California AHMCT Program
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TELEOPERATED AND AUTOMATED MAINTENANCE EQUIPMENT ROBOTICS PHASE II

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ABSTRACT

Sensory feedback has been discovered to be extremely important in teleoperation of highway maintenance vehicles such as a front-end loader, where the vehicle must be navigated over unfamiliar and very rough terrain while simultaneously performing bucket operation. The primary means of feedback in this investigation for control of a remote vehicle is through the use of a transmitted three dimensional video image used to duplicate the operators on-board visual environment. This paper discusses and evaluates audio and video human feedback systems for use in the control of remotely operated heavy highway maintenance equipment. A three dimensional color video/audio feedback system was integrated into the teleoperated front-end loader which was developed during Phase I of the TAMER project. Performance comparisons are made between in-vehicle operations and teleoperations using line-of-sight, two dimensional, and three dimensional video feedback systems coupled with a simple monaural audio feedback system. Camera mounting and control systems, and field of view requirements are also evaluated. Suggestions for improvements to the system are based on field trials of the complete teleoperated front-end loader and audio/visual feedback system.

EXECUTIVE SUMMARY

A teleoperation system has been successfully developed for a Case 621 three-cubic-yard front-end loader at the University of California at Davis during phase I of the TAMER project supported by the Federal Highway Administration and California Department of Transportation (CALTRANS). The system enables the operator to leave the vehicle cab and continue the operation at a safe site if hazardous conditions are encountered. Tests and evaluations have been conducted at various sites, where the teleoperated front-end loader was operated by Caltrans maintenance workers. The entire system has been proven to be practical, reliable, safe and sufficiently easy to operate.

However, when the operator is removed from the front-end loader to a distant location, the operator loses the information he/she used to receive via his/her sensory perception (visual, auditory, tactile, etc.). This loss creates great difficulties for the operator in decision making. The weakened decision making capability slows down the operation speed. A wrong decision may cause an operation accident such as vehicle tip over. Previous field tests have shown that, at distances over 100 feet, the operator's sense of depth perception deteriorates rapidly and loss of reliable audio feedback from the loader was experienced.

Sensory feedback has been extremely important in teleoperation of highway maintenance vehicles such as a front-end loader, where the vehicle must be navigated over unfamiliar and very rough terrain while simultaneously performing bucket operations. It is possible to provide the operator nearly all the sensory inputs such as vision, sound, tactile, proprioception and motion. However, to do so requires an extremely complicated setup that is far too expensive and possibly unreliable to implement in a fleet of highway maintenance equipment to serve the California highway infrastructure. A feasibility study was conducted in this project that concluded that vision and audition are two feedback systems most appropriate to teleoperation of the front-end loader. The factors for vision feedback including color (black and white versus color), camera mounting schemes and optimum location (fixed versus gravity referenced), the use of multiple cameras, video presentation (stereoscope versus monoscope system) and field of view were also studied.

A three dimensional color video/audio system developed at Metron Optics was integrated into the teleoperated front-end loader. This system does not require the use of view obstructing special viewing glasses, therefore the driver still has the line-of-sight capability. The 3D video/audio feedback system consists of a camera subsystem on the loader and a viewing system that is mounted on the remote operating station. The images captured by the two cameras are encoded and, coupled with the sound signals from the microphone, are sent to the remote station via an additional RF transmission link. The video signal is then decoded and sent to the two monitors that reflect the disparate images on a concave mirror to generate the three dimensional image. The steering slaved camera system can also be panned and tilted remotely by the operator using the joystick to increase the range of view, if desired.

The feasibility of incorporating a video/audio feedback system to the teleoperated front-end loader has been well demonstrated by this project. Field test evaluations showed the advantages of using three dimensional video display system over two dimensional systems. It is clear that three dimensional color systems offer better object recognition such as identification of bumps and ruts that could potentially cause the rollover of a loaded front-end loader, and give the remote driver an accurate driving and manipulating capability.

It is suggested that a 3D head mounted display (HMD) set be used for the practical application on the teleoperated front-end loader. Evaluation and implementation of a HMD system that would allow for both line-of-sight and three dimensional video feedback should be included in the future work. Side mounted two 2D cameras with corresponding secondary monitors mounted at the workstation is recommended to allow for a duplicated peripheral view for the remote operator. Since the front-end loader is frequently engaged in driving in reverse, a back up camera view is also suggested.

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DISCLAIMER / DISCLOSURE

"The research reported herein was performed as part of the Advanced Highway Maintenance and Construction Technology (AHMCT) Center, within the Department of Mechanical and Aeronautical Engineering at the University of California, Davis and the Division of New Technology and Materials Research at the California Department of Transportation. It is evolutionary and voluntary. It is a cooperative venture of local, state and federal governments and universities."

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Chapter 1
Introduction

The University of California at Davis in conjunction with FMC's Corporate Technical Center has in past two years been involved in the prototyping of a remote vehicle operations system for application to large scale earth moving machinery necessary in maintaining California's roadways (TAMER project). The main goal of the TAMER project is to remove the vehicle operator from the vehicle cab to a safe operating station during hazardous operating conditions.

Once the operator has been removed from the in-vehicle environment, consideration must be given to information necessary to remotely pilot the vehicle with the same or higher degree of speed and safety as with an in-vehicle operator. If the vehicle cannot be operated safely and accurately in a remote position, then little benefit is gained from removing the operator from a hazardous environment. Also, if the performance of the vehicle is greatly declined and tasks cannot be executed with similar speed as an in-vehicle operator, the safety gains of the remote system will quickly lose favor to time constraints. In addition to removing the operator from hazardous operating environments, the goal of this project is to develop a remote operation system with equal or greater productivity when compared to an in-vehicle operator.

To achieve acceptable productivity rates in remote vehicle operations, the operator must be provided with information on the operations being performed. The primary means of information gathering by the operator is through sensory feedback. In teleoperation there are four primary inputs: vision, audition, and the cutaneous and kinesthetic senses (sight, sound, touch, position and motion) [11]. In true teleoperation man is part of the machine control loop creating a closed loop system. Thus, human feedback plays a critical role in remote vehicle operation. It is therefore necessary to optimize the human feedback for the best results.

The easiest way to optimize human feedback would be to provide the operator with all the senses he would use in vehicle operations. In heavy vehicle operations nearly all senses are employed; sight, sound, motion etc. However, to provide all these sensory inputs remotely would be extremely complex and expensive, and require a very large bandwidth for signals communication.

One therefore must choose among the major inputs. The cutaneous and kinesthetic would be difficult to reproduce. Motion simulation at the station would require complicated hydraulic systems. Such systems would be very expensive, heavy, space consuming and could only roughly approximate motion as acceleration is difficult to simulate in a fixed system. Therefore, motion feedback is too prohibitive to be incorporated as a kinesthetic sense though it could be displayed visually through accelerometer indicators if needed.

Force feedback through the controls probably is not necessary as in most heavy earth moving machines and in TAMER the primary controls: steering, brake, throttle, bucket and arm do not offer levels of resistance proportional to the vehicles loading as these controls have already been isolated from force through their boosted hydraulic actuation systems. Force feedback could be employed in order to provide the operator with enhanced input not found on the front end loader. The operator is already largely isolated, in this sense, for the in-vehicle situation. Thus, it is not necessary to incorporate control force feedback in the remote stations.

The remaining two feedback systems, vision and sound, offer the greatest amount of information to the operator. In most operations sight is indispensable to the human operator as the eye represents the largest sensory input channel to the brain [11] while sound broadens the perceptory range. Vision and audition systems are also easily incorporated into teleoperation systems. Thus, it seems that vision and audition are the two feedback systems most appropriate to remote operation of the end loader.

As visual information is the most important factor to operator feedback in remote vehicle operations, care must be taken as to how this information is collected and presented. The TAMER project is different from nearly all teleoperated scenarios which have been studied in that the front end loader operates within a variety of ranges. The visual system must be used to navigate and guide the end loader in both close proximity and long distance from the operator. The visual system must also be used to manipulate the arm and bucket controls for the multitude of operations possible with the two-yard bucket and other accessories. In order to determine the most effective visual setup, it is necessary to investigate the tradeoffs in visual systems ranging from direct line-of-sight to transmitted three dimensional imaging systems.

In Phase I of the TAMER project, a fully remote vehicle control package has been developed and successfully incorporated. The remote control package serves as the platform from which several telepresence and control concepts can be evaluated. The research covered in this report is specifically concerned with the means by which visual information can be best presented to the operator utilizing current technology. It is the goal of this research to evaluate the practical applications, considerations, and limitations of using three dimensional viewing systems to provide the operator with adequate feedback for remote control of heavy earth moving equipment.

Chapter 2
Background

2.1 AUDITORY FEEDBACK

Among feedback channels to the human operator the easiest to incorporate is the auditory display. Basic systems require only a microphone for sound pickup or some means of sound generation and a speaker requiring significantly less bandwidth to transmit than video images.

Studies have demonstrated that auditory feedback can also serve to generate information about spatial conditions much as video does. Experiments in aircraft design have revealed that with the use of sweeping tones proportional to aircraft turn rates, pitch changes proportional to bank angle and varying frequency interruptions of pitch to represent airspeed resulted in auditory tracking nearly equivalent to visual tracking. However, auditory inputs are more susceptible to disruption by other tasks [27].

When combining visual and auditory information visual information often supersedes auditory perception through human visual dominance. Often display systems like map guidance systems utilize verbal information as guidance or warnings in addition to visual displays. However, when a situation arises which demands attention across modalities to both audio and visual information concurrently, the visual information is acquired at the cost of the audio inputs which may go completely unnoticed by the operator [27].

In earth moving operations the vehicle itself provides signals to its condition through mechanical vibrations of the equipment resulting in distinct sounds. On-board the operator can determine: engine loading and applied loads through the engine pitch and noise level caused by rpm changes, the position of controls through the sounds caused by hydraulic actuation, and often the condition of the bucket through scraping noises or decreased motor rpm due to overloading. However, once removed from the cabin to a remote location the operator may become de-coupled from these auditory inputs. Major reasons for losing auditory input may include simply being too far from the vehicle to hear it or through masking. In masking one sound masks another especially when the masking frequency is similar to the desired signal frequency [31]. This situation would be prevalent in earth moving operations when multiple vehicles are in use at once generating similar frequencies resulting in the inability of the remote operator to isolate the sound signals originating from the remote vehicle.

When designing for an auditory feedback system in the remote end loader, signals such as spatial positioning probably will be ineffective. The operator should be provided with enough visual information for positioning especially since auditory positioning is not accurate enough for earth moving operations. Auditory warnings as to vehicle indicators, such as oil temperature, water temperature, extreme pitch angle, may be advantageous especially due to the intrusive nature of auditory signals. The intrusive nature of these signals may prove useful especially when the operator becomes visually saturated and is unable to monitor warning lights on the workstation display. However, the most advantageous use of auditory input is probably the transmission of vehicle loading information. While navigating visually, auditory information about engine loading and control activation will serve to increase the operators sense of telepresence as more cues found in in-vehicle use can be provided to the remote operator. To further enhance the sense of telepresence stereo audio system should be employed so that the operator can isolate the location of the sound to help determine its cause. The many studies done on remote vehicle operation have revealed through subjects responses that the presentation of vehicle operating sounds are indeed desirable [11,22,27,31].

2.2 VISUAL FEEDBACK

2.2.1 Line Of Sight

Presently, there are several teleoperated systems that are operated with direct vision as the only sensory input [10,25,30]. These systems are usually found in nuclear reactor systems where object manipulation is the only concern. However, studies from these scenarios have revealed that as distances increase, visual resolution and depth perception drop off increasing task performance times. The loss of depth perception is the major factor causing deterioration of performance with distance [11]. However, in TAMER project distances may become large enough such that visual resolution will also become a significant concern.

Teleoperation has also found uses in remote operation of earth moving equipment in steel furnace operations. United Systems Engineering Corp. uses it's URC15000 Portable remote control system to operate bulldozers to clear slag from furnaces in 300 degree Fahrenheit conditions. Operation feedback is purely visual through close proximity line-of-sight. Using this methodology they have been able to develop a reliable and safe system [30].

Initial field trials of the TAMER system have demonstrated that operation by line-of-sight is effective. One concern however is with frequent disorientation during maneuvers resulting from confusion in determining steering direction from startup. Since the end loader is articulating, both front and rear wheels steer, turning in opposite directions. When viewing the end loader and initiating a turn from stop it is normal to observe the wheel angles to determine initial heading, but as both sets of wheels turn the operator often incorrectly references off the rear wheels resulting in a reverse of the desired direction. This problem is most frequent when driving in reverse or when the loader approaches the operator head on. This phenomena becomes less frequent as the operator becomes more familiar with remote piloting.

Line-of-sight operation has been an effective means of operation for decades. The significant considerations are unobstructed views, close viewing proximity and good lighting. These can all be achieved using a workstation with a 360 degree field of view when operated during daytime and within about a hundred feet of the remote vehicle.

2.2.2. Video Systems

Although line-of-sight is an effective means for teleoperation its limitations can be overcome to greatly broaden the operating potential of any teleoperations system. Through the incorporation of a video system and displays, the distance, obstruction, and lighting limitations inherent to line-of-sight can be significantly reduced. The problem lies in determining the necessary video system to be effective and affordable. The major factors in video selection are; color vs. black & white, field of view, stereo vs. mono, mounting, and display.

2.2.2.1 Color vs. Black & White

When viewing video systems individuals tend to favor color over black & white systems for viewing pleasure. Thus, many video systems have been tested in teleoperation to determine if color offers a performance advantage in addition to individuals predisposition for its use [5,20,21,32].

The most significant drawback to color is its complexity and cost. The Naval Oceans Systems Center (NOSC) has been involved in the development of Unmanned Ground Vehicle systems for battlefield use. NOSC chose not to rely on color imagery as its high cost and color imagery in low light illumination precluded its use at night and the technology to support color head mounted displays were not adequately developed. System complexity is also increased by the need to sense, transmit and display color images [32].

