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A 3-D television system for remote handling

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ABSTRACT

The paper refers to work previously described on the development of 3-D Television Systems. 3-D TV had been developed with a view to proving whether it was a useful remote handling tool which would be easy to use and comfortable to view. The paper summarizes the work of evaluation trials at UK facilities and 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. The initial development has been previously reported[1,3]. In brief, this concentrated on determining the factors which would make 3-D TV easy to use and comfortable to view. The control of the depth and shape in 3-D images was studied, as well as the accuracy required in matching the two images. Guidelines for system design were derived and these were used in the design and manufacture of prototype 3-D TV systems. Subsequently prototype systems have been evaluated at Central Electricity Generating Board (CEGB), Marchwood Engineering Laboratory, who are collaborating in the work, and at UKAEA facilities. These evaluations have confirmed the original design philosophy and have suggested refinements which have been incorporated into subsequent designs. The purpose of this paper is to summarize the evaluations and design changes that have resulted, and to report on the current state of development. This development work has made available 3-D TV systems for a wide range of viewing requirements and environmental conditions.

PRELIMINARY EVALUATION: PROTOTYPE BLACK AND WHITE 3-D

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. The robot was controlled remotely via a hand controller. Television viewing arrangement was the independent variable, and the floor plan is shown in Fig 1:-

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.

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 or tilting the cameras.

Lighting was fixed and not within the operators' control. Times to complete the series of crops were measured. The average times were 9 mins 22 secs for 3-D and 11 mins 33 secs for orthogonal, but it was not possible to establish statistical significance. 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.

EXPERIENCE AT CEGB, MARCHWOOD: PROTOTYPE BLACK AND WHITE 3-D

A prototype black and white system 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. 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 has 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 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 Fig 2. 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 8cm 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. At present, it is envisaged that the real operation will use only a single view (the main view).

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. The time taken was divided into 4 components for each plate transfer:-

Component 1: From start position (or end of component 4) to the first touch of the plate by crane grab.

Component 2: End of component 1 till plate is clear of stand or toast rack, including grabbing the plate.

Component 3: End of component 2 till plate is inserted fully home in toast rack or stand.

Component 4: End of component 3 till crane grab is released.

Thus, assuming that moving the two plates was equally difficult, each component was repeated 8 times for each viewing condition by each operator. For the four components, at each repetition by each operator, the 2-D times were subtracted from the corresponding times with the 3-D system. The mean differences are shown in

Fig 3. Statistically, components 1, 2 and 4 are not significantly different, but overall and for component 3, the difference is significant at 5%. One-sided t-tests were used because it was expected, a priori, that 3-D would give the faster times.

The absolute mean times for the components were:

	3-D (Seconds) ± 1 Standard Error of Mean	2-D (Seconds) ± 1 Standard Error of Mean
Component 1:	39.9 ± 3.6	42.7 ± 3.4
Component 2:	36.8 ± 4.1	40.7 ± 3.3
Component 3:	103.1 ± 9.8	124.7 ± 10.0
Component 4:	20.8 ± 3.9	18.1 ± 2.1
Overall:	200.6 ± 13.4	227.2 ± 12.9

Table 1

Mean Component Times

Component 3 was the part of the task which required the most positional accuracy, and also shows the most benefit from using 3-D; an improvement of 17%.

Video tapes of two of the operators recorded during the trials showed that the supplementary view was used differently when the main view was 3-D rather than 2-D. With 3-D, the operators looked at the supplementary view for only a small percentage of the time:

	Mean % of Time 3-D	Mean % of Time 2-D
Main	94.6	60.1
Supplementary	0.2	32.7
Controls	4.0	5.0
Other	1.2	2.2

Table 2

Percentage of Time Spent Looking at Main View, Supplementary View, and Controls

A third operator showed a less marked difference between 2-D and 3-D. However he was not typical and had considerable experience of using orthogonal, 2-D viewing systems, preferring to use a way of working which was familiar.

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 (the third of those video taped) 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.

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:

- 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.

Brightness and contrast controls were not provided on the 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 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.

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 4. 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. To date camera designs have not permitted such a link which would only otherwise be a requirement for 3-D cameras using zoom lenses.

