J Intell Robot Syst (2008) 52:139–154
DOI 10.1007/s10846-008-9203-z

UNMANNED SYSTEMS PAPER

Vision Enhancement Using Stereoscopic Telepresence For Remotely Operated Underwater Robotic Vehicles

V. Iastrebov · G. Seet · T. Asokan · Y. P. Chui · M.W.S. Lau

Received: 8 January 2007 / Accepted: 9 January 2008 /
Published online: 20 February 2008

Abstract Remotely operated Underwater Robotic Vehicles (URV) are widely used for subsea tasks such as cleaning, repair and inspection of long objects such as pipelines. The ability to perform such inspections by a remotely located human pilot, over extended periods, is highly desirable. Due to underwater currents and the inability to maintain a fixed distance from the object, produces a constantly varying image for the observer. Incorporation of stereoscopic imaging, with the option of maintaining a constant image size, was perceived to be desirable. This effect was implemented by dynamic compensation of the camera zoom, and shown to negate the negative motion effects and allowed the operator to perform close inspection for extended periods of time. This paper describes the design, structure, and preliminary evaluation of an experimental Telepresence Viewing System (TVS) for Underwater Robotic Vehicle (URV) to enhance the observation capabilities of its remote pilot during an inspection task. The Telepresence Viewing System enables an automatic projection of suitably prepared and adapted underwater stereoscopic video images from the video cameras of the URV, into the operator's visual field. The processed images aid the coupling of the operator's vestibular and kinesthetic sensations to the visual information from the URV.

Keywords URV · Tele-presence · Stereoscopic · Adaptive convergence-zoom control

1 Introduction

Underwater structures and pipelines are periodically inspected to ensure their structural safety and integrity. With the advances in remotely operated underwater operated vehicles, unmanned inspection methods are gaining wider acceptance and the techniques for unmanned underwater inspection are being developed to replace human divers in carrying out hazardous and complicated inspection tasks. A typical scenario of deployment of a URV for unmanned inspection is shown in Fig. 1. A robotic vehicle with an onboard

V. Iastrebov · G. Seet (✉) · T. Asokan · Y. P. Chui · M. Lau
Robotics Research Centre (RRC), School of Mechanical & Aerospace Engineering,
Nanyang Technological University, Nanyang Avenue, 639798 Singapore, Singapore
e-mail: mglseet@ntu.edu.sg

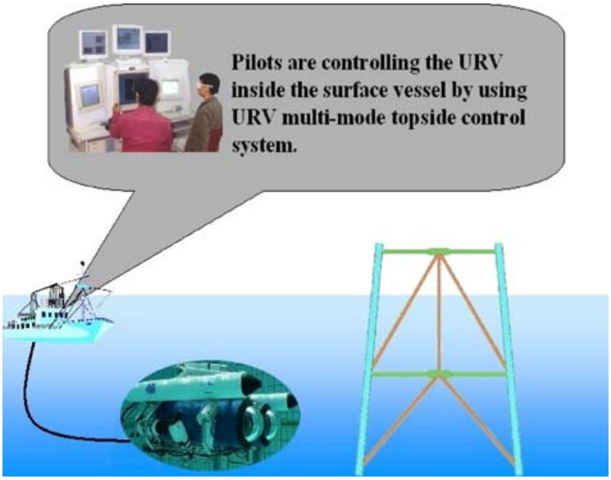


Fig. 1 Typical scenario of URV deployment for unmanned inspection

inspection system is deployed from the base station and remotely navigated to the targeted workspace by the URV pilot, located at the base vessel. Using mechanical constraints, the URV is docked to the structure and inspection is carried out. Depending on the autonomy of the subsystem, operations are performed with differing levels of pilot intervention. The success of such missions depends, to a great extent, on the subsystems like vehicle control system, manipulator system, pilot vision system, inspection system etc. Developing systems and techniques for such applications are crucial in the growth of unmanned inspection methods. As underwater inspection is a precise task carried out in an unstable and unstructured environment, pilot vision as well as depth perception of the environment is paramount. In an attempt to achieve realistic view of the environments, researchers have attempted to model the operation of URVs and their subsea manipulators in a virtual world using virtual reality technologies [1, 2]. As part of the ongoing research work on the development of a compact tele-operated URV system for Non Destructive Testing (NDT) inspection of underwater structures, researchers at the Robotic Research Centre(RRC) of NTU have developed a compact URV, unified pilot training and control system, and a multistage manipulator, which are in the final stages of realization [3, 4]. Virtual reality (VR) based modeling and simulation was one of the tools used in the development. It was found to be very useful in pilot training and control applications. VR simulations provide the human operator with valuable sensory feedback information that is critical for successful underwater missions. In deployment and inspection, where there is not available an accurate representation of the work environment, VR simulations may be of limited use. Better visual systems that enhances the pilot's image perceptions are needed. It has been long established that stereoscopic vision systems can improve the visual perception of a viewer [5, 6]. There have been reported works [7–9] of stereoscopic vision systems being incorporated into URV systems. In almost all cases, two cameras were placed adjacent to each other separated by a distance of 6.5 to 7 cm, this being the human eye separation distance. The images from these cameras were processed to get a stereoscopic image.

In order to enhance the capabilities of the URV system being developed at our Centre, and to improve on pilot performance, we implemented a Telepresence Viewing System (TVS) on our URV [10]. Due to the inherent design features of the URV, it was not possible to adopt existing stereo vision system configurations. One of the major design features for our URV was the camera separation. The two cameras were housed in separate pods separated by a distance of approximately 30 cm. This is almost five times normal human inter-pupillary eye separation of 6.5–7 cm. As a result, both cameras had different view paths and the images could not be used to create a stereo image. It was necessary to design a stereo system, different from existing systems. The only way to overcome this problem was to control the cameras independently and make them continually converge at the same object. In order to achieve this and to reduce visual discomfort of the operator, we adopted a system that uses “active” convergence control for image generation. A customised TVS configuration was proposed that would provide a comparable feeling of ‘Being There”. Subjectivity of such “feeling” is based on relatively similar distortions of the stereo image, introduced by the water medium, for the operator’s vision perception as if he was underwater himself. Divers often combine visual perception with the image, obtained from the Sound Vision Camera (SVC). Complementing vision with acoustic sonar data could be valuable to overcome the deficiencies that may arise by resorting to vision only. In this proposal we concentrate on close inspection in clear (or mildly turbid) waters. In extremely turbid waters, range-gated imaging [17] may be used to enhance image quality but are generally accepted to be for monocular imaging.

