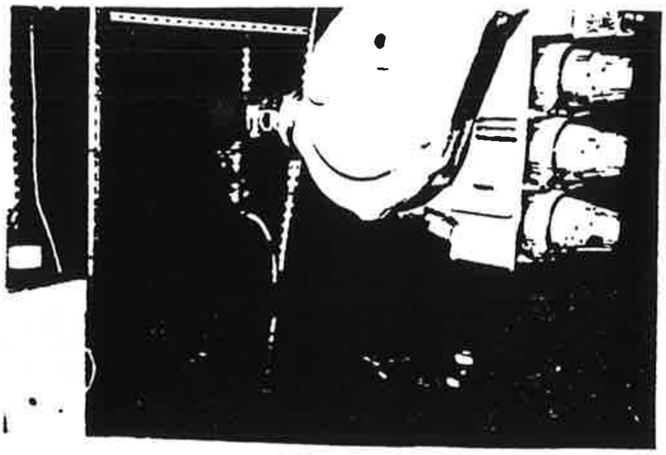


Figure 3: Reinforcement Bar Cropping Task

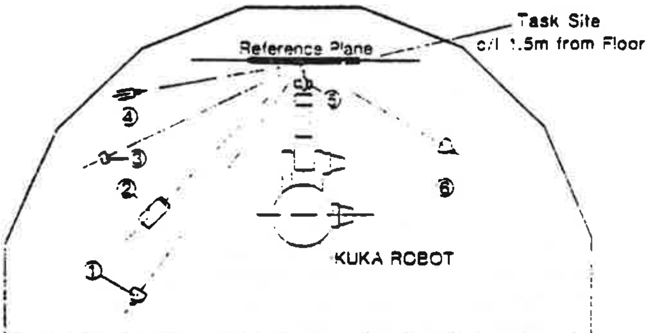
shown in Figure 2. We have suggested guidelines for the matching of the left and right pictures, and for the control of depth and shape reproduction[1,3]. We have found that, if these are adhered to, 3-D pictures can be comfortably used over long periods of time.

FIRST PROTOTYPE SYSTEM AND EVALUATIONS

The first engineered systems to be made to the suggested guidelines have been evaluated in non-radioactive conditions in facilities within the UKAEA and CEGB. The camera uses four solid-state cameras to give wide and narrow angle stereo pictures. The focus and convergence of the cameras are linked so that both pairs are focussed and converged on the same plane, a single front panel switch movement operates focus and convergence for both cameras. This makes control of the camera relatively simple. The display uses two monitors set at right angles and viewed through a semi-reflective mirror. Polarizing filters at the monitor faces and in spectacles worn by the viewers separate the left and right images. The spectacles are lightweight and are similar in appearance to sunglasses or corrective spectacles.

Preliminary evaluations at Windscale Laboratory showed a 23% improvement in the time taken to complete a typical decommissioning task - cropping a reinforcement bar - via a remotely operated industrial robot in a mock-up facility. The facility is designed to test and develop equipment for nuclear decommissioning, particularly with respect to the decommissioning of the pressure vessel of Windscale's Advanced Gas-cooled Reactor (WAGR).

Four operators were asked to carry out a series of cropping tasks using a KUKA robot fitted with a small hydraulic scissor-shear. Figure 3 shows



	Description	Angle from Ref Plane	Height from Floor (m)	Angle from c/l of Task	Radius from c/l of Task (m)
1	Lamp 500W	55	2.3	11	3.5
2	Stereo Camera	45	2.1	13.5	2.3
3	Lamp 500W	25	1.5	0	2.5
4	C.C.D. Camera	10	1.5	0	2.0
5	C.C.D. Camera	90	3.5	80	3.3
6	Lamp 800W	30	2.0	21.5	1.8

Figure 4: Camera Arrangement for Cropping Task

the robot with the scissor-shear and the steel grid on which the cuts were made. The robot was controlled remotely via a hand controller. Television viewing arrangement was the independent variable, and the floor plan is shown in Figure 4. The viewing conditions were:

Condition 1, 3-D - The stereoscopic camera was mounted obliquely to the task as shown. Operators were allowed to switch between wide and narrow angles-of-view and to pan and tilt the camera. The narrow angle view just covered the complete area of the task - there was no need to switch to the wide angle if small pan-and-tilt movements were made. If the wide angle-of-view was used exclusively, pan and tilt motions would not be needed.