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 for use in inspection and repair of gas-cooled reactors and for use in post-irradiation examination and experimental fuel-reprocessing facilities. 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 from 40° to 10° and will converge and focus down to 300mm for the wide angle-of-view. A technical decision on whether to use zoom lenses or two pairs of fixed focal length lenses has not yet been made. 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.

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 the 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 crosstalk between the left and right pictures to an acceptable level. Autostereoscopic displays are feasible; these use an image-forming screeen to transmit 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). Such a display showing live 3-D video has recently been demonstrated at Harwell Laboratory.

The colour polarized light display developed at Harwell, see Fig 5, 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 display; this can be seen in Fig 5. 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 Fig 6, is displayed on both monitors to allow geometry comparison - the scan circuits of the 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 Fig 7. The grey scales are thus displayed on one monitor each. The display is viewed without spectacles so the two scales can be compared. In Fig 7 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 setup would be required, in addition to concise written instructions. Similar developments are being included in black and white displays currently in manufacture.

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.

ACKNOWLEDGEMENTS

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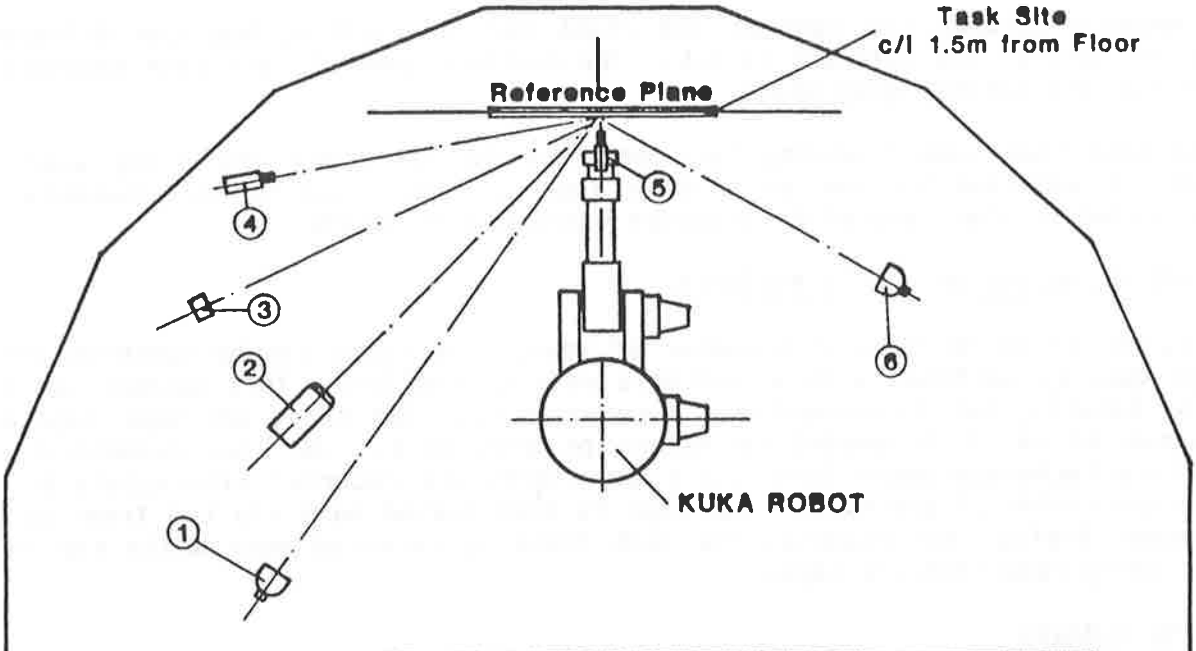

	Description	Angle from Ref.Plane	Height from Floor (m)	Angle from c/l of Task	Radius from c/l of Task (m)
1	Lamp 800W	55	2.3	11	3.5
2	Stereo Camera	45	2.1	13.5	2.3
3	Lamp 500W	25	1.5	0	2.5
4	C.C.D Camera	10	1.5	0	2.0
5	C.C.D Camera	90	3.5	80	0.3
6	Lamp 800W	30	2.3	21.5	1.8