The overall topology of our URV telepresence system is presented in Fig. 2. Details on the design, implementation, and testing of the TVS are provided in the following sections.

2 An Overview of Telepresence Technologies and Stereoscopic Imaging

Humans are imbued with binocular vision, i.e., separate images of the visual field are formed by each eye, and the two images fused to form a single impression. As each eye forms its own image, from a slightly different perspective, a stereoscopic effect is obtained and depth, distance, and solidity of an object are appreciated. Video camera generally functions much like the human eye. To get stereoscopic images, it receives and focuses light onto a photosensitive receiver – the retina. Light rays are bent and brought to focus as they pass through the cornea and the lens. The shape of the lens can be changed by the action of the ciliary muscles so that clear images of objects at different distances (and of moving objects) are formed. This ability to focus objects at varying distances, known as accommodation, helps to zoom in on objects to create stereoscopic images. An important area of use of stereoscopic vision, in engineering, is in telepresence. Telepresence enables

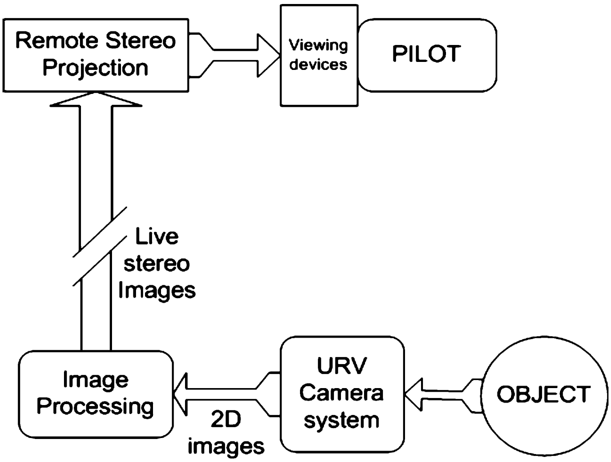


Fig. 2 URV telepresence system overview

an observer to view a remote location in 3-D by using a live stereo video feed. The added depth cues, generated by a stereoscopic display, can greatly improve the dexterity of remotely operated tasks. The fictional origin of the concept of telepresence can be traced back to Robert Heinlein's short novel "Waldo," written in the 1940s [11]. Presently, scientists are pursuing telepresence as a pragmatic and operational medium that aims at equating robotic and human experience. The goal is to reach a point at which the anthropomorphic feature of the robot matches the nuances of human gestures. In this search for an "operational double," humans wearing flexible armatures will have a quantifiable feeling of "being there". In a telepresence link, images and sounds are transmitted but there are no "senders" attempting to convey particular meanings to "receivers." Telepresence is an individualized bi-directional experience, and as such, it differs both from the dialogic experience of telephony and the unidirectional reception of television messages. In this case the operator or user acts or performs at the level of reality and virtuality simultaneously. According to Abraham A Moles [12], as we enter the age of tele-presence, we seek to establish equivalence between "actual presence" and "vicarial presence". Application of telepresence in practical situations is growing at a very fast pace. Robotic applications in medical field, field robotics, space engineering etc. are some of the emerging fields where telepresence makes a great impact.

With advances in camera and computer technology it has become feasible to compute 3D models from photographs. Usually 3D models are created from multiple views of the same scene. Stereoscopic 3D video representation provides significant benefits in many application areas, including endoscopy and other medical imaging, stereo 3D-CAD, molecular modeling, 3D computer graphics, 3D visualization, video-based training, entertainment, telemanipulators, telerobotics, telepresence experiments, etc. In most cases a basic question to solve is; how to generate stereoscopic 3D video, which could be displayed on a television or VGA monitor, and viewed using liquid crystal shutter glasses.

The majority of human beings have good depth perception but tests indicate a wide variation in ability. This variation should be considered in the development and deployment of stereo systems. As with all physiological systems, stereovision may improve rapidly with use, both short term and long term. Repeated use of a stereo display can lead to more rapid fusion and greater comfort.

The main component of the vision enhancement system is the stereoscopic telepresence system or Telepresence Viewing System (TVS). The TVS is an active camera system, consisting of two video cameras and a digital synchronizing multiplexer. These are used to produce analog stereoscopic video images, which are digitally captured, synchronized, and multiplexed into a field-sequential composite video and further converted to VGA format, and processed to derive flicker free stereo images in the operator's visual field. An adaptive