The common factors used in determining performance advantages between color and black & white seem to be: distance to object detection, object height estimation, object range estimation and errors in estimation. These factors have been tested by Sandia National Laboratories (SNL), New Mexico [20,21] and a joint effort between NASA, RCA and Perceptronics [5]. Each group concurs that there is little gain achieved by color imagery.

NASA's, RCA's, and Perceptronics' findings indicate that the use of color over black & white in video systems does not appear to have a strong overall effect. The only significant variance between the two was that the color system produced a greater positioning error when performing aligning, clearance and docking tasks of a four degree of freedom frame [5].

D. P. Miller of Sandia National Laboratories utilized a remotely operated Jeep Cherokee to ascertain performance of varying video systems during off-road teleoperation. In testing for distance to object detection participants demonstrated an average range advantage of about nine feet for the color system; average detection range for B&W = 51.4 ft (15.7 m), color = 59.9 ft (18.3 m) (Figure 2.1). In distance to object estimation overall overestimation for color was 64.5 % while black & white was only 45.9% (Figure 2.2). When asked if the Cherokee would clear two obstacles the frequency that participants overestimated using color was 89.6% and 54% for black & white [20,21]. Thus, the added cost and complexity of color system are not offset by a performance gain. Although color offers increased range detection, black & white demonstrates a significant advantage in distance and clearance estimation which are most important to earth moving operations with the end loader. In addition black & white offers improved operation in low light conditions making it suitable for dusk and dawn use. Unfortunately, these tests were conducted in on road or simple off road environments where scene complexity was not of major significance. In operations conducted by heavy earth moving equipment scenes are often very unfamiliar and very complex. In these conditions, the image recognition advantage of color systems may offset the advantages reported in using simple black and white systems. There have also been advances in color camera technology to improve viewing in low light conditions.

2.2.2.2 Field of View:

The horizontal field of view (HFOV) that most of us are accustomed to is not easily reproduced through video systems. The human eyes horizontal field of view covers nearly 135 degrees, while the combined view of both eyes creates an overlap approximating a total of 180 degrees [4]. Multiple cameras and displays are required to simulate the eyes HFOV. As this approach is very expensive and not easily accomplished many teleoperation systems incorporate a steering slaved camera system which offers increased HFOV by successively scanning smaller view fields to generate a larger HFOV much as one turns one's head to maximize HFOV.

NOSC's Unmanned vehicle tests utilized a steering slaved unit and head mounted display (HMD) to relay images, while head mounted sensors were used to enable the HMD to turn the camera producing hands free operation. This method made proprioception possible as the driver was able to use his neck and body positions to locate objects and generate three dimensional perception. NOSC tests revealed that drivers used this system to adequately negotiate sharp turns and to relocate objects. Although this method appears to have aided in remote driving, some operators became annoyed by perceptible time lags between head and camera movements [32]. Testing at Sandia National Labs (SNL) involved more qualitative analysis of steering slaved cameras. In detection ranging steering slaved color performed worse than fixed color (56.5 feet vs. 61.5 feet). Respondents to SNL's test were also annoyed by the slow turning rate provided by the steering slaved camera [20].

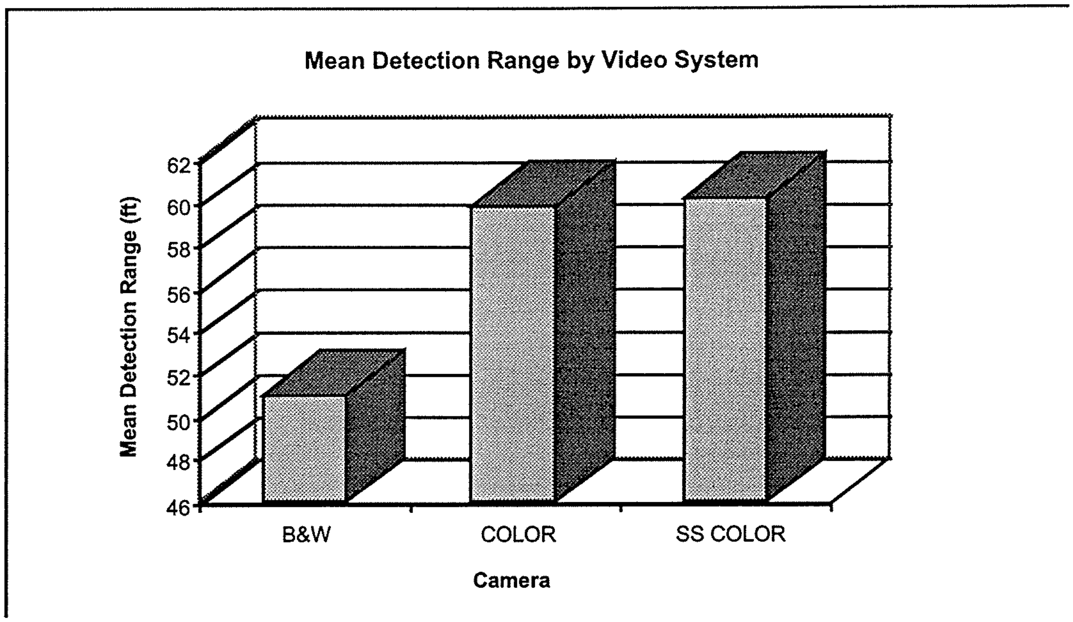


Figure 2.1 Mean detection range (reproduced from SNL (D.P. Miller) [20,21])

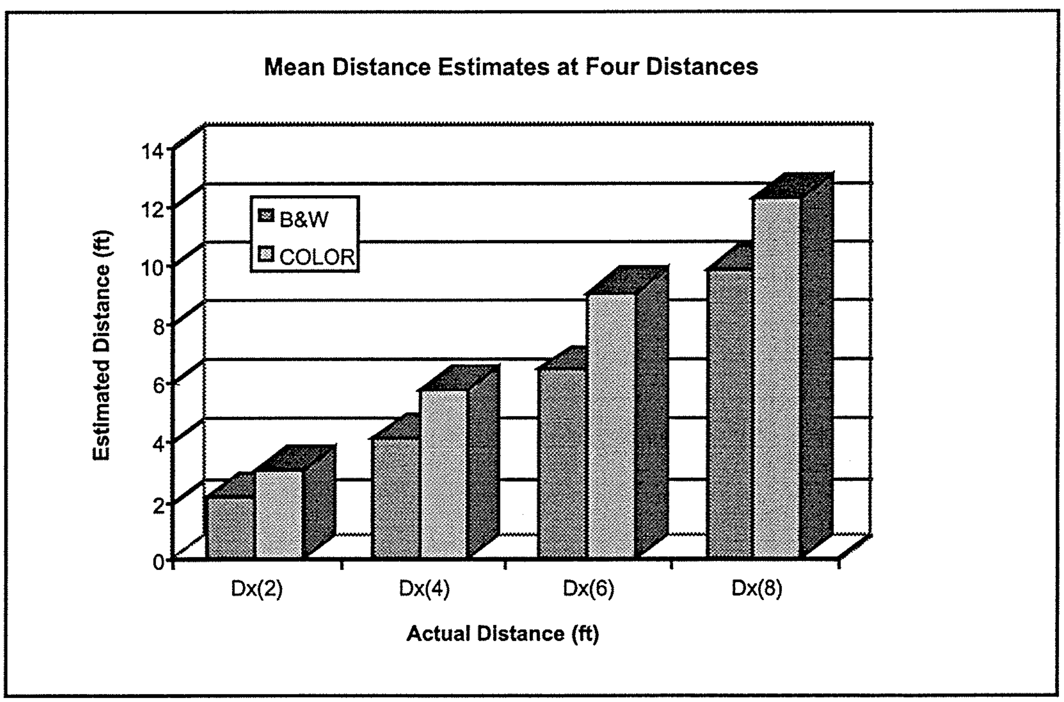


Figure 2.2 Mean distance estimates (reproduced from SNL (D.P. Miller) [20,21])

The actual instantaneous HFOV presented by camera systems in fixed conditions has been tested by NOSC. In an attempt to determine the HFOV necessary to pilot a vehicle, NOSC participant's operated in-vehicle with visors limiting their HFOV to 60 degrees. These results were compared to unimpaired vision tests. Results indicated that there were no consistent performance differences between limited HFOV and unimpaired vision, while with practice drivers were able to produce better course times with limited HFOV than initial unimpaired tests [22]. Although it appears that steering slaved viewing systems are not necessary to create a larger field of view, the application of steering slaved systems to the front end loader may be a necessity. This is due to the fact that the front end loader used by TAMER is articulating, meaning it steers by pivoting about a center point and not by turning its front wheels (Figure 2.3). Thus, for the front end loader a steering slaved system may be necessary in order to see where the vehicle is going as a cab mounted fixed camera may not display the view directly in the vehicles path. Furthermore, most earth moving machines involve extensive manipulation in the vertical axis of view. When lifting a bucket or other device, the operator needs to view ranges from the ground where digging occurs to elevated heights for dumping. Thus, the camera system may also need to slave to the vertical direction.

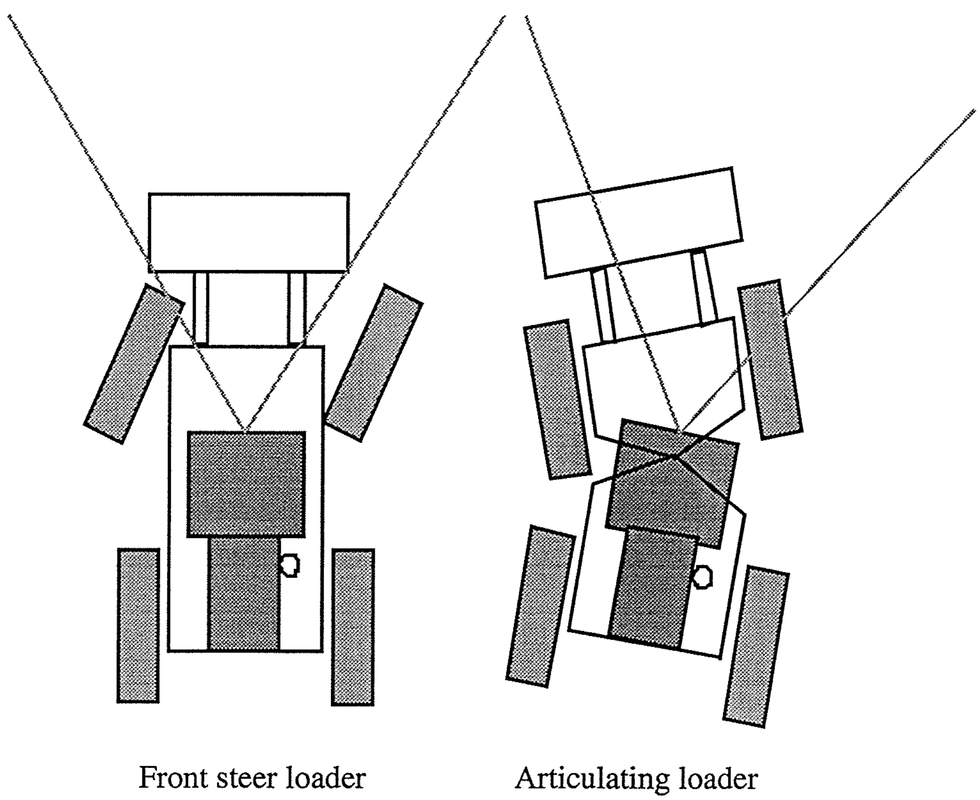
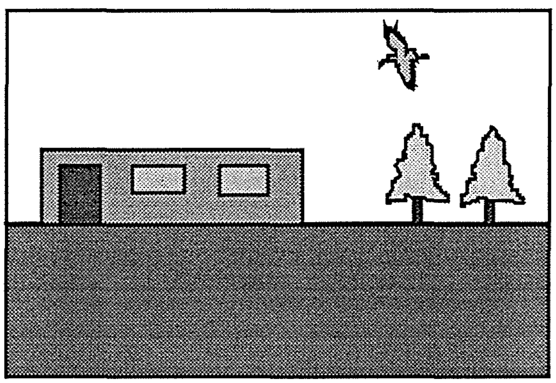


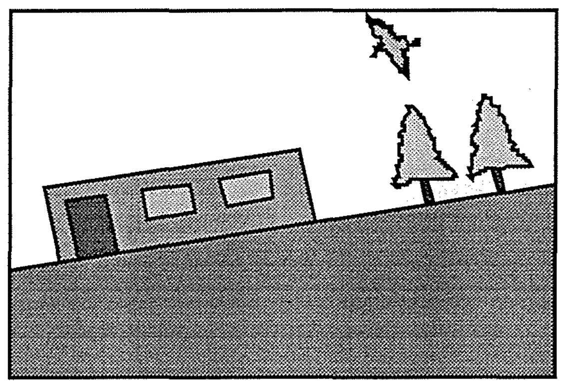
Figure 2.3 CASE 621 loader steering

2.2.2.3 Mounting:

In earth-moving operations a critical indicator of vehicle status is the roll angle. If the operator manages to get the vehicle into too radical a roll angle, roll over is possible. Although roll angle indicators can be used, the most effective means is through viewing the vehicles attitude directly through the video system to improve response times. NOSC studies originally utilized a fixed camera mount on the vehicle to provide attitude information. However, with the camera fixed, the vehicle was constantly in a level position while the earth was shown to be rolling relative to the vehicle. In this scenario operators often left the vehicle parked on steep banks and were surprised to see objects at extreme angles relative to the vehicle, not initially realizing the vehicle itself was at the extreme roll angle and not the object [32] (Figure 2.4). The lag in adjusting to this difference may cause rollover due to the extreme roll angles often encountered in earth-moving operations. One way to counter this effect is to mount the camera such that it floats with the vehicle and is always level with respect to the horizon. This way the HFOV will always be shown level as one is accustomed to and the vehicle will be shown at the proper roll angle through bucket, roll cage, and hood referencing. Thus, the camera should be mounted with a reference to the horizon to eliminate confusion resulting from a rolling HFOV.