Condition 2, Orthogonal Cameras - Two cameras were placed at right angles to each other with respect to the task and manipulator tool axis. Informal trials were used to determine the positions of the cameras. Whereas the 3-D camera was found to give acceptable views at the first try, two subsequent attempts were needed for the orthogonal cameras. The cameras were originally mounted further forward, but this gave operators orientation problems. Both orthogonal cameras had fixed focal-length lenses, giving a slightly larger angle-of-view than the 3-D narrow angle, so that the task could be completed without panning and tilting the cameras. For both TV conditions lighting was fixed and not within the operator's control.

The operators each made eight cuts in a pre-determined order on the simulated reinforcement bars. Figure 5 shows the order in which the cuts were to be made. At the start the cutting tool was placed near the centre of the grid; operators were asked to proceed from one cut to the next until all eight were completed. The time was recorded when each cut was made and the times are recorded in Figure 6. The average times to complete the eight cuts were 9 mins 22 secs for 3-D and 11 mins 33 secs for orthogonal, but it was not possible to establish statistical significance. Figure 6 shows that the times averaged over the four subjects showed an improvement for each of the eight cuts, except for cut 2 which was the same for 2-D and 3-D. It also shows more consistent standard errors for 3-D than for 2-D. A study of video tapes made of the operations showed that the reduction in time for stereo was linked to fewer discrete movements of the robot being made. A number of operators who used the equipment during these trials and other operations expressed a preference to work with the 3-D system. None said they preferred the orthogonal or expressed any difficulty in using the 3-D system.

One of the prototype black and white systems is in use at the Central Electricity Generating Board's Marchwood Engineering Laboratory. It is set up in a test and evaluation rig for in-reactor manipulators[2]. The 3-D system provides visual feedback for a range of simulated in-reactor operations such as welding repairs. Operators have chosen to use the 3-D rather than alternative two-dimensional (2-D) systems also available and report improved visual feedback.