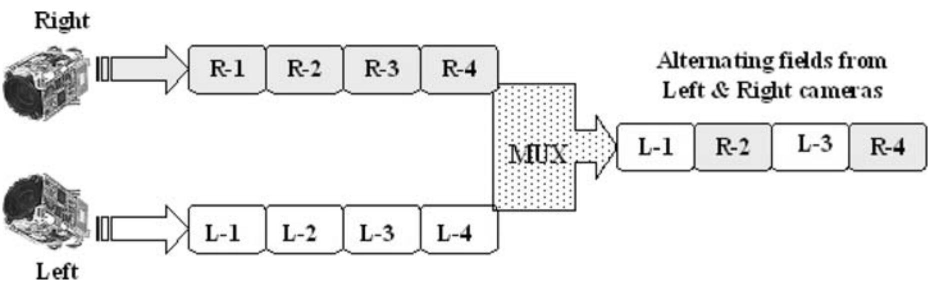


Fig. 3 Combining of video streams to generate stereoscopic image

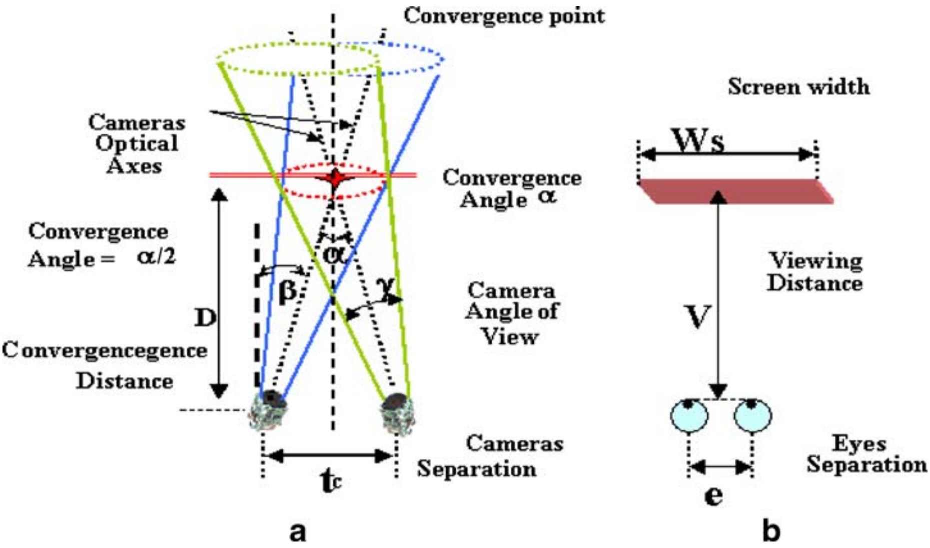


Fig. 4 Components of a stereoscopic system and its basic parameters **a** camera system **b** viewing system

camera convergence/divergence control system is incorporated in the system to reduce geometric distortions of the images resulting from the camera separation distance. A zooming control feature has been added to improve the eye comfort. These features have been tested and verified, in a limited human assessment trial. Initial results indicate lower levels of operator eyestrain and discomfort. The system has also been demonstrated to overcome constraints imposed by the URV design requirements.

The heart of the stereoscopic system is the module that holds and controls the positioning of two cameras. In order for stereoscopic video to be possible, the cameras must be synchronized (genlocked). The two video streams are combined (multiplexed) using a switching circuit that switches every other field from each camera into the outgoing stream. This becomes a series of alternating fields, one from each camera. The result will be a sequence: L1 from the left camera, R2 from the right camera as shown in Fig. 3.

To reach a realistic image, there is a need to control the zoom, focus, interaxial distance (distance between the cameras), and the convergence point of the two optical axes. There are precise relationships between these parameters and thus, mechanisms for manual interlock of focus and convergence, or of zoom and focus, or for manual adjustment of one parameter at a time for both cameras have been developed [13–15]. Altering the convergence by changing the scanning position on the image pickup surface or automating these functions by computer have been implemented. Digital storage and image processing has also been employed to compensate for binocular asymmetries from zooming, to reduce excessive horizontal parallax.

Another common problem associated with telepresence system is flicker. It results from a variety of factors, the most important being the monitor's refresh rate, i.e. the speed at which it is redrawn. This is most noticeable in standard frequency (50–60 Hz) field sequential systems. Image at a 120 Hz refresh rate may also flicker, if the image is not updated in a proper manner. Flicker may also appear due to other factors, especially bright and large screens. In addition, the image may flicker due to high luminosity areas or low rates of update. Flicker due to ambient illumination ("room flicker") must also be distinguished from the flicker due to the image display (“image flicker”). Decreasing the level of ambient illumination in the room can reduce the room flicker to an imperceptible levels while reducing screen luminosity with brightness and contrast controls will reduce image flicker to low or imperceptible levels. This may reduce the contrast excessively. Some level of image flicker is usual in 50–60 Hz displays. A design of a TVS system, addressing all these issues is discussed in the following sections.

3 Telepresence System Components

The Telepresence Viewing System consists of two main components: (a) camera system and (b) viewing system, as shown in Fig. 4. The camera system consists of two cameras and its associated components for the control of camera settings, image processing system and communication system. Some of the common parameters to be controlled in the camera system are the convergence distance, convergence angle, and camera separation. The viewing system consists of a projection screen and associated viewing devices for stereovision. Screen size and viewing distance are the two major parameters to be controlled here for viewing comfort.

4 TVS System Design for URV

The basic idea is to make both the cameras active, by making its convergence and focus continually adjustable, so that the convergence point and focal distance will remain on the same plane, similar to the human vision system. The system maintains convergence of the cameras based on the range of the observed object from the URV. Range data is continually obtained from the ultrasonic sensor directed at the object of observation.

Another feature that is considered to improve visual comfort is the continuous maintenance of a fixed relationship between the viewing distance from display screen to the eye and the camera focal length. As reported in reference [16], the relationship between object distance away from the camera system and image distance away from the eyes (viewing distance) is almost linear within the range of 1 m, as shown in Fig. 5. Beyond, 1 m, it is highly non linear.