Fig 1 - Camera and Task Arrangement - Preliminary Trials

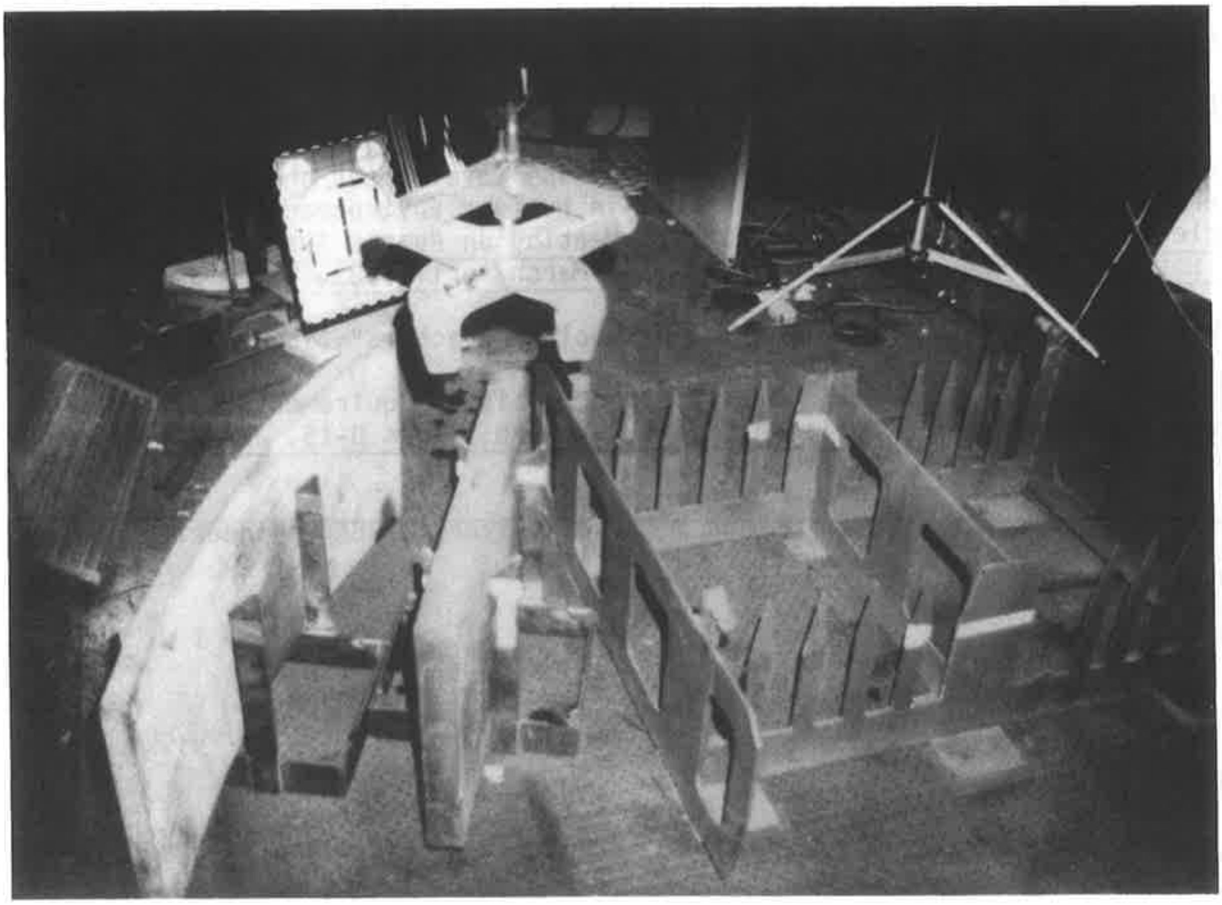

Fig 2 - Windscale Evaluation Showing