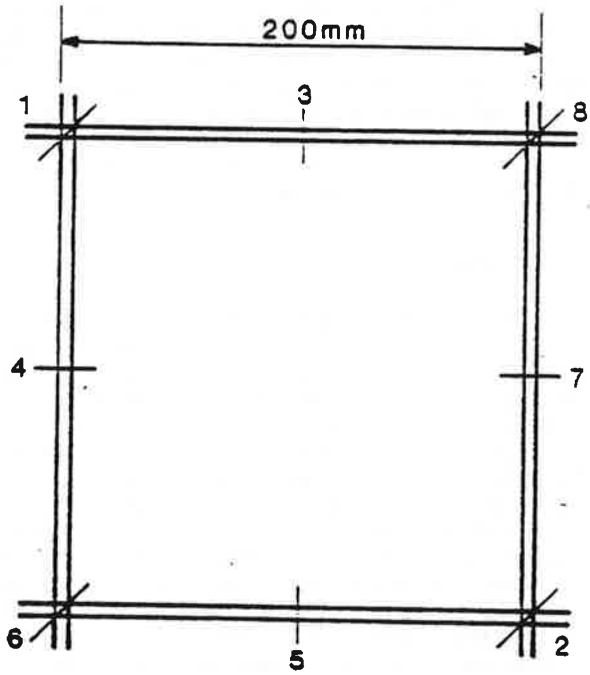


Figure 5: Cropping Task: Cut Order and Orientation

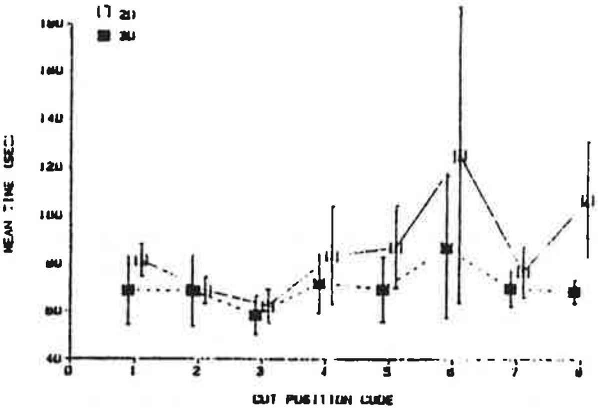


Figure 6: Cropping Task: Mean Times and Standard Errors for 2-D and 3-D TV

The extended time over which the system has been used at this facility has provided an opportunity to check the stability and performance of the camera and display in the hands of operators with no expert knowledge of television equipment. Regular inspection has shown no routine requirement to set up the camera mechanisms. There has been some drift in monitor geometric alignment after one year, but this was small enough not to give operational problems and was easily corrected. The display brightness and contrast controls, which need to be carefully matched on the two monitors, had been locked off during installation and so had not been adjusted by operators. The settings had not drifted significantly during the eighteen months of use. Part of the design philosophy had been that the operator should not be able to change settings that are not essential for operations. This has been largely confirmed by trials - operators have not expressed a wish for more adjustments, and the equipment has stayed well set up.

TRIALS AT WINDSCALE: COLOUR 3-D

Evaluations of the second generation colour 3-D system described later in this paper, were carried out at the Windscale facility described previously. A task was based on an operation planned as part of decommissioning WAGR; two heavy steel plates were to be moved between stands and a 'toast rack' using an overhead gantry crane, see Figure 7. The task involved rotation and accurate positioning of the plates. One was a curved piece of thermal shielding 5cm thick, and the other was flat and 8cm thick. Respectively, these were to be inserted into slots 9cm and 8.3cm wide. Two television views were provided - a main view looking along the slots from 1.6m above the toast rack and an oblique supplementary view - based on camera positions possible for the real operation. The supplementary view was always in 2-D but the main view could be either 2-D or 3-D.

Six operators were timed using both 3-D and 2-D. Half used the 3-D first, the others 2-D. In turn, with each viewing system, the operators moved the curved plate from stand to toast rack, the flat plate to the toast rack and then returned both to their stands. The sequence was then repeated. For analysis the task was split into sub-components. This showed that the part of the task which required the most positional accuracy benefitted most from 3-D TV. This was the part of the task where the plates were aligned with the toast rack; a 17% time improvement was found for 3-D.

A questionnaire was completed by the six timed operators plus two more who had also used both the 2-D and 3-D arrangements. The 3-D was highly rated on picture quality and ease of use. All except one had preferred using 3-D and would have been happy to do so for extended periods. Some operators commented that the 2-D views could have been better placed - plan and elevation views would have been preferred - but with 3-D, the camera positions were satisfactory. This is in accord with earlier findings that the positioning of a single 3-D view is far less critical than the optimal siting of a pair of 2-D views. A fuller report of this trial has been published recently[5].

CONCLUSIONS FROM EVALUATIONS AND OPERATING EXPERIENCE

The experience of trials and operations shows that 3-D TV systems give a number of benefits for remote handling:

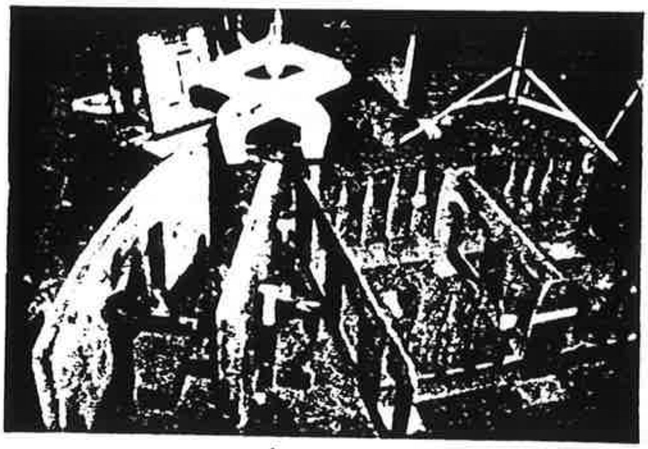


Figure 7: Windscale Evaluation Facility Showing Crane-Grab and Mounting-Rack

- A reduction in the number of views (cameras) required.