In order to get a realistic image with good eye comfort, it is necessary to maintain this relationship, which is practically impossible in current configurations. Most of the existing

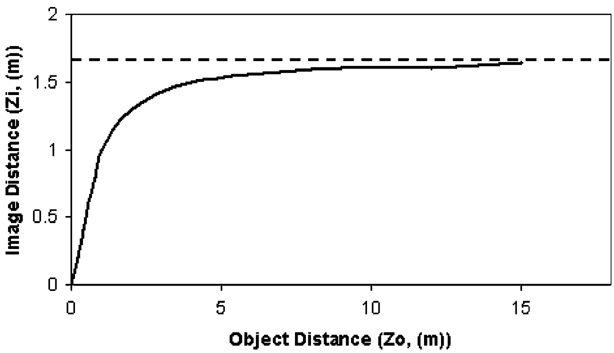


Fig. 5 Relationship between the object distance and image (viewing) distance

stereo systems have not taken this into account and maintain a fixed viewing distance irrespective of the object distance. Moreover, it was reported [14] that the optimal configuration for visual comfort is when the focal length of the camera and the viewing distance are equal to 1 m. Under this condition, there will be experienced an added comfort to the eye and also provide a more realistic image. It is, therefore, necessary to design the stereo system in such a way that the object distance is equal to the viewing distance, within the1 m range. This was achieved by changing the focal length of the camera using the zooming facility. By zooming in on an object, we are varying the object distance and bringing it almost equal to the set viewing distance. By this, we can actually overcome the non-linearity relationship and give a constant visual perception to the viewer, irrespective of the object distance. Based on the above concepts, we designed an intelligent automatic controller for video convergence and zooming. An ultrasonic range finder, which is directed towards the target of viewing, was used to determine the actual range of the target. A digital image encoder consisting of two video grabbers, field-sequential multiplexer and a processing system was used to process the images from the camera and project it in to the TVS. The structure of the system designed is shown in Fig. 6.

4.1 System Components

The major components of the system are:

- Two cameras (Sony AVI-371D PAL CCD) with active control of the zoom, brightness, contrast, color, focus, shutter speed, iris;
- Ultrasonic altimeter (Tritech PA500/6-S) to measure the distance to target;
- Pan-Tilt-Zoom intelligent control system;
- Stereo Image Encoder (NTSC/PAL-field-sequential
- 3-D ImageTek Corp.)
- Stereoscopic Display system (Sync D-TV-Converter for shutter glass control and sync doubling; and a 21" VGA monitor).

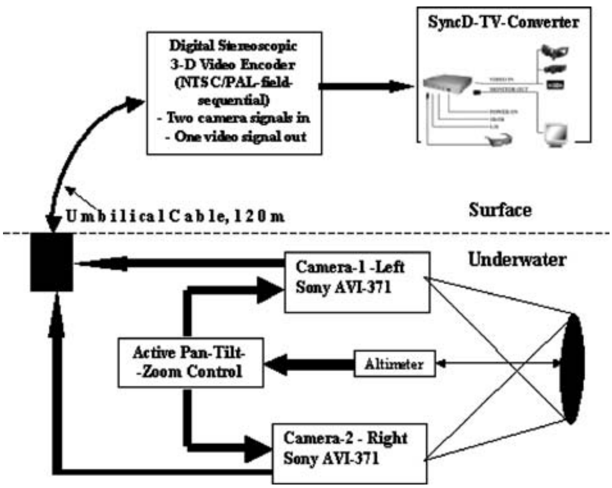


Fig. 6 URV telepresence system structure various components of the system and their functions are explained in the following section

Two cameras with automatic focus and zoom control were used to acquire video images of the objects. The cameras were mounted on a platform with pan and tilt control and are separated by a distance equal to the distance between the pods of the URV (~30 cm). In order to converge the cameras on a particular object, it is necessary to rotate these by an angle, which depends on the distance from the camera to the object. The pan angle, by which the camera should rotate in a horizontal plane, is calculated by taking the camera separation and object distance as shown in Fig. 7.

If the left and the right lenses of the URV cameras are located at L and R respectively, and the lenses converged at point Z in space, we can measure the angle of convergence, θ. The convergence angles $\theta_{l,}$ and θ_r need not be equal. In the typical observation arrangement, the convergence angles can be assumed to be equal. In such an arrangement, the angle of convergence may be specified as:

$$\theta = \mathrm{atan}\left(\frac{t_c}{2D}\right)$$

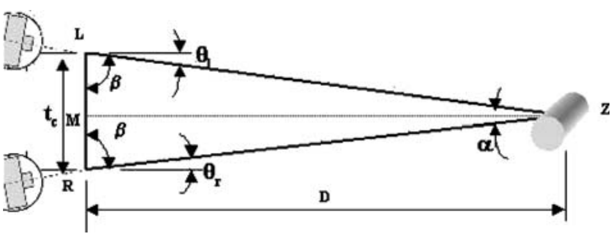
Where, t_c is the inter-axial distance, and D is the distance from camera to subject Z. Except for extreme close-ups, we can approximate the distances LZ or RZ to be equal to D or ZM. A pan-tilt controller is used to achieve the correct camera convergence.

4.2 Pan-Tilt-Zoom Control System

The pan-tilt-zoom control system consists of two DC servomotors (Futaba S9102) for each camera and an electronic circuitry for control. Two micro controllers (Parallax Inc. Basic Stamp, BS2p) were used to control the pan-tilt motion. An SD-20 pulse width modulation (PWM) chip is used for generating the necessary control pulses for the servomotor. Position commands are sent to the chip over the I^2C bus. The SD20 chip is a pre-programmed PIC16F872 running at 8 MHz. Its buffer can be read as well as written to, saving valuable memory resources on small controllers. The standard mode has a 256 bit resolution varying from 1 to 2 ms. The standard involves two-wires that perform peer-to-peer serial communication. This 2-wire bus can communicate at substantial communication rates with the industry standard being 400 kbs and some of the more capable devices handling much faster rates of 1 Mbit or better. Figure 8 presents components of pan-tilt control system.

Each camera has a serial RS-232 interface, allowing the control of parameters such as zoom, brightness, contrast, colour, shutter speed and iris, by sending the appropriate SONY camera command. As the distance to the target of observation is continually acquired, and the distance between the viewer and the display is known, we can automatically and continually control the zoom of both cameras to make the distance from cameras to the target identical to the distance between the viewer and the display. This is maintained at 1 m.