Crane-grab and Mounting-rack

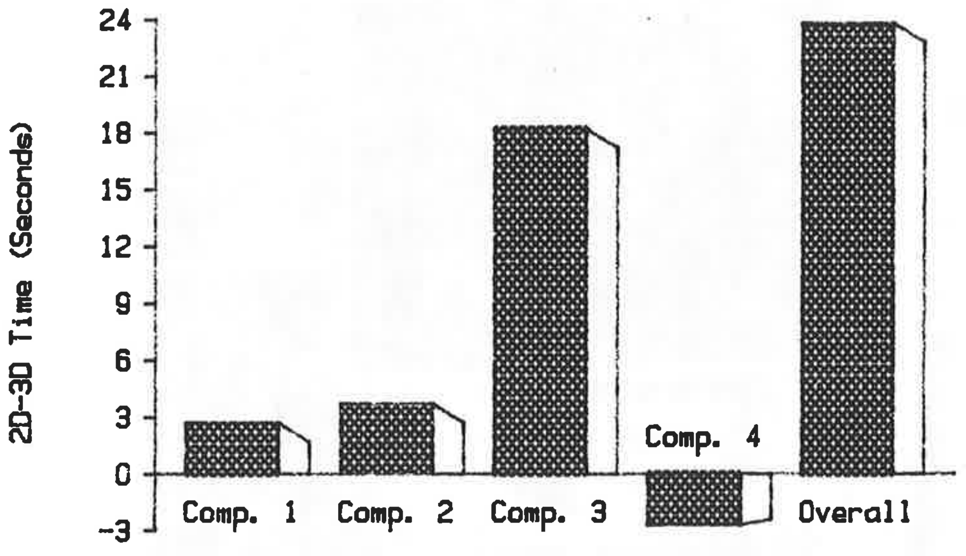

Fig 3 - Time Difference, 2-D minus 3-D, for Task Components