View as seen by remote operator with vehicle on slight incline using gravity referenced camera



View as seen by remote operator with vehicle on slight incline using fixed camera

Figure 2.4 Gravity referenced viewing

In addition to mounting for horizontal referencing, the camera system must also be mounted to account for the shocks encountered in off-road driving. Heavy earth moving equipment is rarely fitted with damped suspension systems, usually the tires provide for the only shock absorption, resulting in often violent operating conditions. Normally, when the operator is in the vehicle, natural head and body movements dampen the shocks resulting in a relative stable viewing environment. However, camera systems do not share the human body inherent damping capabilities and the resulting image at the viewing station could prove difficult for the observer to manage. A well designed viewing platform should be horizon referenced and incorporate a damping system to provide a stable picture for the viewer.

2.2.2.4 Stereoscopic Viewing:

When utilizing standard viewing devices to present information to a remote operator, major perceptual cues are lost in the reduction of a three dimensional environment into the limited two dimensional translation for which standard video systems are designed. During off-road driving conditions, operators need to navigate hazardous terrain features such as rocks, hills, ditches and other obstacles whose apparent presence may be diminished or altogether eliminated when viewed using two dimensional techniques. The primary failing of two dimensional viewing devices in the presentation of the three dimensional environment is the lack of depth cues required for the operator to mentally reconstruct the operating environment. The need for three dimensional information can be provided by utilizing one of the many recently developed three dimensional viewing devices presently available or under development. An effective telepresence system should therefore be designed to incorporate the advantages of three dimensional viewers as suggested by several studies on this point [11,20,31].

Creation of the three dimensional environment is dependent upon establishing depth cues for which there exist many possibilities [4,11,25,28].

1) Rendering: This term can loosely be applied to cover a wide range of methods for conveying a sense of three dimensionality through visual interpretation. Some features of rendering are:

- Light - through manipulation of brightness levels across an object depth can be perceived, this is conversely achieved through shading.
- Color - an object depth can be perceived through changes in hue, saturation and brightness.
- Linear Perspective - as an objects depth recedes into the distance, parallel object lines are viewed to converge at the far endpoints.
- Texture gradients - as an object recedes into the background its constant texture appears to become more dense.
- Aerial perspective - environmental conditions, haze, dust, etc. reduce the clarity of distant objects by obscuration.
- Height - the higher an object is located in the visual frame the more distant the object appears.

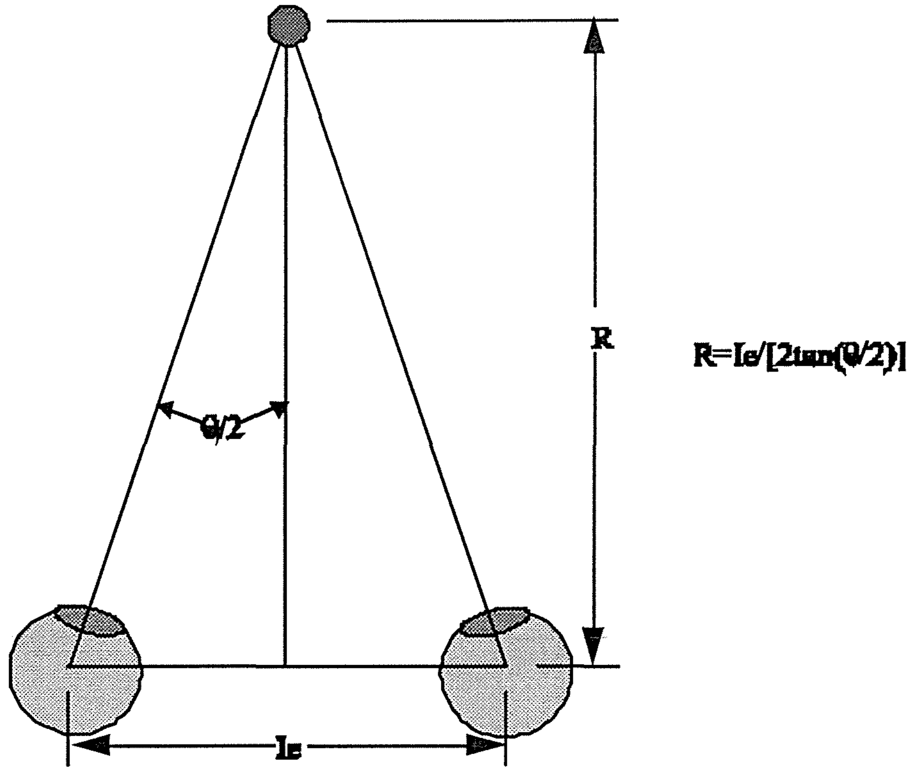
These cues are normally employed by artists in creating the illusion of three dimensionality on a two dimensional background, though these same effects can be viewed in two dimensional devices.

2) Interposition and motion parallax: For interposition the depth of objects is affected by the relative placement of the object relative to the observer, the observer can determine distance through head movements whereas the closer the object the more increased the movement of the object relative to the observers movements. Motion parallax is similar in that when two objects moving at the same rate are viewed, the closer of the two objects is perceived to move faster.

3) Constancy: The operator has accumulated over a lifetime knowledge of the sizes and shapes of many objects. Through geometric and size constancy an operator can determine the range to an object based on its apparent size from experience.

4) Accommodation: Accommodation is the result of the eye focusing of the lens for viewing close and distant objects. The degree of accommodation (focus) relates to the distance of the object as the observer can relate the eyes muscles changes to distances. Accommodation is required for objects in the range of about 4 inches to 20 feet [28]. A properly designed viewer can eliminate the need to focus by fixing the focus in the range from 16.5 feet to infinity where the focus remains constant [1]. Although, the need for dynamic focusing lenses is not necessary one possible drawback is in the inducing of headaches as the visual process expects varying accommodation [4]. This phenomena should be largely compensated for by the system utilized in TAMER since both line-of-sight vision and video is utilized allowing the operator to accommodate for different viewing distances within short time spans. One problem frequently encountered by teleoperators when using only video systems as their vehicle reference is the occurrence of motion sickness. Symptoms of motion sickness are possibly explained by sensory conflict theory where visual information is de-coupled from any anticipated vestibular information (motion) due to the removal of the operator from the system [22]. Motion sickness has been reported by participants in remote vehicle operations with both SNL and NOSC. Hopefully, the use of line-of-sight vision with video in the TAMER project will eliminate symptoms of motion sickness as the remote operator should not expect motion feedback through direct observation

5) Stereopsis: Stereopsis is the basis for nearly all three dimensional video systems and is based on the principal of binocular convergence (retinal disparity). Because the human eyes are separated by approximately 2.5 inches, each eye is presented with a slightly different view of the same object. The fusion of these two images by the brain results in a three dimensional picture (Figure 2.5). A weaker cue resulting from binocular convergence is the range estimation made possible by muscular action as with accommodation [28]. Retinal disparity is effective to distances when the inter ocular separation creates an arc of at least two arc seconds [4] (Diner and Fender report 20 arc seconds as a human mean value [6]). When designing a three dimensional viewing system, the designer may take advantage of not being restricted to the human eyes 2.5 inch (6.5 cm) inter ocular separation. By increasing the focal separation, 'hyperstereopsis' or enhanced 3-D may be achieved [26]. If a system were designed with a focal separation of five inches, objects at ten feet would have the same depth resolution as an object normally viewed at five feet. This effect could be used to improve a teleoperators capabilities though at the expense of some distortion.



Human eyes focusing on object at a distance R. R is the range to the object, Rs is defined as the stereoscopic range. Stereoscopic ranges are dependent upon an individuals visual acuity and is generally about 670 meters as the human eyes inter ocular distance is about 6.5 cm (2.5 inches). With video systems, the effective inter ocular distance can be magnified increasing stereoscopic range and enhancing the three-dimensionality of closer objects.

Figure 2.5 Stereopsis

When designing the three dimensional system, consideration must be given to which of the depth cues can be designed for and their relative strengths. When processing visual information the brain first disseminates the monocular cues as they are the fastest. These cues include the 'rendering' cues, constancy and motion cues. These are also the cues for which dynamic video systems have little control over. The rendered cues could be modified in a virtual environment, however, this would require extensive computing power and would be difficult to display in real time. Constancy cues are the result of the operators experience and are therefore fixed. Motion cues are the result of the observed environment for which the operator would have little control. The remaining depth cues are stereopsis and accommodation. These are the binocular cues which the brain uses to continually calibrate the three dimensional image initiated by the monocular cues. Without binocular cues the brain could easily misinterpret visual information resulting in the degradation in performance experienced in two dimensional telepresence systems.

Studies have shown that stereoscopic video systems offer significant advantages over monoscopic systems especially when remote scenes are unfamiliar or changing, new task learning rates are important, image quality is low, and operations require significant depth positioning [32]. In remote vehicle operations, focal distances are in the range of 16 feet to infinity where focus remains fixed, eliminating accommodation as a means of binocular information. Thus, a successful telepresence system must incorporate a stereoptic viewing device to present adequate information for the productive remote operator.

2.2.2.5 Display Systems:

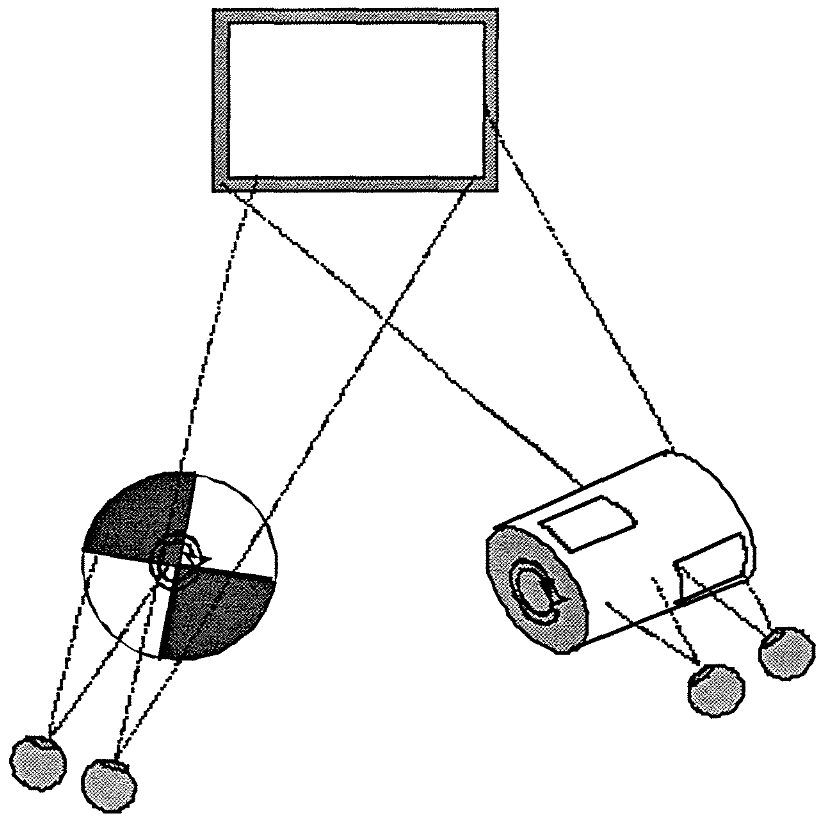
Although, stereoscopic based video systems are the most predominant three dimensional systems used, certain systems have utilized some of the other fundamental depth cues to create three dimensionality. This section discusses the available three dimensional viewing devices and their advantages and disadvantages when selecting for an appropriate telepresence system.

Stereoscopic displays operate on the principle of presenting two disparate images to the viewer to construct the three dimensional environment. The method by which these views are presented determines the classification of the system. These classification can usually be generalized into two categories; time multiplexed and time parallel systems [14,25,28]. Time multiplexed systems present the two disparate images in alternation usually in the range of 30 Hz. These systems must incorporate some sort of shuttering systems which ensures each eye is presented with the proper image. Time parallel systems present each disparate image simultaneously to each eye. So that each eye receives the appropriate left or right image, filters or dual displays must be used. Finally, these systems are autostereoptic if no special glasses must be worn by the operator to perceive the three dimensional image.

The earliest device for the presentation of a stereoscopic image was the stereoscope invented by Charles Wheatstone in 1838. This device supported two disparate photographs of the same object which a viewer could observe through slight magnification to realize a static three dimensional scene. It was not for nearly another century until the principles used by Wheatstone could be applied to real time using video (though there were some novel devices used at the turn of the century for viewing cinematic footage stereoptically).

2.2.2.6 Time Multiplexed

Two of the earliest stereoscopic video devices were the rotating drum and the rotating disk [13]. These devices relied on a system to display images in alteration using dual displays or electronically controlled alternating monitors. In order for the observer to view the corresponding image for the left and right eye, one eye must be blocked while the other receives the transmitted image. Rapid alteration of blocking/transmitting produces a fluid presentation of the three dimensional view. The rotating drum and disk are each phased with slits or openings which would block or transmit light to the observer's eye (Figure 2.6).



Rotating Disk and Drum methods for three dimensional viewing. These methods rely on mechanical shuttering which presents each eye with the respective image in synchronization with alternating disparate images at the monitor. The monitor may use electronic or mechanical (disk) means to produce the alternating image.

Figure 2.6 Rotating disk and drum display systems

By matching the rotational frequency of these devices to the time multiplexed display the three dimensional image is created. Although these devices are very good at providing full transmission, they are large, awkward and difficult to keep in synchronization with the display system.

Although the rotating disk and drum are no longer utilized, they were the basis for the shuttered systems used presently for stereoscopic viewing. In any shuttered stereoscopic device a pair of alternating disparate images must be transmitted to the corresponding eye. Success of the shuttered system depends on how well they transmit and block images while not being cumbersome for the operator. Mechanically shuttered systems have given way to various electro optical shuttering devices.