- Faster operational times, with greater improvements for elements requiring alignment.

- Fewer manipulator movements for a given task, suggesting that fewer errors and collisions would be made.

- Positioning of cameras is less critical with 3-D.

Furthermore we can hypothesize that operators are better able to interpret unfamiliar scenes with 3-D TV. From observations made during evaluations we have made a number of refinements to the designs of the systems which have been incorporated into the second and third generation systems.

Brightness and contrast controls were not provided on the first prototype 3-D system because of the difficulty foreseen in re-setting the matching of the brightness and contrast of the two monitors. These should only require

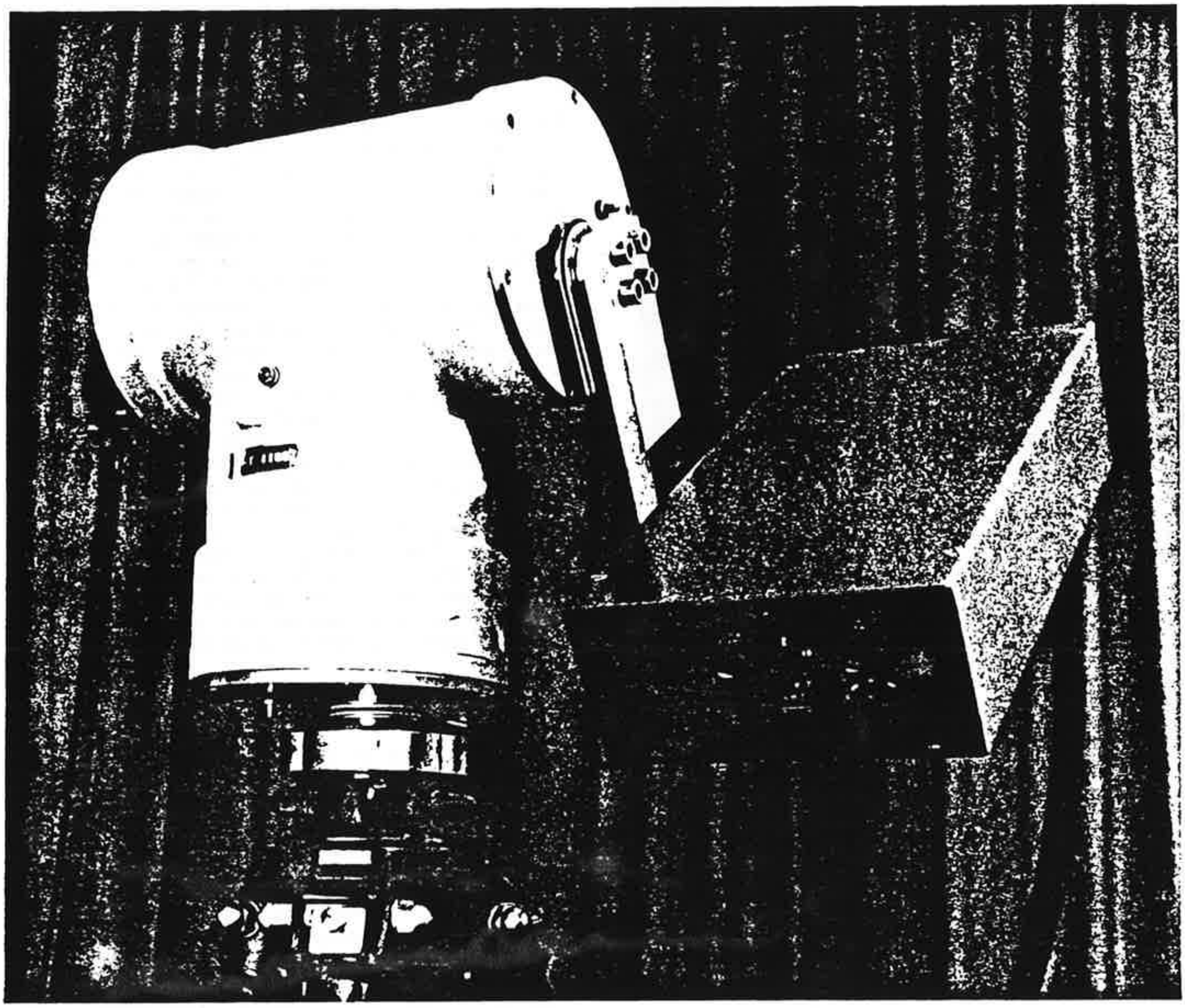


Figure 8: Colour 3-D Camera

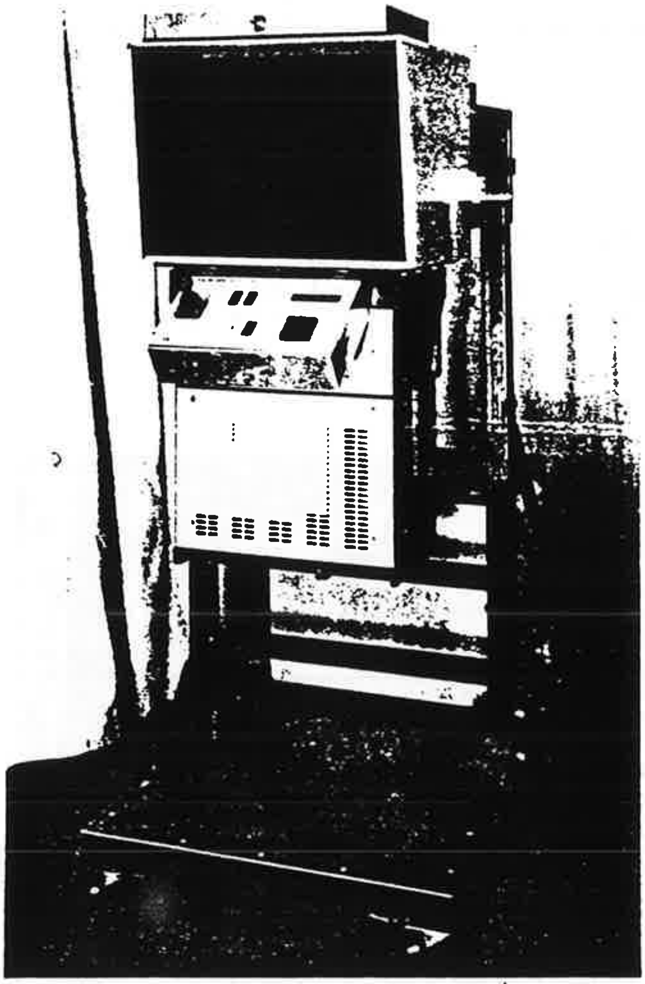


Figure 9: Colour 3-D Display

adjustment if lighting conditions change in the viewing area, or to compensate for inadequacies in the video signal. Some facility for adjustment with ability to match the pictures would give a more useful display. Although the geometry corrections needed on the display were slight, it would be helpful to operators if they could check the adjustment themselves and adjust if necessary. We found that operators tended not to adjust camera controls as soon as they needed slight adjustment, and only made adjustments when the viewing conditions had changed significantly. This suggests that the option of automatic focus/convergence and iris control would be helpful.

CAMERA DEVELOPMENT

A requirement to develop a fully engineered colour camera, subsequent to the production of the first black and white cameras, has provided the opportunity to incorporate some of the refinements to the original designs suggested by the mock-up evaluations and operational experience. The cameras have been built and were used for the second series of trials at Windscale Laboratory, see Fig 8. The camera has included: the choice of automatic or manual iris control; a mechanism accurately linking focus and convergence, convergence is achieved by axial offset of the lens so no trapezium errors are suffered; mechanically linked iris control giving very accurate iris matching; the position feedback of the focus mechanism which could be used to provide a binocular range-finding facility. The camera uses two re-packaged single-sensor solid-state cameras and a range of photographic lenses which make angles-of-view from 30° to 8° available. As with the earlier cameras, video is transmitted via twisted pairs. The camera is designed to allow radiation-tolerant sensors to be fitted to give a radiation-tolerant and environmentally sealed version.