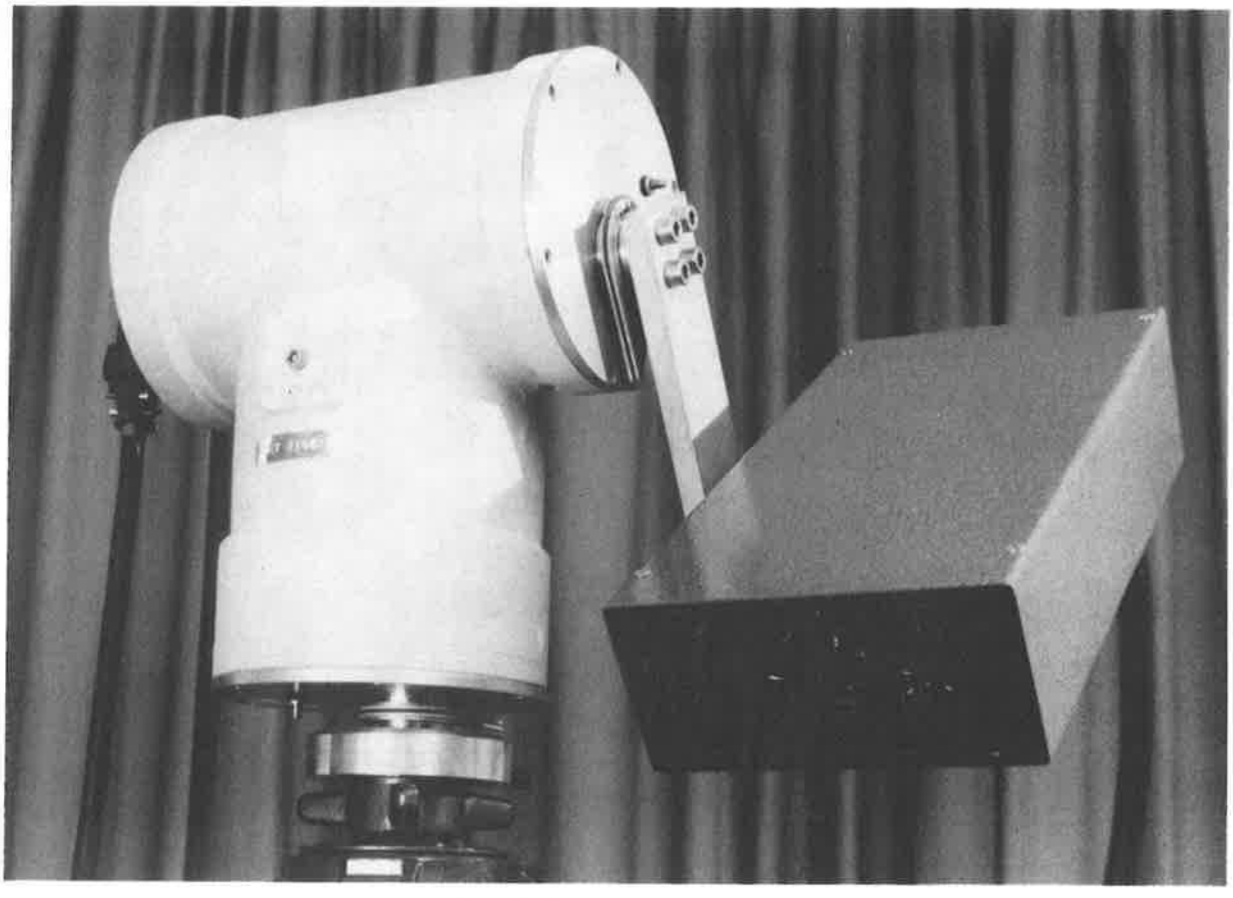

Fig 4 - Colour 3-D Camera

Fig 5 - Colour 3-D Display

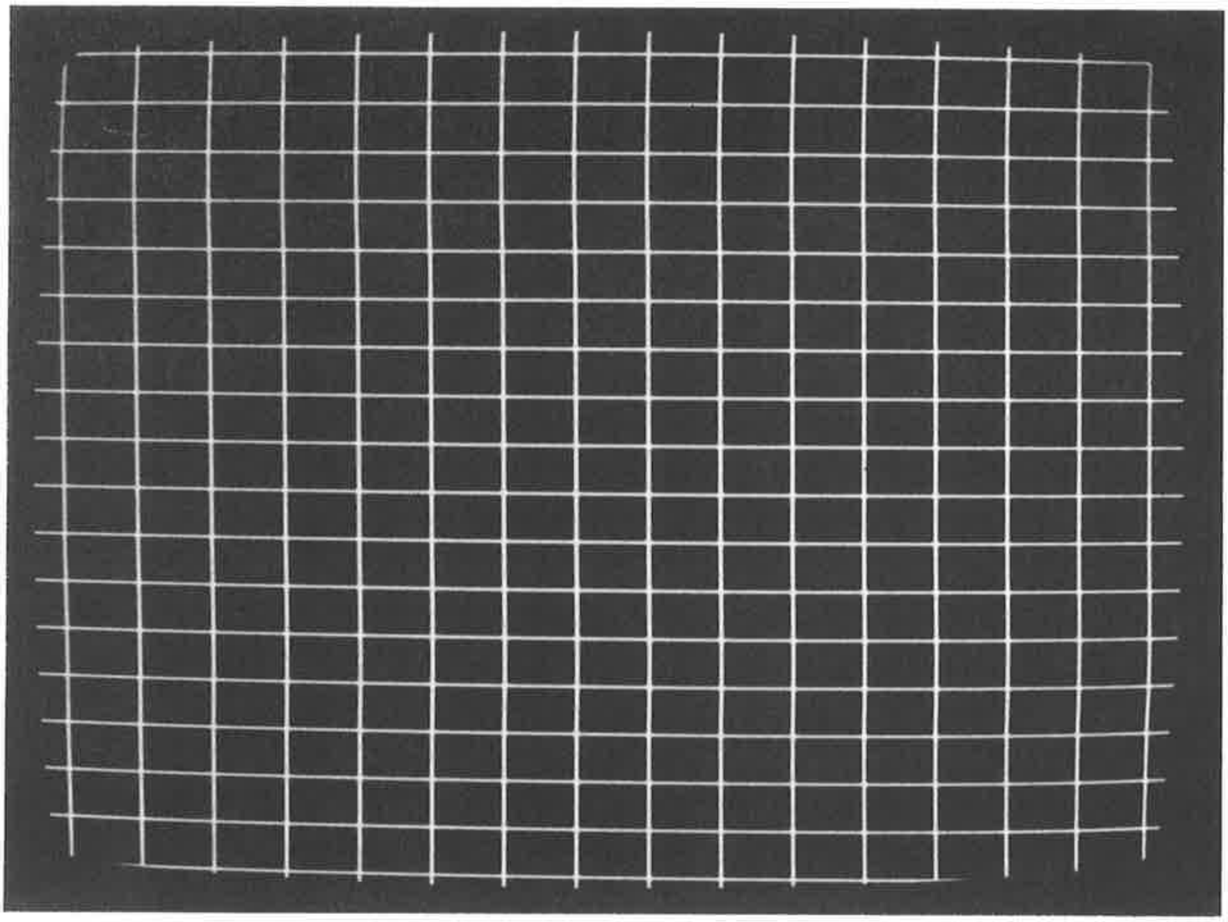