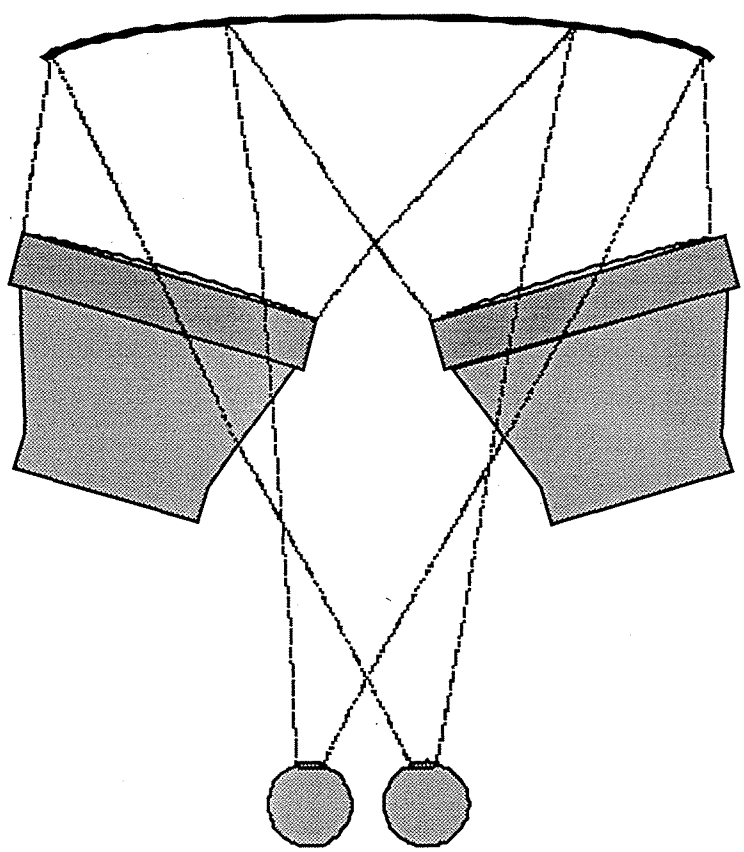
Two approaches to electro optical shuttering time multiplexed systems are based on polarized lead-lanthanum-zirconate-titatnate (PLZT) and liquid crystal shutter (LCS) technologies [13,14,26]. PLZT devices use solid ceramic wafers with embedded electrodes to control the transmission and blocking of light. PLZT devices are glasses with no moving parts, voltage controls the crossing and uncrossing of polarizers to regulate light transmission. One major drawback to this system is that it requires several hundred volts in relatively close proximity to the observers head. The potential for a shock was demonstrated at the University of North Carolina when during evaluations of stereoscopic viewing devices a user received a painful shock to the head [12]. Another drawback to this device is its poor light transmission and open/closed transition. L. Lipton of StereoGraphics Corporation reports that PLZT devices by Motorola transmitted only 3% of peak [13]. Another drawback to electro optical time multiplexed shuttering devices is ghosting. Monitor systems utilizing CRTs have relatively slow phosphor decay creating a persisting image which may overlap. This is further complicated by the retinas tendency to retain an image as well. Ghosting results in an undesirable double image[28]. Although these devices are relatively small, lightweight and provide flicker free imaging, they would not be suitable for remote vehicle operations as the light transmission is too low to be used in outdoor environments where ambient light would drown the image and the glasses would prevent any possible direct line-of-sight viewing without removal.

Liquid crystal shutter and display systems are now available with substantial improvements in transmission over PLZT systems. Liquid crystal devices require significantly less switching voltages than PLZT's, have transmission rates of approximately 30% and can be incorporated on the view screen. CrystalEyestm by StereoGraphics is a relatively low cost LCS stereoptic device requiring eyeware. This system also allows the viewer to observe the three dimensional image from a wide range of head positions through the use of an infrared synchronizing sensor [13]. There are also several high end semi-autostereoptic liquid crystal devices. J. Lipscomb of University of North Carolina reported on a polarized liquid crystal plate device [12]. This system uses liquid crystals in the monitor to polarize light clockwise or counterclockwise. The user wears special glasses which have correlating fixed polarized lenses for each eye. True autostereoptic LCD devices are offered by Dimension Technologies and NTT (Japanese Telegraph and Telephone) [14]. These devices do not use light as efficiently as LCS systems and require the observer's head to be precisely located, though the NTT device offers an expensive head tracking system to compensate for limited movement. Although there are many liquid crystal viewing systems offering required improvements over PLZT devices, they still fail to transmit sufficient light for use in outdoor environments.

2.2.2.7 Time Parallel

A familiar technique to anyone who has viewed three dimensional movies at the theater is the anaglyph. The anaglyph is a time parallel display where both images are presented simultaneously on the same monitor. So that the images can be differentiated by each eye, the left and right eye images are displayed in the green and red color bandwidths respectively and the observer wears a pair of glasses with red and green filters so that each eye receives the corresponding disparate image [6,24]. The advantages of this system are its simplicity, need for a single monitor and flicker free imaging. However, this is not a true color system as only two colors can be used. The filtered glasses would also give the observer an interesting though distorted view of the environment for any line-of-sight operations.

A natural progression of stereoptic viewing devices is the use of two monitors, one for each eye. True time parallel stereoptic devices can be easily incorporated using head mounted displays (HMD) or autostereoptic displays using fresnel lenses or concave mirrors. Metron Optics of Solana Beach, California offers an autostereoptic concave mirror system. In this device two monitors, one for each eye, reflect disparate images on a concave mirror which directs the images to the corresponding eye when the observer is properly located (Figure 2.7). This image appears to be suspended in space and offers the advantages of nearly 100% transmission, flicker free presentation, and no obstruction of direct line-of-sight viewing. Matron's system is also configured for 'real world' viewing in that the camera/viewer configuration is such that there is no magnification or image distortion.



Mirror based viewing systems use two monitors each presenting a disparate image to the observer simultaneously. Each image is reflected off a concave mirror to the corresponding eye. The observers head must be within a certain range in order to see the three dimensional image. Off center viewing results in a two dimensional image. One side effect of using a mirror is that the images are reversed, Metron uses a second mirror (not shown) to conteract this effect (this can also be conteracted by manipulating the video images electronically).

Figure 2.7 Mirror based display system

This may be advantageous when translating from stereoptic viewing to direct line-of-sight though the tradeoff is a limited field of view. The disadvantages to this system are its relatively large size and need for precise alignment of monitors and color matching. Although the observers head needs to be properly located, there is still a relatively large freedom of movement and lines are projected by the display to indicate when the observer is out of position.

HMD devices have long been popular for military applications and are now becoming widely accepted for use in virtual reality environments, especially gameplay [3,8,15,29]. HMDs use either small CRTs or LCDs to project disparate images directly in front of the observers eyes. HMD can be designed to fully immerse the observer or to provide partial immersion. The fully immersed viewer would have an exceptional image however such an observer would not be able to view anything else and may become easily disoriented and possibly sick. At the University of North Carolina, a user became so disoriented during a test as to require fifteen minutes of recovery time [3]. Some manufacturers allow the HMD to permit the observer some peripheral external viewing for orientation. Another method is to superimpose the stereoscopic view over the environment using silvered mirrors allowing a 50% transmission rate. This is probably only effective for computer generated images as overlays of real world environments would prove very confusing. A possible solution is the use of a bifocal HMD. A bifocal setup would allow the viewer to easily switch from the real environment to the video environment and be effective for remote operations, however the strain on the eyes due to focus changes would need to be investigated. HMDs also add substantial weight to the observers head which may cause discomfort due to the increased inertia, though advances are quickly bringing weights down to comfortable levels. Finally, the HMD can be coupled with a head tracking device which can slave the viewing cameras to look where the observer is looking.

2.2.2.8 Alternative Displays

One system which offers a departure from the stereoscopic systems is the multiplanar display [24,28]. Multiplanar displays generate a three dimensional view by rapidly presenting the observer with successive object views along the depth axis. To accomplish this, a synchronized loudspeaker is driven to vibrate a viewing mirror back and forth. As the mirror translates in the z-axis an image from a camera representing each depth position is projected. The quality of this system is dependent upon how many cameras are used to create each depth view and how well the mirror is synchronized to the corresponding view. The advantages to this system are that it is autostereoptic, can be viewed by many observes at once, and is not restrictive in head placement. The major drawback to this system is the large number of cameras required and the difficulty in synchronization.

When considering relative cue strengths for depth perception, motion parallax may be as influential as stereopsis. Motion parallax requires object movement relative to the observer to be effective and is difficult to control. One approach to this problem is accomplished by effectively moving the observer rapidly back and forth relative to the object. This method is employed by the VISIDEP^{TM} system [16,17]. VISIDEP^{TM} uses two cameras to observe object images from slightly different view points. These images are then presented in rapid alteration (7-15 frames per second) on a single monitor. The rapid alternating presentation of the offset images creates the illusion of three dimensionality. This system is autostereoptic since both offset images are viewed by each eye. Advantages of this system are its simplicity and full transmission as no special viewing devices are required. Since VISIDEP^{TM} is based on motion parallax, only one eye is necessary for three dimensional viewing and the viewing position is not restrictive. However, one drawback to the rapid presentation of alternating images simultaneously to both eyes is a slight rocking sensation though McLaurin and Jones report no significant viewer discomfort. Although VISIDEP^{TM} enhances three dimensional perception relative to two dimensional systems its performance relative to stereoptic systems has not been established.

2.3 SUMMARY

Remote operation of heavy earth moving equipment such as the front-end loader used in TAMER is a challenge in that many factors not normally encountered in simple telepresence systems must be designed for. Heavy earth moving equipment involves operation in very complex and unfamiliar environments as well as the manipulation of external attachments (buckets, scrapers, backhoes...) which demands the attention of all the operators senses. When the operator is removed from the in-vehicle environment to the remote workstation, consideration must be given as to what senses need to and can be reproduced. Because of the complexity of using force feedback and motion systems the two fundamental sensory inputs that can be reproduced are sight and sound. Sound is simple to design for in that basic microphone systems can transmit a stereophonic signal requiring little bandwidth to a speaker system at the station. Visual requirements are not so simple.

When designing for a remote visual system several factors must be considered: color medium, mounting methodology, viewing field, and dimensionality. Although studies have shown that black and white offers advantages to color video systems, color systems need to be utilized in TAMER project as color is better suited for object recognition in complex environments. The presentation of the video image must be stable and indicate the attitude of the vehicle so as to present the operator with a familiar scene. Mounting should then be such that the camera system is isolated from shocks which would make image readability difficult and the cameras should be mounted such that they are constantly level with the horizon so the operator can quickly perceive dangerous vehicle roll attitudes (rollover). The video system must also present as much as the visual environment as possible. This is best done by maximizing the horizontal field of view. A HFOV of at least 45 degrees should be adequate for this task. Although studies have shown steering slaved systems to be somewhat unfavorable, they are required by TAMER as the vehicle uses articulation for steering and large vertical fields of view must also be presented for dumping/-digging operations. The topic of most complexity is in the level of dimensionality of the image. Remote off-road operations require precise positioning for which depth is a requirement. Although two dimensional displays offer some depth cues they lack the strongest and most dominant cue of stereopsis. Stereoptic systems also offer the advantage of improved object and terrain feature recognition in complex environments. An ideal stereoptic viewing device would be flicker free, provide 100 % transmission, allow for a range of head movements, and be unobtrusive to the observer. Also of importance is the need for line-of-sight view. The operator must be able to view the control surface of the remote workstation as a minimum. It remains to be seen the level of advantage line-of-sight vision will be in addition to transmitted video, though for testing the stereoptic device must allow for line-of-sight viewing as well. Thus, an autostereoptic, time parallel stereoscopic system is needed. HMD system may also work given they are bifocal. Hopefully, by incorporating these design parameters, remotely operated heavy earth moving equipment can be proven as or possibly more effective than in-vehicle operations for all operations as well as hazardous working environments.

Chapter 3

Telepresence System

3.1 REVIEW OF THE REMOTE CONTROL SYSTEM

A remote control system was designed and constructed for Case 621 front-end loader in Phase I of the TAMER project. The system is broken into several subsystems: Remote Operator Unit (ROU), Operation Control Computer (OCC), Loader Control Computer (LCC), a trancseiver RF modem, and necessary actuator and sensor interfaces. The OCC receives commands from the ROU and sends them over the RF modem to the LCC which then controls machine operations through the actuator and sensor interfaces.

Two remote operator control units have been developed, a stationary on-truck workstation and a backpack style portable unit. The on-truck workstation is essentially a duplication of the CASE 621 loader cabin interior providing the operator a familiar operating environment. The portable control unit is supported by the operator via chest straps and tummy pack with all communication equipment carried in a backpack. The controls are hand held.

Field tests have revealed that the system is reliable, durable, safe, and sufficiently easy to operate. However, with line-of-sight operator feedback, the limited range in which the vehicle could be successfully operated was encountered. At distances near one hundred feet or more, positioning became very difficult to perceive visually. The use of telepresence systems is necessary to make teleoperation of such heavy earth moving equipment feasible.

3.2 THE AUDIO/VISUAL OPERATOR FEEDBACK SYSTEM

An audio/visual operator feedback system has been developed using the guidelines discussed for teleoperation of remote vehicles. In following with the recommendations set by the previous sections, the telepresence system was designed to meet several specifications, some of these are:

- Line-of-sight capability
- Audio feedback
- Color video
- 45 degree horizontal field of view
- Horizon referenced camera system
- Steering slaved camera system
- Auto-stereoscopic display
- Bright image
- Allow for normal in-vehicle operations

To accomplish these goals, the Metron Optics remote 3D video/audio system was selected.