Fig. 7 Calculation of the cameras convergence angle



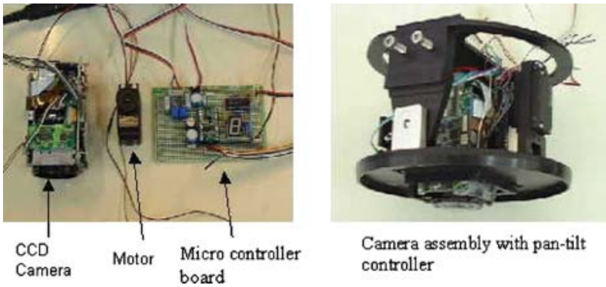


Fig. 8 Components of the pan-tilt control system

4.3 Image Generation and Multiplexing

As described in the previous section, a pan-tilt-zoom control system was used to converge and to zoom in and out, the cameras, onto an object. The cameras generate analogue images of the object, which are transmitted to the surface via the 120 m umbilical cable. In order for stereoscopic video to be possible, the two cameras must be synchronized. Two cameras can be considered synchronized when both are generating video under the same timing signal. This means, that the vertical sync pulse from each camera occurs at exactly the same time. Synchronization is necessary to ensure that; when the field, generated by one camera has been sent out, the other camera is starting the next field. Composite videos from left and right cameras are captured, synchronized and field-sequentially multiplexed, in the Stereoscopic Image Encoder onboard the URV. The resulting field-sequential stereoscopic composite video signal is then amplified and transmitted through the umbilical cable, amplified and filtered at the reception point and processed in the 100/120 Hz Stereoscopic SyncD-TV converter, a commercially available device. It is a signal converter, which is capable of converting video signal into VGA signal as well as doubling the input vertical scanning frequency for flicker free display. The SyncD-TV-Converter is one of the solutions to remove the flickering problem for 3D video application. The main advantage of using the SyncD-TV-converter is that, instead of using a TV for display. Any colour monitor that can accept 100–120 Hz of vertical scanning can be used as a display device. This provides for a higher quality image (Fig. 9).

5 Experiments

Preliminary tests were conducted to evaluate the system design and operations of the various sub-systems. Experiments with the automatic converging and zooming system were conducted under laboratory conditions, with the underwater ultrasonic rangefinder temporarily replaced by a specially designed “Polaroid air ultrasonic range-finder”. Figure 10 shows the experimental set up.

The following setup and calibration activities were conducted:

– Calibration of electrical controls and mechanical motion controls of the system;
– Estimation of automatic pan convergence control, based on the range data obtained from the ultrasonic air rangefinder;
– Estimation of system response to external environment variations.

A cylindrical object of 250 mm diameter was used as a test object. Whilst the form of such an object might not be rich, it demonstrates the potential of the prototype system. It is

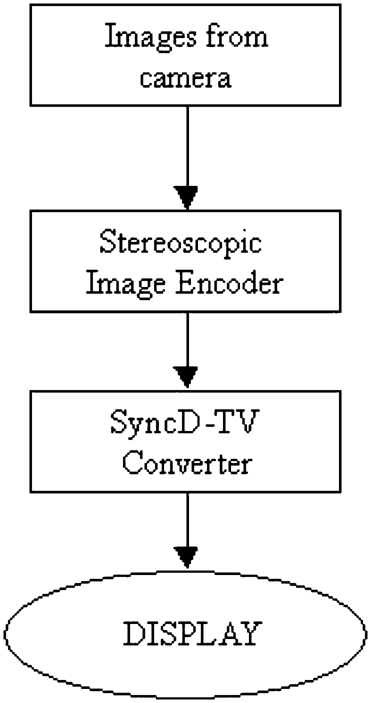


Fig. 9 Image creation and processing sequence

similar in shape to a water pipeline, the object of our intended URV application. The object was placed in a vertical orientation.

The operator observes the image of the object on the screen of a SVGA CRT 19″ display through shutter glasses. The distance between the monitor and the observer was set at 1 m. A few experiments were conducted to ensure the basic performance features of the system, before going for a detailed experimental analysis. (Figs. 11 and 12 show some of the screen shots during the preliminary tests.)

- Calibration of converging angles of cameras relative to the "realness" and comfort of static and dynamic stereoscopic perception,
- Estimation of the comfort of stereoscopic perception in the context of symmetrical and asymmetrical convergence,
- Determination of an optimal distance between the operator and the screen in conjunction with screen dimensions and real range between the cameras and an observed object.

After the preliminary setup, a detailed analysis of the comfort level and stereo perception of the TVS was undertaken. Telepresence and stereovision effects are highly subjective and difficult to quantify objectively. Experiments were conducted to determine the subjective perceptions and observations of a group of people. The group comprised of volunteers from different age group, cultural background, and gender. A questionnaire was prepared and each was required to observe various functions of the TVS and to complete the questionnaire.

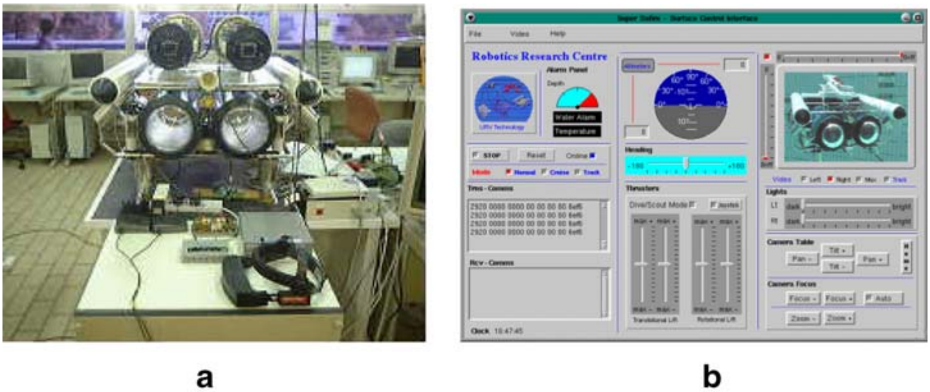


Fig. 10 Experimental setup **a** camera system **b** GUI for TVS manual control

The questionnaire focused on the following attributes of the TVS:

– Visual effects in a 3D environment
– Viewer comfort/eye strain
– Eye/brain accommodation
– Image flickering
– Auto zoom/convergence
– Viewing distance
– Convergence point

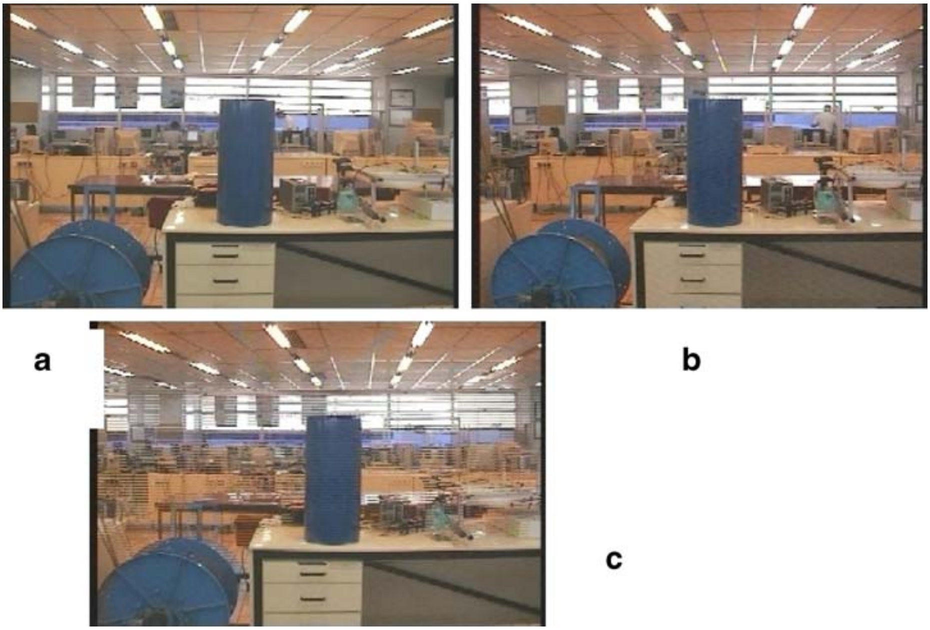


Fig. 11 Snap shots from stereo image without zoom control **a** left camera image **b** right camera image **c** multiplexed image

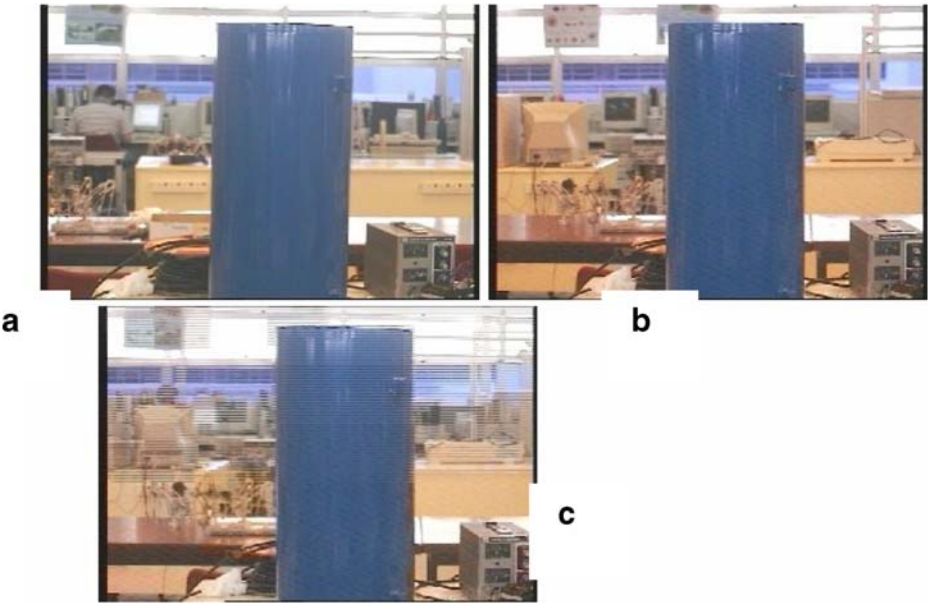


Fig. 12 Snap shots from stereo image with zoom control **a** left camera image **b** right camera image **c** multiplexed image

- Depth perception
- Target motion, object separation, view distortion

The image plane of the projected stereo cameras can be in front, on, or behind the focal plane, enabling both real and virtual images to be formed on the monitor screen. Images, which we call "real", are given the appearance of an object floating in space between the viewer and the screen, whereas the so-called "virtual" images are behind the screen of a monitor. When we direct the cameras to intersect on an object, the object appears at the video screen level. Everything in front of it appears in front of the video screen and everything behind it appears behind the video screen (Fig. 13). Experiments were conducted to assess the best form of convergence that gives better eye comfort to the viewer.

In order to study the effects of moving objects on stereo perception and to simulate the URV motion during a sea experiment, the object was allowed to move in a predefined path. A linear slide was used for this purpose. The object was moved to and fro on the slide and the observer was asked to record his observations. The effect of auto zoom was also analysed in this test.

6 Results and Discussion

The experimental results, for a group of subjects, are presented in Fig. 14. A total of 12 subjects (10 males and 2 females) were evaluated. Their responses are presented in terms of percentage responses to the attributes under investigation. Figure 14 shows the results obtained. Most of the subjects were able to experience stereo perception and telepresence