Fig 6 - Cross-Hatch Pattern for Matching Display Monitors

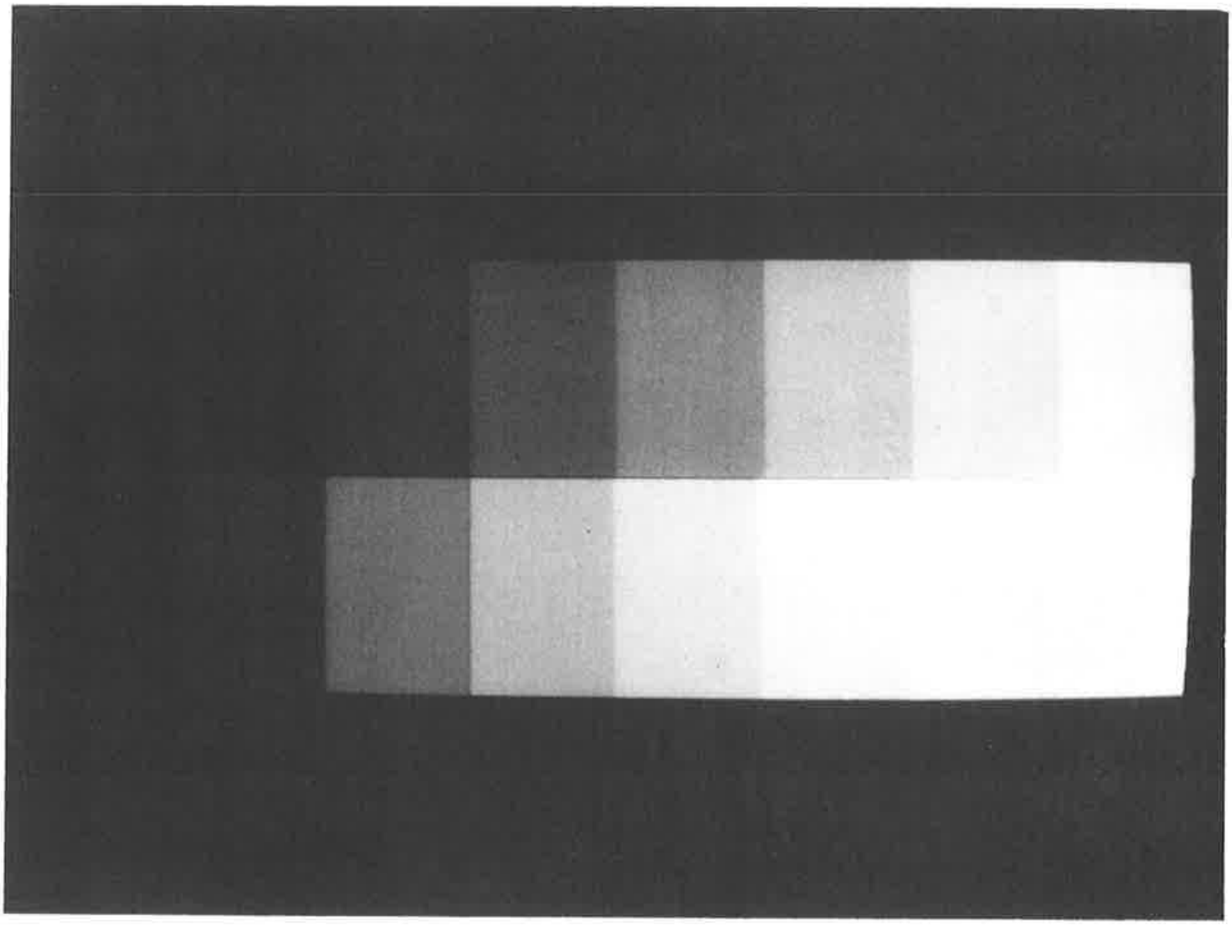

Fig 7 - PLUGE Pattern for Matching Display Monitors