3.2.1 Overall Features

Metron Optics system is auto-stereoptic and time parallel. This allows for use of line-of-sight operations as well as of a full view of the workstation controls by the operator as his natural view is unobstructed by the use of any head mounted viewing devices. Metron system uses a concave and flat mirror to project each disparate view to the eyes . The use of a mirror results in nearly 100% transmission of the images unlike shuttered systems which transmit only up to 30%. The high transmission allows the Metron viewing system to be used in environments where ambient light levels may be high, such as outdoors, and not drown out the three dimensional image. The image projected by the viewing system is color so that operators can better identify objects in unfamiliar environments.

Two disadvantages of Metron system are its relatively large size for a small viewing area and a narrow horizontal field of view. The projected three dimensional image is 13 inches (33 mm) diagonal while the display system measures 26 inches high by 32 inches wide by 25 inches deep (66 cm x 81 cm x 63.5 cm). This did not prove to be a major problem as the stationary workstation was over designed to allow for the support of a large viewing device such as Metron's. Fortunately, the viewing area is also located at the top most region of the display so when the display is mounted to the workstation, the operator can easily look over the top of the display for unobstructed line-of-sight operations (Figure 3.10). As delivered, the Metron viewing system provided a limited horizontal field of view of only 22 degrees. This value was far lower than the recommended values of 45 degrees for successful teleoperation. To achieve a 45 degree field of view, the camera focal lenses were replaced resulting in the magnification of the image size by 1/2.

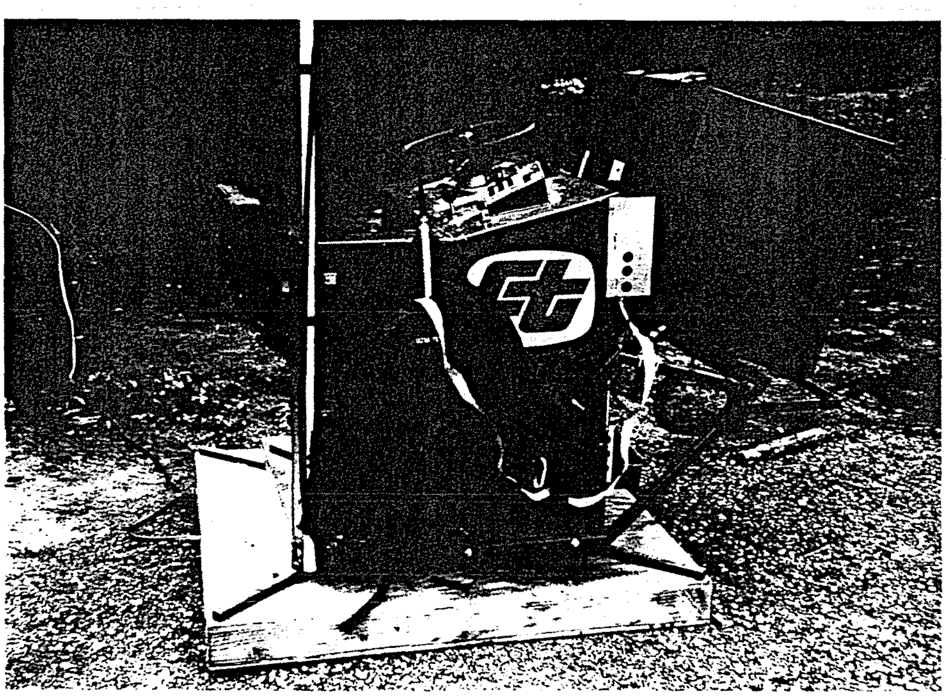
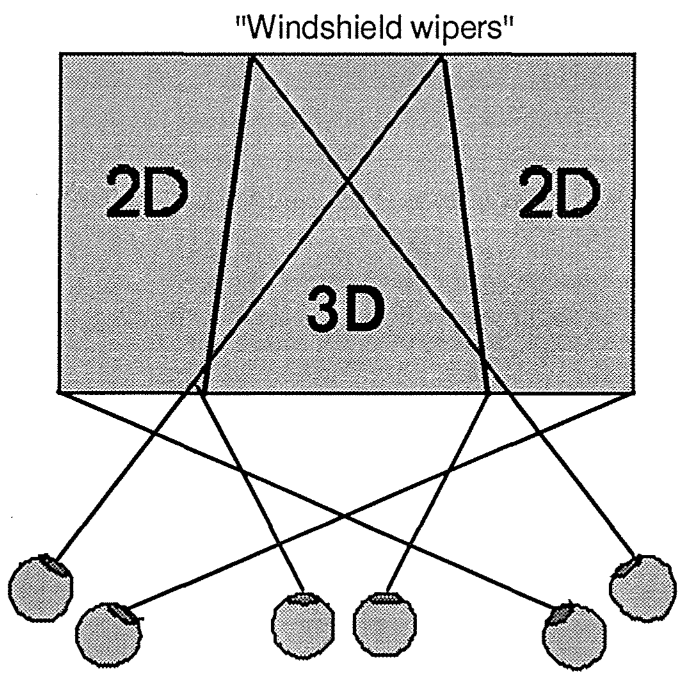


Figure 3.1 Workstation with display system

Although the Metron system does not use any special head mounted viewing devices, the operator is still allowed a fairly wide range of head movements to maintain the three dimensional image. The viewing image is broken down into three ranges. If the operator's head position is too far to the left or right, only a two dimensional image can be seen. On center viewing results in a three dimensional image. So the operator can be sure that the image is three dimensional, the image has a pair of vertical black lines which indicate the ranges for three dimensional viewing. These black lines appears as windshield wipers and if the operator is viewing to the left of the left line or the right of the right line the image is two dimensional (Figure 3.2). When the observed image is between the two black lines it is three dimensional. The advantage of allowing the two dimensional images to be observed is that the operator is allowed a broader range of head movements even though three dimensionality may be lost. To observe the three dimensional image, the observer needs to be positioned approximately 26 inches (66 cm) from the viewer screen. The Metron viewing system is mounted to the stationary workstation such that a wide range of operators can adjust the seating position to be within the ideal viewing distance from the display system. The actual image appears to hover about four inches in front of the display screen. The three dimensional integrity of the image is maintained as long as the operators head is approximately within +/- 4 inches (10.2 mm) vertically, +/- 5 inches (12.7 mm) horizontally and +/- 10 inches (25.4 mm) in and out. This allows the operators to easily monitor all workstation controls, make line-of-sight observations and view the three dimensional image with little effort. The viewer box is also equipped with a front panel controlled tilting mechanism which allows the display to be adjusted for operators of differing heights.



Off center viewing of display results in 2-D images. When properly located, the observer will see 3-D and will not see the windshield wiper lines indicating off center viewing.

Figure 3.2 Display ranges

In addition to visual feedback, the Matron system also incorporates an audio feedback system. This system uses a microphone which is located in the vehicle cab to transmit loader engine and operation sounds to the viewer system. A pair of amplified speakers with individual volume control surrounds the viewer screen, So the operator can eliminate background noise at the workstation, a headphone jack is also included. One drawback to this system is that it is only monaural. Stereo sound was not possible due to the limitations in the transmitter/receiver system used to broadcast the audio/visual information from the remote vehicle to the workstation.

Since the audio/visual feedback system was incorporated into TAMER after the remote control system was established, the two system are relatively independent. A pair of COHU 1300 series NTSC genlock CCDTV 12 VDC 1/2 inch format color cameras with auto iris are used to capture images.

3.2.2 System Description

The audio/video system consists of two subsystems: a camera system which is incorporated on the front-end loader and a viewing system which is mounted on the stationary operating unit (Figure 3.3)

3.2.2 1 The Camera System

A pair of Pentax Cosmic CS mount CACTI 6 mm lenses are used to generate the desired 45 degree HFOV. The cameras are mounted to a subframe on the camera support system and adjusted such that the focal separation is 2 1/2 inches (6.4 mm) and the convergence and focal point are set at 16 feet (4.9 m). These cameras are housed in an environmental housing using a small dc fan to induce positive pressure to prevent dust from entering. The signals from each camera are then resolved into a single signal using a special proprietary encoder from Metron. A microphone is mounted to the housing for sound pickup. The encoded signal from the cameras and the signal from the microphone are then transmitted using a PELCO model WVL1000 series wireless video transmission omni-directional transmitter operating on 2414.5 MHz. Power for the transmitter, cameras, fan, and microphone amplifier is provided by a DC to DC converter located in the loader control computer (LCC).

3.2.2.2 The Viewing System

The transmitted signal is then received by a Pelco patch antenna type receiver. To allow for recording, a Sony EV-C3 NTSC video cassette 8 mm recorder has been installed. The video signal is then resolved into two signals using a decoder located in the viewer box which sends the corresponding video signals to the respective monitor for generation of the three dimensional image. The audio signal is amplified by a pair of volume adjustable speakers mounted to each side of the display screen. Two Toshiba CX467XC NTSC 13 inch 60 watt color television monitors are used for image projection.

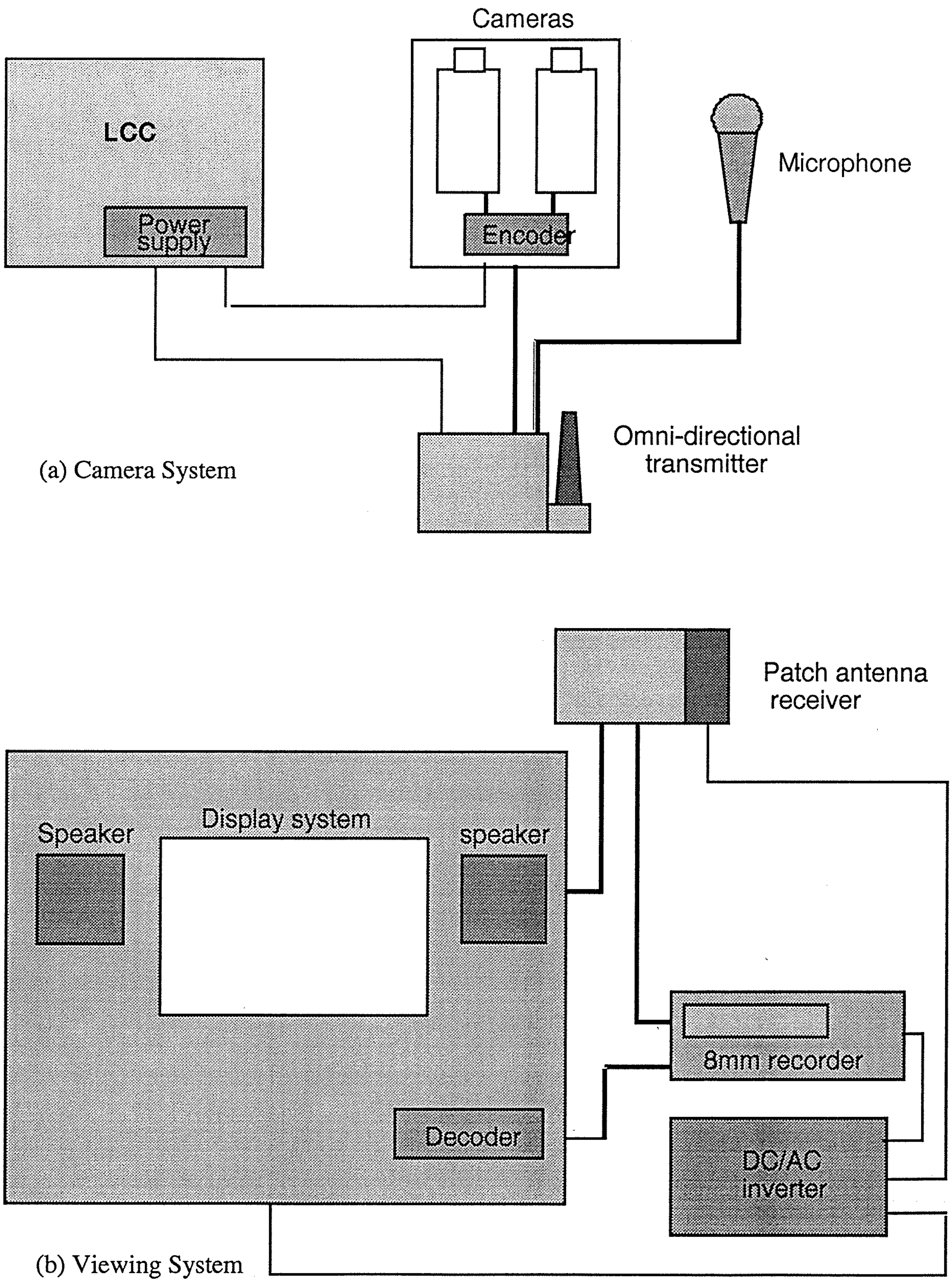


Figure 3.3 Audio/visual feedback system

Power for the receiver, recorder, speakers, decoder, and monitors is provided by a PROwatt 250 DC/AC inverter by STATPOWER Technologies. A standard 12 volt automotive battery and charging system is used to provide power to the inverter. The images from the two monitors are reflected off a specially shaped concave mirror fabricated by Metron Optics and then reflected off a flat mirror to the observer. A Plexiglas front plate prevents dust from entering the viewing box.

Pelco reports their wireless video transmission system to have a direct line-of-sight range of 1000 feet. This range is acceptable as it exceeds the present range of the remote communications system. Field tests have shown the video system to operate up to 2500 feet in unobstructed line-of-sight conditions, with audio capabilities beyond that. One concern with the video system was possible interference from engine systems, though this has not been a problem. The only drawback to Pelco transmission system is that it is not completely omni-directional. Although the transmitter is omni-directional, the receiver is only capable of receiving within a horizontal 180 degree arc of its position. Since the stationary workstation is capable of a full 360 degree rotation, operators have no problem maintaining the video link.

3.2.3 Design of the Camera Support System

When the operator is located in the vehicle, a wide range of natural head movements is used to stabilize images and increase the viewing area. In designing the mounting system for the cameras several parameters needed to be met. The mounting system needs to provide for damping from the harsh environment the loader is subjected to and the cameras needs to be stabilized with reference to the horizon. The cameras should be able to pan with the vehicle as it steered and the cameras also should be able to tilt so the operator could view the range of bucket movements. Finally, the camera mounting system has to be such that it still permitts in vehicle operations.