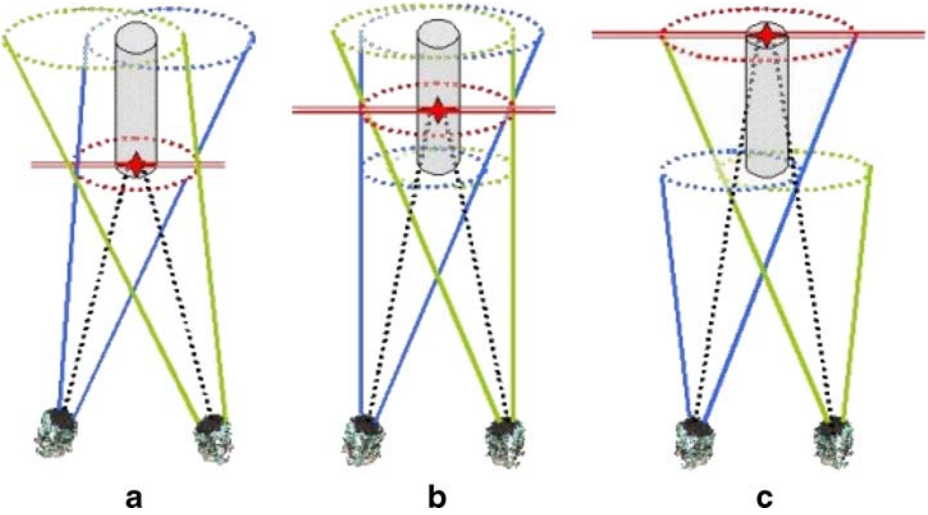


Fig. 13 Camera convergence point variations **a** convergence at the front **b** convergence at the middle **c** convergence at the back

effect, confirming the effectiveness of camera convergence in creating 3D scenes that overcome the effects of excessive camera separation. The depth perception and visual accommodation, however, varied from person to person. This was quite natural as the stereo/depth perception varies from person to person and with greater exposure to stereovision. It was observed that those who had previous exposure to stereo images were able to appreciate stereo perception better than those without prior experience.

Tests conducted to study the effects of auto zooming provided interesting results. Two identical patterns, separated by a distance of 350 mm on a plane, were placed in front of the camera system and the observed object separation on screen was recorded (See Fig. 15). As shown in Fig. 16, without auto zoom being activated, the observed object separation decreased as the target was moved away from the camera. When auto zoom was activated, the observed object separation remained at a constant level irrespective of the distance of the target. This allows the observer the experience of a constant image perception irrespective of how far the target is from the camera system. This provides the observer enhanced depth perception.

In order to determine the best viewing distance, tests were conducted with and without auto zoom. Without auto zoom, the image and object distance relationship following the pattern shown in Fig. 5. However, when auto zoom was activated, it was found that the best viewing distance remained somewhere near to 1 m, the set zoom distance of the camera. Variations from this ideal viewing distance caused distortions in the view. Thus, we could bring the viewing distance to the linear range, irrespective of the object distance.

As explained in section 5, the camera convergence point affects the way the images are projected on to the screen. It was widely perceived, that the best convergence arrangement was when the cameras converged at a point forward of the object of focus. This gives better depth perception and realness of object. When the target object was in continuous motion, without the auto zooming function activated, a number of subjects felt that the images were slightly ‘distorted’. This effect was not perceived the with auto zoom function activated. An increased level of visual discomfort was reported with auto zoom activated. This was

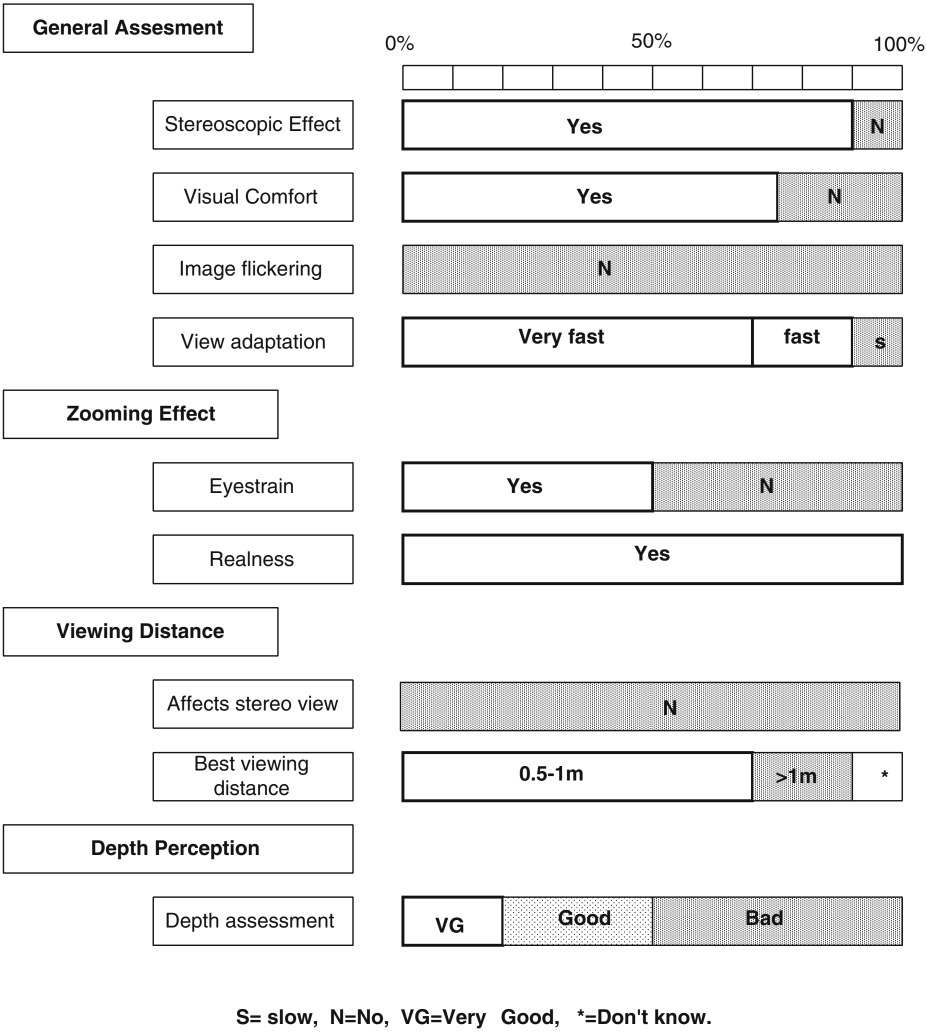


Fig. 14 Experimental results. *S* Slow, *N* no, *VG* very good, *Asterisk* don't know; *Stereoscopic Effect* ability to perceive three dimensional objects displayed on the monitor screen, *View adaptation* brain/eye accommodation to dynamic changes in view, *Realness* ability to relate the images to the real objects, *Depth assessment* ability to correctly assess the object size/separation using stereo images

attributed to the stepwise zoom control. A smoother, continuous zoom control would solve this problem.