The combined focus and convergence control was originally designed to give simple operation - one control instead of two. It is generally true that the cameras should be converged on the object plane that is in focus, which is the plane of interest. However, it is sometimes desirable to focus on a plane behind the optimum convergence plane. The optimum convergence plane normally corresponds to the nearest object in the view of the camera. Simple automation of linked focus and convergence to focus and converge on the nearest object would be useful, an option of reverting to manual control should be included. Experienced operators would be able to make use of a facility to adjust focus within a limited range about the convergence plane. The convergence distance being automatically or manually set. In this case, a switch to return focus to the convergence plane would be helpful. This latter requirement to unlink focus and convergence has implications for the complexity of the camera, and could best be made as a software option on suitable cameras such as the radiation tolerant camera currently being built.

SPECIFICATION FOR AN IN-REACTOR AND IN-CELL CAMERA

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 and repair of gas-cooled reactors; post-irradiation examination and fuel-reprocessing facilities; and decommissioning. A specification for a camera to work in these environments has been produced by consulting with experts on remote viewing systems and on in-reactor repair, mainly within the CEGB and the South of Scotland Electricity Board (SSEB). The specification encompasses the temperature requirement to 150°C with chilled air cooling, lighting requirements, materials and mechanical constraints. The camera will have angles-of-view of 40° and 10° and will converge and focus down to 300mm for the wide angle-of-view. Cable lengths of up to 100m will be allowed for. Target radiation-tolerance will be to 10^6Gy with dose rates to 10^4Gy/hour. We did consider and experiment with the use of zoom lenses for this camera. We believe that it is possible to use zoom lenses in fully engineered and remotely controlled 3-D cameras. However we found that we could not obtain a suitable radiation tolerant zoom lens because of the limited range commercially available. The camera is currently being manufactured.

DISPLAY DEVELOPMENT

The polarized light displays use two modified picture monitors set at right angles and viewed via a beam-splitting mirror. Polarized light filters at the monitor faces and in spectacles worn by viewers separate the two pictures. These have proved to give good quality pictures which are comfortable to view and with no operational difficulties. We anticipate that this display will be the preferred option for serious use of 3-D television over the next few years, because of its high standard of performance. Some applications may demand smaller displays for a given size of screen. In this case we now believe that a time-division display of acceptable quality could be made, but at considerable financial cost. The display would be required to show a video at twice the normal rate and suitable framestores would be needed to buffer the video, if conventional cameras were to be used. This would give anomalous picture components for moving objects, but we believe that picture quality could be acceptable for most subjects. The polarity switching should be carried out at the monitor face, with polarizing spectacles being worn by the viewer. Care must be taken in the choice of picture phosphor and polarizing materials to keep cross-talk between the left and right pictures to an acceptable level. Autostereoscopic displays are feasible; an autostereoscopic TV display has been demonstrated at Harwell. An image-forming screen transmits the left and right pictures to the eyes without the need for a viewing aid to be worn (though the viewer's head position must be reasonably fixed to obtain the 3-D view).

The colour polarized light display developed at Harwell, see Figure 9, is a development of the original black and white display, but using Grade 1[4] colour monitors which have preset controls for allowing control of the picture shape. By collaboration with the manufacturer, the important preset controls for each monitor have been brought out to a lockable control panel on the top of the displays; this can be seen in Figure 9. A test pattern generator has been included in the system so that the operator can follow a relatively simple procedure to check, and if necessary, adjust the geometry, colour and grey level of the monitors so they are well set up and matched. A cross-hatch pattern, see Figure 10, is displayed on both monitors to allow geometry comparison - the scan circuits of the