As mentioned earlier, heavy earth moving equipment is rarely fitted with damped suspension systems as the tires are usually very large and compliant. In the front-end loader, the tires are the only means of damping forces transmitted through the loader from the ground. Thus, the loader cabin is usually subjected to a large range of sometimes violent motions in nearly all directions. The human body usually does a good job of absorbing these vibrations and shocks, and allows for a relatively stable viewing environment at the expense of operator fatigue. When mounting the camera system to the loader, the human body is no longer available to stabilize the viewing environment and alternate methods must be used. Another problem encountered is during operations at abnormal roll angles. The on-board operator can compensate for any roll action by simply tilting the head to maintain a level view with respect to the environment. Thus, the camera mounting system must dampen vibrations and be horizon referenced. One method of accomplishing this task is the use of a gyro stabilized platform. However, this is complicated and costly. A simple pendulum setup was chosen instead.

The main support for the cameras is a three inch square 1/8 inch (3.2 mm) thick square tube mounted to the roof of the loader cabin using standard automotive transmission mounts to allow for high frequency damping (Figure 3.4). To the beam is mounted a bearing support which suspends the cameras with a simple swing arm. This arrangement allows the cameras to swing freely about the roll axis by gravity to maintain a horizon reference. The mount is such

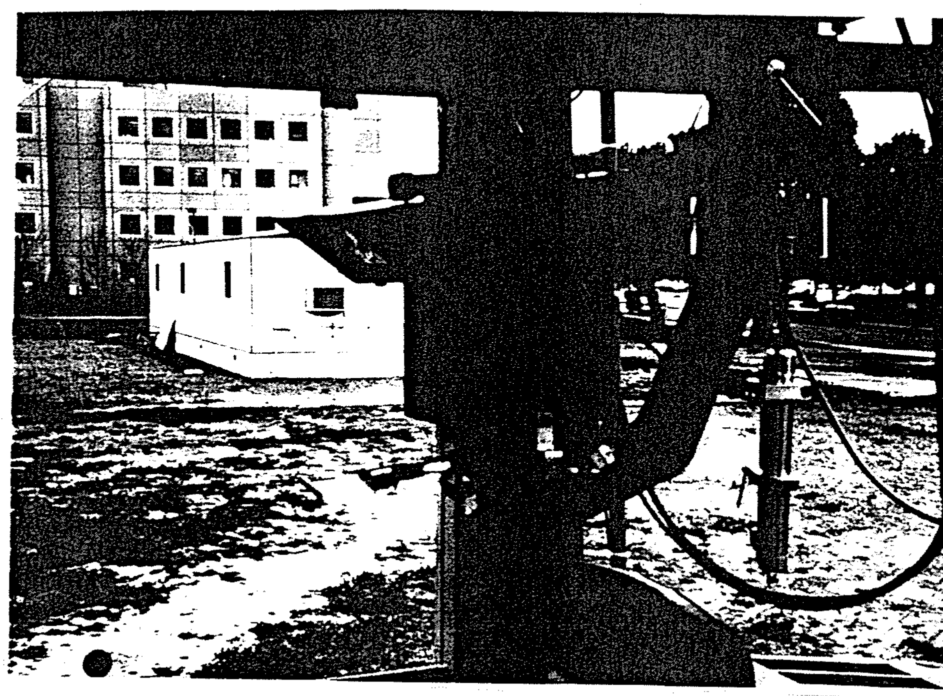


Figure 3.4 Camera support system

that as the cameras roll, the roll center is located about the camera lens center so that there is little or no lateral translation during roll of the image. To prevent vibrations and vehicle movements from swinging the swing arm uncontrollably, a linear damper has been fitted. The damper is a double acting Bibco air cylinder, one inch diameter and six inch throw, which has been refitted to serve as a hydraulic damper so as to have a linear response throughout its range of movements. The damper is adjustable so the optimal damping ratio can be determined through experimentation. This setup does a reasonable job of meeting the required parameters at a relatively low cost.

The unique nature of the loader articulating steering system requires that the cameras also be able to track with the steering position. In addition, since the loader bucket performs operations at a wide range of heights the camera system must also be able to tilt. Therefore, the camera mounting system includes pan and tilt drive systems to allow for a wide range of viewing frames. The panning mechanism allows for rotation +/- 90 degrees from the forward position. A 12 VDC Dayton 1L480 482:1 gearmotor mounted to the swing arm base drives the camera support through a 2:1 No.31 chain reduction to achieve a maximum rotational rate of 18 degrees/second, the rate at which the loader turns in the remote mode. The camera support rotates about the swing arm through light grade two roller bearings. To prevent the camera support from rotating freely due to the backlash inherent in the gearmotor a plastic friction pad clamps the drive sprocket so that only force from the gearmotor will turn the mechanism. To monitor the position of the rotating camera support a rotational potentiometer is fixed to the base. The LCC uses position values from the rotary potentiometers on the vehicle steering system and the camera support base to determine which direction the cameras must be turned. This position can be offset if the operator at the stationary workstation uses the camera control joystick to move the cameras. The tilting mechanism operates much as the panning mechanism. A second gearmotor fixed to the camera support drives the camera tilt platform through a 4:1 reduction to achieve a 9 degree/ second tilt rate. The tilt axis is located to approximate the tilt axis of a humans eyes relative to the head. A return spring is used to compensate for backlash in the gearmotor. Control of the tilt function is through the workstation joystick only. The cameras can be tilted approximately +10 and -30 degrees of level. To prevent the pan and tilt mechanism from exceeding the range limitations, a set of micro switches for each axis is used to cut current to the gearmotors when travel in a particular direction is out of limits. The command for pan and tilt from joystick are transmitted to the camera system through the main RF transmission link from the remote station.

To allow for normal in-vehicle operations, the camera mounting system needed to be unobtrusive. The main frame member mounted to the vehicle cabin also serves as a slide rail for the camera system. The camera swing arm support is mounted to a slotted square steel tube which slides over the main support rail. To fix the support in place once positioned a pair of bolts are tightened to clamp the slotted rail to the main rail. When the loader is not being used remotely, the cameras are slid back to clear the cab for operator use. Once in the remote mode, the cameras are slid forward and positioned such that the camera position closely approximates the location of the operators head when in the vehicle.

Chapter 4

Testing And Results

The goal of the TAMER project is to remove the operator from hazardous operating environments while still maintaining control of the loader from a safe control point. The testing procedure has been developed to evaluate how effectively the operator can control the loader in the remote environment. The purpose of the tests is to;

1) Demonstrate the loss in performance as distances increase for pure line-of-sight operations.
2) Evaluate the video system when used as a two dimensional and three dimensional feedback viewing device.
3) Determine if three dimensional video coupled with line-of-sight viewing offers a significant improvement in performance.
4) Identify which vehicle controls, systems and video support systems need improvement or modification.

4.1 TESTING

4.1.1 Course Setup

To evaluate the remote loader for control in a typical workplace environment where course navigation is necessary a simple figure eight course was set up. The purpose of this course was to represent an operating environment where the loader would be required to navigate in all directions, turn sharp corners, approach the remote operator in head-on attitudes, track over rough terrain, and avoid obstacles (Figure 4.1).

The course layout was identified using fifty orange construction pylons. The pylons were nearly identical throughout the course and were evenly spaced. No markings were placed on the pylons to indicate if they were either inside or outside pylons. By using identical pylons throughout the course the remote operator is forced to use depth perception as the primary means of distinguishing between inside and outside pylons so that the difficulties in line-of-sight remote navigation could best be demonstrated. The width between the inside and outside pylons, 18 feet (5.6 m), was determined by running the course with the loader normally and remotely to approximate a reasonable course width through trial and error. A narrow course would have been too difficult to navigate without continuously hitting cones with the loader bucket.

To prevent the operator from memorizing the course and using constant steering angles, the two outside turns were of different radii. One of the turns of the figure eight was of an increasing radius (or decreasing, depending on direction of travel) to force the operator to continually adjust the steering angle of the loader. To further prevent course memorization, the loader was run in opposite directions for each test.

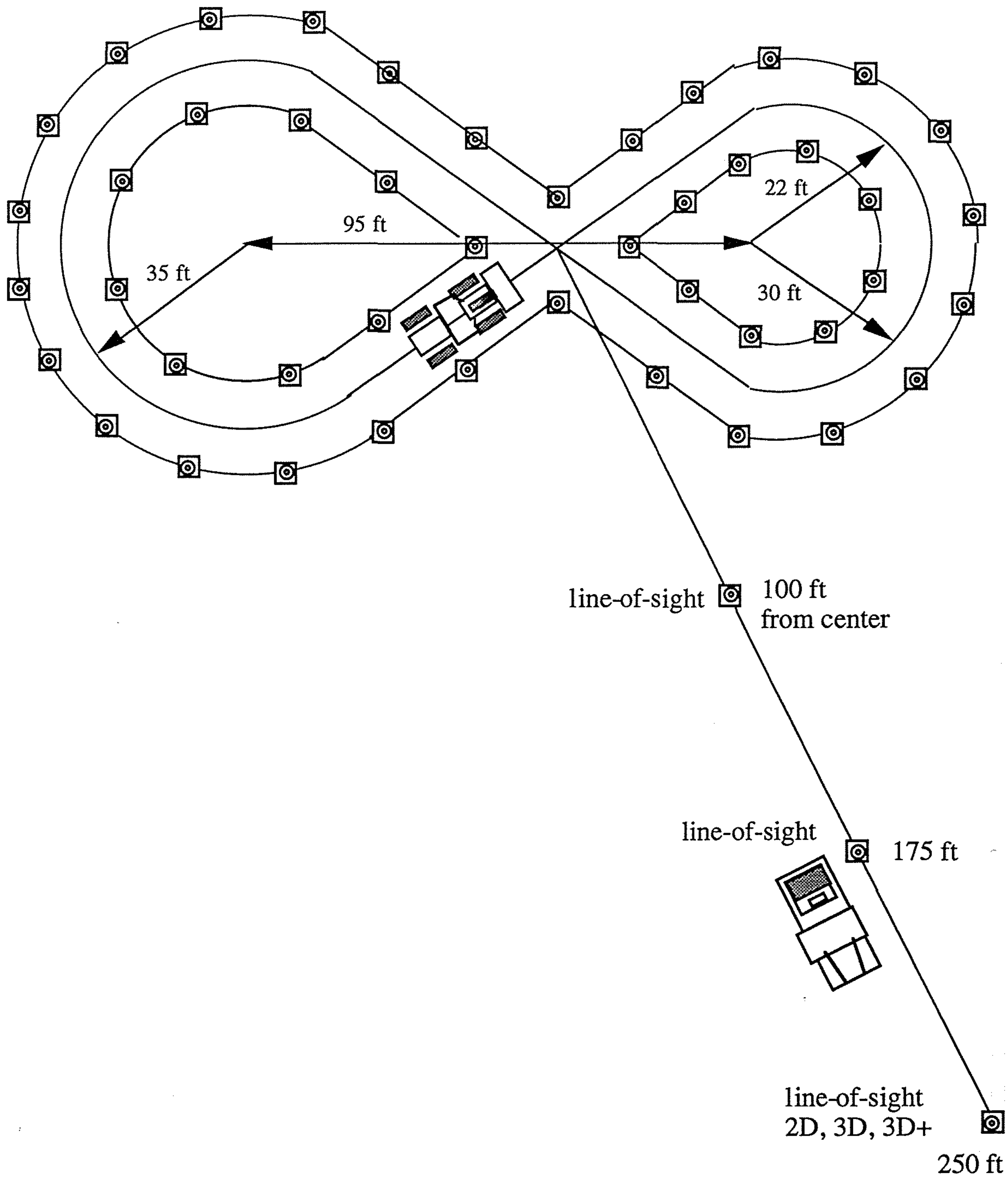


Figure 4.1 Course layout for remote loader navigation evaluation

The length of the course was determined by running the loader at full speed in first gear. The length was set such that any speed past the maximum capable of the loader in first gear would be unsafe. The maximum speed possible was slightly higher than an on-board operator would have been comfortable with for routine use. The nature of the course was such that continuous travel at maximum speed would exhaust the on-board operator quickly due to the unevenness of the track.

The unevenness of the track was due to the many ruts and bumps in the course from the location used, though the course did not include any elevation changes. The bumps and ruts were useful in evaluating the camera support system to determine if the picture stability was acceptable or distracting to operators.

The locations of the remote control positions was based on a straight line extending from the center point of the figure eight. The figure eight was well suited to this test as it forced the operator to control the loader in head on and normal approaches. The line of control was offset from perpendicular to the course to skew the operators perspective and create a more realistic and difficult operating environment. The test was conducted at three positions. Line-of-sight operations were tested at 100, 175, and 250 feet (30, 53, and 76 m). Two dimensional (2D), three dimensional (3D), and three dimensional plus line-of-sight (3D+) remote operation were conducted at 250 feet (76 m).

4.1.2 Procedures

Eight engineering students participated as subjects (operators) to test the remote loader. None of the subjects had any previous loader experience. Each operator performed seven tests to evaluate the remote loader system both qualitatively and quantitatively. The operators ran the loader for three continuous laps around the course for each test and were timed, and cones hit were tallied. The operators then responded to a simple questionnaire to evaluate the system.

Prior to beginning the tests, the operators were thoroughly briefed on the operation of all the workstation controls and allowed 15-30 minutes to become familiar operating the loader remotely. The operators performed all six tests consecutively before the next operator could begin testing. The operators performed the first test where the loader was run for three laps around the course using line-of-sight feedback only at a distance of 100 feet (30 m). The second test was also line-of-sight and was conducted at a distance of 175 feet (53 m), though the course direction was reversed to prevent memorization of the course. The third test was conducted at 250 feet (76 m) and the direction was again reversed. The operators were allowed to rotate the workstation if they desired to maintain a comfortable field of view.