7 Conclusions

The design of a stereoscopic telepresence system for a URV was presented. The primary objective of providing enhanced visual perception to the pilot was demonstrated. It was shown that by employing an auto convergence, linked to object distance, the camera system

Fig. 15 Auto zoom experimental setup

could overcome the geometrical disadvantage of camera separation of the URV system, and that effective stereo images may be created. This provides for more flexible URV designs. It was also shown that the auto zooming feature can increase the visual perception of the viewer and provide better telepresence effects. It was also indicated to minimise motion effects. Distant objects can be viewed under an improved (more linear) "image distance vs. object distance" relationship.

Experimental analysis conducted, on a group of subjects, has validated the effectiveness of the TVS, in improving visual perceptions. Further studies and modifications are planned to resolve issues pertaining to: implementing a smooth (step less) zoom control to reduce eye strain during auto zoom, determination of system settings, for the TVS, when operating in a water medium.

In transitioning from a laboratory to field deployment, water turbidity would be a significant factor and warrants further discussion. In the work presented, 'clear water' conditions have been assumed. The effectiveness of stereoscopic images can also be expected to be less effective under turbid water conditions.

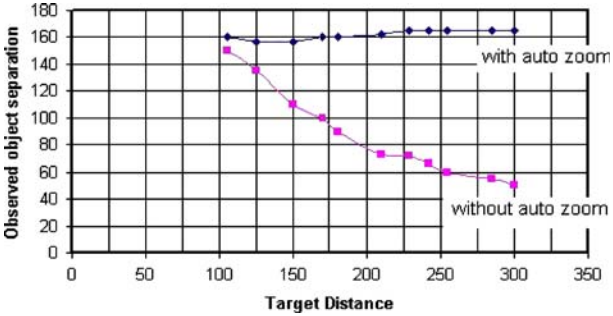


Fig. 16 Variation of object separation with target distance

References

1. Asokan, T., Tan, K.H., Seet, G.: A virtual reality based interactive simulation system for underwater robotic tasks. Int. Conf. Intelligence, Robotics and Autonomous systems, Singapore. 2003
2. Seet, G., Lau, M., Low, E., Cheng, P.L.: A unified pilot training and control system for underwater robotic vehicles. J. Intell. Robot. Syst. **32**, 279–290 (2001)
3. Asokan, T., Seet, G., Iastrebov, V., Senanayake, R.: Kinematic design and analysis of a 7 d.o.f dual stage manipulator for dexterous underwater applications. J. Intell. Robot. Syst. **38**, 277–295 (2003)
4. Seet, G., Thondiyath, A., Iastrebov, V., Ho, J.H.: Towards a modular, sub-compact underwater intervention robotic vehicle. Journal of Nanyang Technological University, Mechanical and production Engineering Research, Singapore 25–26 (2004)
5. Drascic, D.: Stereoscopic vision and augmented reality. Sci. Cumput. Autom. **9**(7), 31–34 (1993)
6. Tachi, S., Arai, H., Morimoto, I., Seet, G.: Feasibility experiments on a mobile tele-existence system. Proceedings of the International Symposium and Exposition on Robots. Sydney, Australia 625–636 (1998)
7. Murray, S., Murphy, D.: Underwater telerobotics and virtual reality: A new technology partnership. Ph.D thesis, Naval Command and Ocean Surveillance Centre (1996)
8. Woods, A.J., Penrose, J.D., Clark, D.: The development of a compact underwater stereoscopic video camera. Stereoscopic Displays and Applications VIII, San Jose, California (1997), February
9. Silva, L.C., Petraglia, A., Petraglia, M.R.: Stereo vision system for live submarine inspection of oil pipelines and equipments in deep sea. IEEE Int. Conf. Intelligent Vehicles 593–598 (1998)
10. Seet, G., Iastrebov, V, Thondiyath, A.: Stereoscopic telepresence system for remotely operated robotic vehicle. In Proc. 4th Asian Conference on Industrial Automation and Robotics, Bangkok, Thailand, (2005), May
11. Robert, A., Heinlein, W., Magic Inc., Ballantine book, NewYork (1990)
12. Moles, A.A.: Design and immateriality: What of it in a post-industrial society? in The Immaterial Society; Design, Culture and Technology in the Postmodern World, Prentice-Hall, New Jersey 27–28 (1992)
13. Starks, M.: Stereoscopic video and the quest for virtual reality. In: Merrit, J., Fisher, S. (Eds.) Stereoscopic Displays and Applications 2. Proc. SPIE Vol. 1457, pp. 327–342. (1991)
14. Starks, M.: Stereoscopic video and the quest for virtual reality. In: Merrit, J., Fisher, S. (Eds.) Stereoscopic Displays and Applications 2. Proc. SPIE Vol. 1669, pp. 216–227. (1992)
15. Starks, M.: Stereoscopic video and the quest for virtual reality. In: Merrit, J., Fisher, s. (Eds.) Stereoscopic Displays and Applications 2. Proc. SPIE Vol. 1917 (1993)
16. Woods, A., Docherty, T., Koch, R.: Image distortions in stereoscopic video systems stereoscopic displays and applications IV. Proceedings of the SPIE Volume 1915, San Jose, CA, (1993), Feb
17. Tan, C.S., Seet, G., Sluzek, A.: A novel application of range gated Underwater Laser Imaging System (ULIS) in Near Target Turbid Medium. Opt. Lasers Eng. **43**, 995–1009 (2005), EU