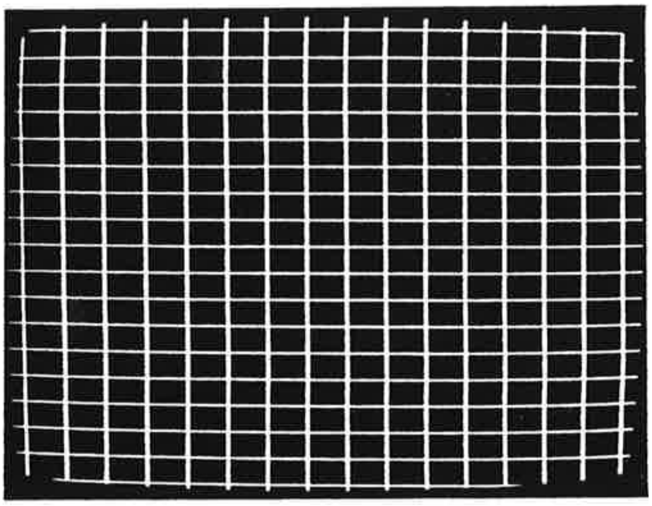


Figure 10: Cross-Hatch Pattern for Matching Display Monitors

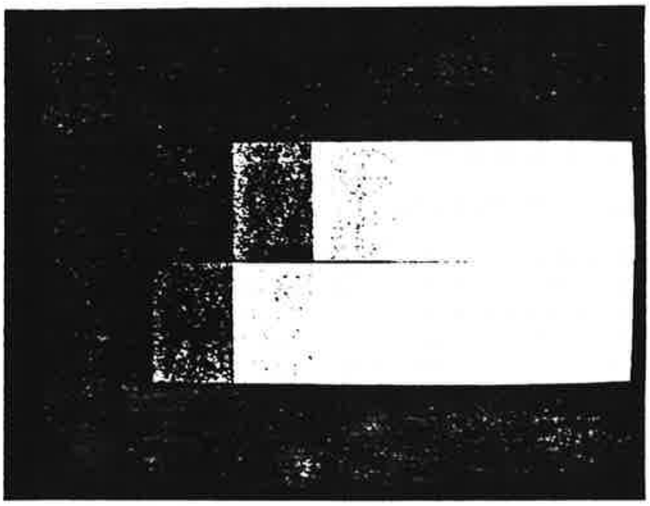


Figure 11: PLUGE and Grey-Scale Pattern for Matching Display Monitors

two monitors are adjusted until the two patterns exactly overlay. A picture line-up generator (PLUGE) signal is sent to the top half of the right monitor and the bottom half of the left, see Figure 11. The grey scales are thus displayed on one monitor each. The display is viewed without spectacles so the two scales can be compared. In Figure 11 the two pictures have been deliberately set out of balance to show how they are compared. The black level, set by the brightness control on a high quality monitor, is set using the three bars at the top or bottom of the picture. The central bar is at the black level voltage of the video signal, the bar to the right is 2% above black and the bar to the left is 2% below black. The brightness is adjusted so that the difference between the central and right bar is visible, but the difference between the central and left bar is not. The contrast controls are then adjusted to give correct and matched grey scale.

We anticipate that some training for operators to carry out the set-up would be required, in addition to concise written instructions. Similar developments have been incorporated into new black and white displays. Grade 1 monitors are used and circuitry has been specially developed to enable geometric matching of the two pictures with the aid of the cross-hatch pattern generator. The electronic controls remove the need to make adjustments to the picture tube and its deflection assembly which require more skill.

VIDEO TAPE RECORDING OF 3-D TV PICTURES

3-D pictures can be recorded in a number of ways. Two tapes can be synchronized on two high quality machines with a suitable edit controller. This method can give very good results, but is expensive and requires that two tapes are kept together. Some degree of skill is needed to record or play back. We have demonstrated a satisfactory technique where left and right fields are recorded alternately to the odd and even fields of the tape. The tape is then played back via two frame stores which repeat fields, for example, the left field is repeated once while the right field is being read from the tape.

CONCLUDING REMARKS

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

ACKNOWLEDGMENTS

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