The operators were not permitted to use the bucket controls for the duration of the navigation tests. The loader bucket was left fixed in a position that placed the base of the bucket well below the top of the pylons so that the bucket could hit the pylons and indicate a course penalty.

After completion of the third test, the operator removed the loader from the course and was briefed on the operation of the video feedback system. The operators were explained how to view the three dimensional image. The operators were required to identify the vertical black lines on the viewer to ensure they were viewing within the three dimensional range of the viewer. For two dimensional viewing the operators viewed the display off center. Off center viewing for the two dimensional image ensured that the image quality and size was similar to the three dimensional image so that the results were not altered by differences in image quality other than the addition of depth perception in the three dimensional mode. The operators were then allowed an additional 15 minutes to become familiar with remote operation and the steering slaved cameras operation using only the 2D and 3D video feedback modes. The workstation was located at a distance of 250 feet (76 m) and rotated to prevent the operator from viewing the loader directly.

One drawback to the testing was the learning curve which allowed operators to become more familiar with the system as the tests progressed and thereby improved their performances. Since the evaluation of the 2D and 3D systems were the most important, it was necessary to eliminate the introduction of a learning curve into the results. Therefore, half of the operators performed operations in the 2D mode first and then the 3D mode while the other half tested with 3D first then 2D. Between tests the direction of travel on the course was reversed. The final test was the use of 3D viewing and line-of-sight at a distance of 250 feet (76 m). For this test, the workstation was rotated so the operator could use both line-of-sight and the 3D viewer. At the conclusion of the tests, the operators responded to the questionnaire.

4.2 RESULTS

The data from the figure eight course corresponded well with expected results. Operators' performance using line-of-sight operations demonstrated the difficulties with direct navigation of the loader as distances increased. As the distance increased operators became less able to keep the loader safely on course as indicated by the increase in cones hit (Figure 4.2, 4.3). Even at the closet distance of 100 feet (30 m) operators averaged 3.92 cones hit each lap, this amount of course deviation would be unacceptable in most work environments. At the furthest distance of 250 feet (76 m) operators averaged 8.29 cones hit per lap. Of importance to the performance at 250 feet (76 m) is that the cones hit were usually in groups of three or more in succession as operators completely left the course unable to differentiate between inside and outside cones with the lack of depth perception at those distances. The increasing number of cones hit and the corresponding deviations in course navigation highlight the extreme difficulties in safely navigating a large vehicle in a restrictive environment as line-of-sight distances increase.

Of interest is the fact that course times actually decreased as the distances of line-of-sight operations increased (102.6 seconds at 100 feet vs. 101.5 seconds at 250 feet). This decrease in time is most likely attributable to the operators becoming more experienced with the remote loader. If the test group had been larger and operators varied between order of testing for line-of-sight operations, the times for the farther distances would likely increase and the average number of cones hit would be higher than indicated.

Figure 4.2 Overall results for course navigation

Operator	100 ft line-of-sight		175 ft line-of-sight		250 ft line-of-sight	
	time (s)	cones hit	time (s)	cones hit	time (s)	cones hit
1	104.3	5.67	114.0	10.00	97.3	11.00
2	96.0	8.00	103.3	7.67	93.3	12.33
3	87.7	5.33	130.0	10.33	115.0	7.00
4	108.7	1.67	95.7	5.67	94.0	4.67
5	123.3	5.33	104.3	5.33	128.3	11.00
6	81.7	0.67	89.7	4.00	95.0	2.67
7	137.0	2.33	102.3	8.67	99.0	11.67
8	82.0	2.33	81.7	1.67	90.0	6.00
Average	102.6	3.92	102.6	6.67	101.5	8.29
Composite	39.4		45.0		47.1	

Operator	2D		3D		3D + line-of-sight	
	time (s)	cones hit	time (s)	cones hit	time (s)	cones hit
1	103.3	1.33	91.7	0.67	81.0	1.33
2	87.7	0.33	88.7	0.00	74.0	0.33
3	115.0	0.00	106.0	0.33	87.0	0.00
4	103.3	0.00	107.7	0.00	100.0	0.00
5	111.7	0.33	91.7	0.00	77.3	0.00
6	89.0	0.00	96.0	0.00	81.7	0.00
7	85.3	0.33	74.0	0.67	71.7	0.00
8	78.7	0.33	73.7	0.33	72.7	0.00
Average	96.8	0.33	91.2	0.25	80.7	0.21
Composite	26.4		20.7		10.1	

The comparison between 2D operation and 3D operation was better controlled than that of line-of-sight comparisons. Since half of the operators ran the loader using 2D first then 3D and the other half used 3D then 2D, the effects of a learning curve were canceled. Many operators commented that they did not notice a significant difference between the two modes, however the averaged results indicated otherwise. The 3D mode was approximately 6% faster than the 2D mode (91.2 seconds vs. 96.8 seconds) (Figure 4.4). The 3D mode was also slightly more accurate than the 2D mode with only 0.25 cones hit per lap vs. 0.33 for the 2D mode.

The 3D and 2D modes significantly outperformed the line-of-sight modes at any range (Figures 4.3, 4.4). In line-of-sight operations the operators had a very difficult time determining the course boundaries as inside and outside cones could not be differentiated. This was not the case with video operation as the cones were easily identified as to being to the left or right of the loader. Another major problem with line-of-sight not experienced with video was steering direction control. Operators often turned in the wrong direction and had to frequently correct, especially in head on conditions resulting in poor performance.

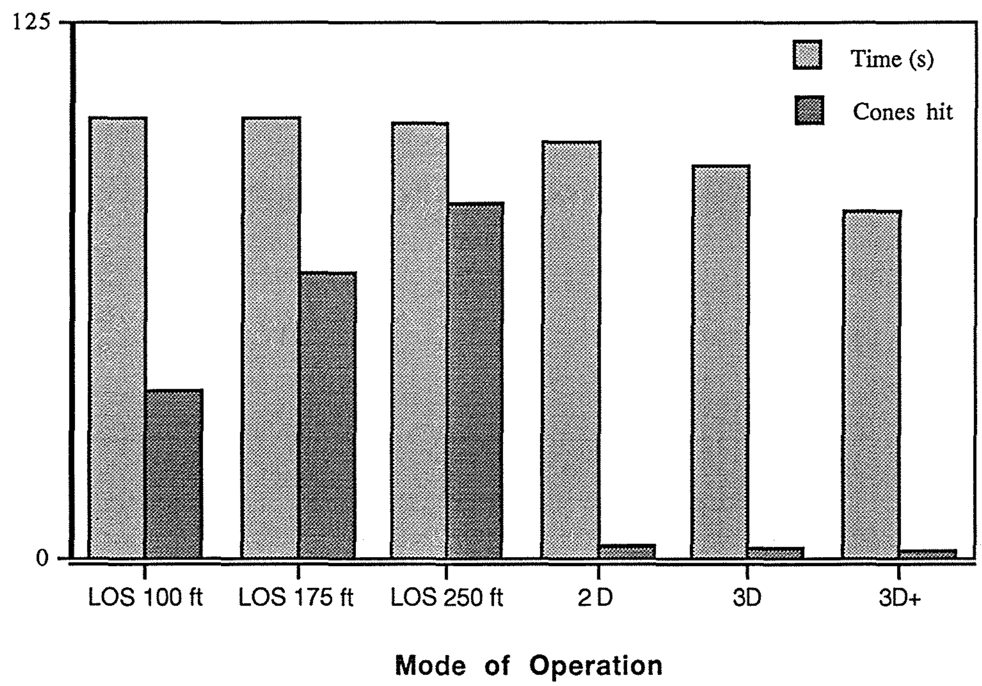


Figure 4.3 Averaged results for course navigation

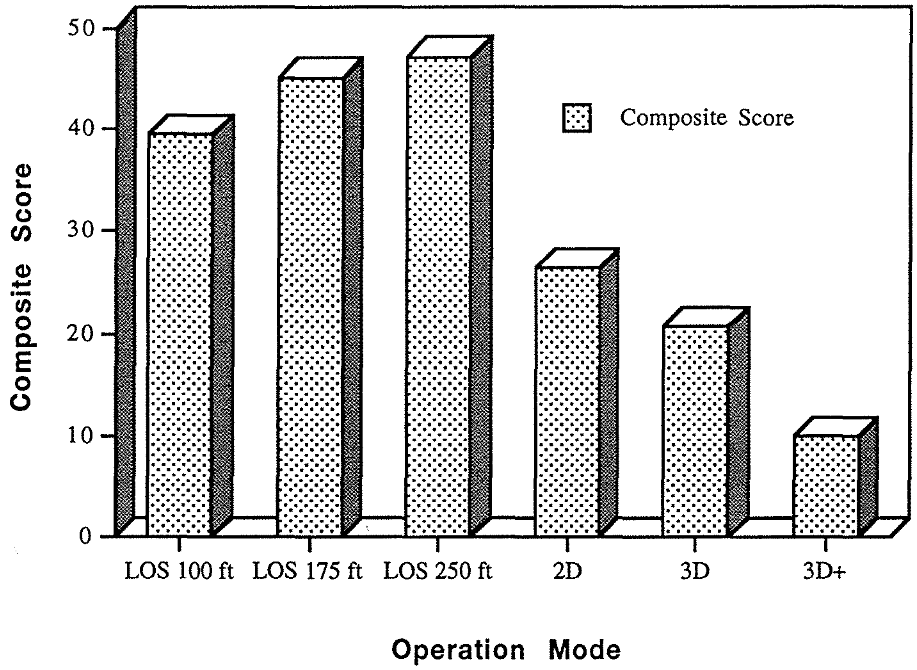


Figure 4.4 Composite score for course navigation
(Composite score = time - 71 seconds + cones hit * 2)

The best performance was consistently achieved using 3D with line-of-sight at 250 feet. This method allowed the operator to navigate using video and to reference the loader position at will with direct sight. Approximately half of the operators commented that they preferred this method as they were constantly reassured of the status of the loader through their peripheral vision. The other half of the operators did not like this method as when they looked up to see the loader they became confused especially when the loader was approaching head on and the video display created the 'feeling' that the loader was headed in the opposite direction. The extremely low course time of 80.7 seconds and 0.21 cones hit are somewhat misleading. The 3D+ test was always conducted after the completion of the 2D and 3D tests, allowing the operator to become more experienced and to improve performance simply by learning. Thus, the results for the 3D+ represent both the possible advantages to the system and the learning curve.

To better qualify the performance between the modes of operation a composite score was calculated for each mode of operation (Figure 4.4). The composite score was based on the performance of the loader on the course when run in the on-board mode. With an experienced operator on the loader the time achieved for the course was 71 seconds. The composite score was then calculated by subtracting 71 seconds from the time for the mode used and then the number of cones hit multiplied by two was added. Using this scoring method, one can see how poorly the line-of-sight modes performed even with the learning curve bias towards the greater distances. 3D outperformed 2D on a course where depth perception was not perceived to be that critical due to its level nature. This indicates that even in a simple environment the benefits of 3D may be perceived. The best score was the 3D+ mode, though this may have largely been the result that the operators become more experienced. Of special importance is the fact that several operators were able to match the on-board time of 71 seconds for a few laps using the 3D and 3D+ modes. If the operators were allowed more time to become experienced they may have easily been able to consistently match or even exceed the on-board performance. Also, the remote operator would be able to operate much longer than the on-board operator as the course proved to be very rough and could quickly exhaust any on-board operator from fatigue.

Response to the questionnaire was very favorable to the use of the 3D system. Most of the operators reported that they did notice a definite improvement in depth perception over the 2D mode. The operators felt that they could better place the location of the pylons and identify bumps and ruts in the course using the 3D mode as well. Overwhelmingly the operators responded as to being the most confident using the 3 D mode though they were also confident using the 2D and 3D+ modes as well. Only one operator complained of slight eye fatigue or sickness when using the 3D mode. This operator however spent too much time focusing on the image of the steering wheel from the loader which was not in focus for the cameras. Since the steering wheel was not in the range for which the cameras were set to converge, the image projected by the display system showed two images of the steering wheel which did not completely overlap causing strain on the eyes. Operators were told not to focus on extremely close objects after the first operator, and none complained of any problems. The duration of the test was also fairly short, so it is still possible that sustained use may cause sickness, though the use of the 3D+ mode may prevent this problem by allowing the operator to continually adjust the eyes and to be less sensitive to de coupling from expected motion.

One area of initial concern was the effect magnification of the display image relative to the environment would have upon the operator. The use of the 45 degree HFOV cameras lenses also decrease the magnification of the display size by 1/2. although the image was 1/2 the size it would naturally appear to the on-board operator, no one complained, indicating that image magnification does not cause discomfort or difficulty for the remote operators.

Areas of improvement suggested by most operators were the use of a wider angle field of view and improvements in the steering system. Operators found the 45 degree field of view to be limited causing the cameras to be continually manually panned to observe the course. The fixed rate and jerkiness of the steering system was adapted to, though most operators felt that performances could have been improved with a rate proportional system. Many operators also found the steering slaved camera system to be too unresponsive. The remote pan was used by the operators to compensate for the steering slaved system so that they could anticipate turns better. Operators also requested a return to center button which would cause the cameras to pan straight ahead on command so that the operators could be sure they were looking completely forward.

In addition to the operators used for the navigation test, a highly experienced Caltrans operator with remote control experience evaluated the loader system over a variety of operations used in the work environment. The Caltrans operator evaluated the loader through terrain navigation, digging, free dumping, and scraping. The operator evaluated the 2D, 3D and 3D+ systems over several hours of operation. The operator was most comfortable with the 3D+ mode of operation. The enhanced depth perception of 3D mode was very useful in loading operations for properly positioning the loader and estimating placements. In the test the loader was used to remove dirt from on location and replace it at another. The 3D system was very effective for perceiving the difference in location for the many mounds of dirt whereas with the 2D mode all the individual mounds of dirt appeared to fuse into one single mound. The 3D system was also very effective for identifying ruts and mounds which had the potential of causing the loader to rollover when loaded with a full bucket of dirt. These bumps and ruts could not be perceived using the 2D mode. The use of the sound system proved to be very effective when scooping dirt as the strain on the loader could be easily identified.

The use of line-of-sight in addition to 3D was also very valuable. The limited field of view of the camera system made it difficult for the operator to establish an overall view of the working environment. Line-of-sight allowed the operator to quickly reference the loader's position on the filed for overall planning. The operator also reported no sickness or eyestrain after continuous use which may have been partly attributable to using line-of sight to prevent many of the phenomena associated with fully immersed video and no corresponding motion.

Several problem areas were identified for use in an actual work environment. First, the limited field of view of the cameras prevented the operator from seeing objects immediately to the side of the vehicle which would normally be identified through peripheral vision. These objects could represent danger, such as drop-offs, which the operator must be continually aware. To prevent this problem a pair of secondary 2D cameras should be mounted to the sides of the vehicle to create peripheral vision by projecting the side views to secondary monitors at the workstation. Also, some sort of back up camera is also needed so the operator can easily see what is behind the loader when backing up.

Chapter 5

Conclusion And Recommendations

There are many hazardous environments in which operators must work on a daily basis in the cabins of heavy earth moving equipment. Hazardous waste removal and land-slide clearings are a few of the many workplaces in which there is a high level of danger present for vehicle operators. This can be eliminated by removing the operator from the vehicle. Once removed from the vehicle, special considerations must be given as how to properly control the vehicle. The TAMER project uses a remotely operated front end loader with audio and video feedback to successfully overcome this obstacle.

Initial operation of the loader used in the TAMER project was through line-of-sight feedback for the remote operator. This method is only effective for short distances where obstacle avoidance and detection is of importance. The operator sense of depth perception deteriorates rapidly at distances over 100 feet and even at closer distances operator performance is still only marginal. Line-of-sight operations are also further complicated by the articulating nature of the loader which makes remote steering of the vehicle difficult especially when the vehicle is approaching the operator in a head-on attitude. Further complicating the use of line-of-sight operations is the loss of reliable audio feedback from the loader.

The addition of a audio/visual feedback system was incorporated to overcome the disadvantages found in the line-of-site system. Most video systems are only two dimensional and lack the third dimension of depth. Front-end loader and other heavy earth moving equipment operations require a wide range of maneuvers for which depth perception is a critical tool for the operator. The addition of depth to the video display requires the incorporation of a three dimensional viewing system.

Three dimensional viewing systems have become more available recently, however many such systems have drawbacks that make them unsuitable for use in the heavy earth moving environment. Most three dimensional systems require the use of special glasses which both prevent line-of-sight operations and have very poor light transmission which precludes their use in an outdoor environment. Metron Optics time parallel, color, three dimensional video system used in TAMER provides 100% transmission and does not require the use of view obstructing special viewing glasses.

Field test evaluations demonstrated the advantages of using three dimensional systems over simple two dimensional systems. Color, three dimensional systems offer better object recognition such as identification of bumps and ruts which could potentially cause the rollover of a loaded heavy earth moving equipment. Operators also reported having more confidence in the three dimensional system. Even simple course navigation where depth perception is not as critical as in loading operations, three dimensional video demonstrated significant performance advantages in both speed and obstacle avoidance over two dimensional systems.

The addition of line-of-sight viewing with three dimensional viewing also appears to offer performance advantages in the heavy earth moving workplace. Line-of-sight allows the operator to reference the vehicle position to the overall workplace for easier overall navigation and course planning. Also, the use of line-of-sight may help prevent the operator from becoming completely immersed in the virtual three dimensional workplace where the de coupling from expected motion could cause potential sickness or nausea.

Design of the three dimensional viewing system and support system must incorporate several features. First, the camera system must be gravity referenced along the roll axis so the operator can quickly identify potentially dangerous roll attitude in the vehicle. A simple pendulum, hydraulically damped device placing the camera center line at the roll center appears to be an effective low cost means of achieving this goal. The ability of the operator to manually pan and tilt the cameras remotely also serves to effectively broaden the cameras viewing range and enhance the operators sense of the environment. The use of a steering slaved camera is effective though design should allow for manual override of the system coupled with a return to forward view feature so the operator may anticipate turns with the camera at will. Finally, the horizontal field of view (HFOV) is critical. The 45 degree HFOV used in TAMER should be considered a minimum as many operators complained that this was insufficient. A HFOV of 60 degrees or more would be better suited to use in heavy earth moving equipment. One drawback to a wider HFOV is the loss in image quality. High resolution cameras and monitors should be incorporated when using larger HFOVs.

Experienced operators complained about the loss of peripheral vision with the video system. Peripheral vision is important to identify obstacles to the sides of the vehicle which could represent a danger to the machine. Future video feedback systems for use in heavy earth moving equipment should include side mounted two dimensional cameras with corresponding secondary monitors mounted at the workstation to allow for a duplicated peripheral view for the remote operator. Operators also requested the incorporation of a back up camera. Since heavy earth moving equipment frequently are engaged in driving in reverse, some sort of back up camera view should also be built into the workstation. Possible viewing arrangement for presentation of peripheral and back-up views with forward looking 3D display is shown in Figure 5.1. Two side displays could be either small CRT monitors or large active matrix LCDs. The third display used for the back-up view could be eliminated by using the side displays to toggle to back-up views when the loader is placed in reverse.

Recent developments into head mounted three dimensional display (HMD) systems have made such devices more attractive for possible use in the TAMER project. The nature of HMD allows for the presentation of a much wider HFOV than the panel mounted display systems. Extremely wide HFOV may eliminate the need for secondary peripheral view cameras. Also, a HMD system could be incorporated into use with the portable remote package system allowing for a very mobile remote operator who would not require the support systems required of the fixed workstation. Future testing should include evaluation of a bifocal HMD system which would allow for line-of-sight and three dimensional video systems.

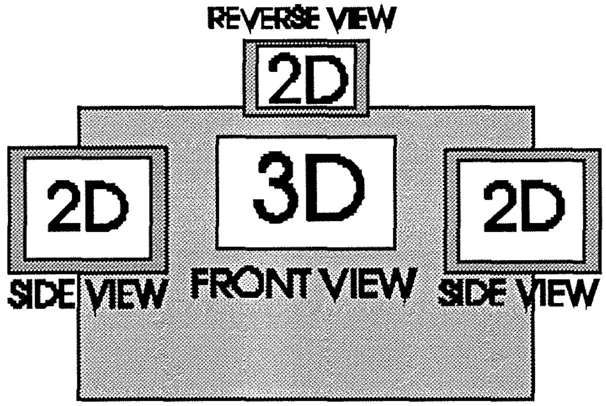


Figure 5.1 Display configuration

The use of remote vehicle control and feedback packages to remove the operator from hazardous working environments encountered by heavy earth moving equipment has the potential to save lives, increase productivity, and reduce equipment losses. It is believed that a properly designed remote vehicle package for use in any heavy earth moving equipment, as demonstrated by the loader used in TAMER project, using color, three dimensional video and audio feedback systems, can successfully remove the operator from the hazardous workplace. Such a system can allow an experienced remote operator to match the performances of the on-board operator and may even enhance the remote operators performance by reducing the operators level of fatigue.

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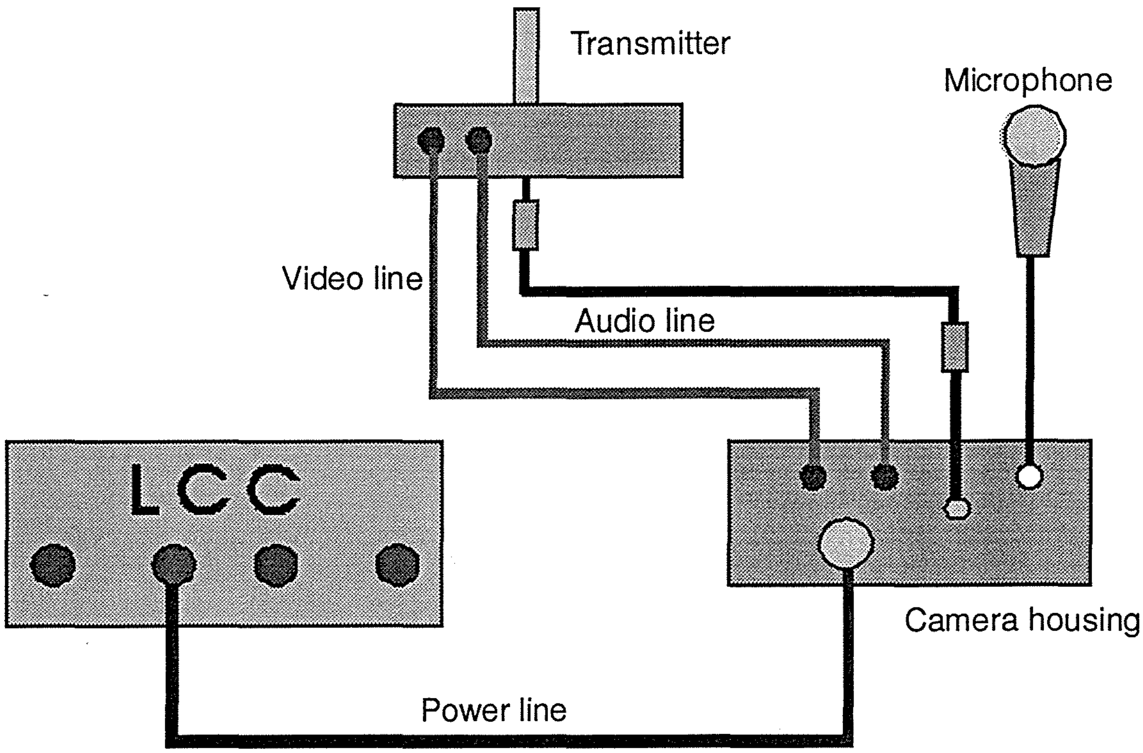
Appendix A

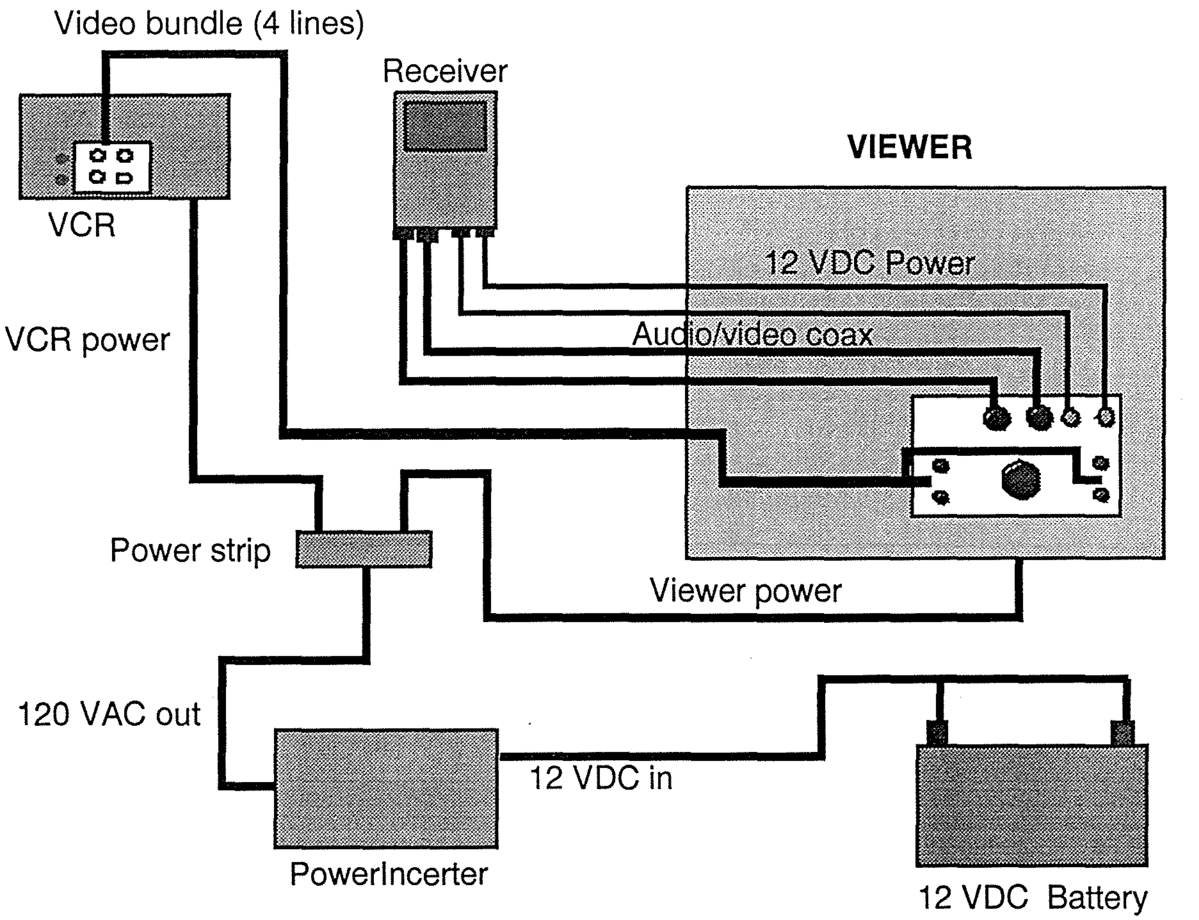
VIDEO/AUDIO FEEDBACK SYSTEM OPERATING INSTRUCTIONS

A. Camera hook-up



1) Ensure that all power supplies are off before connecting or disconnecting lines.
2) Connect the coaxial cable labeled 'video' to the video out on the transmitter and the video in on the rear of the camera housing. Repeat for the 'audio' coax using the audio in and audio out ports.
3) Connect power to the transmitter and camera housing using the quick disconnects provided. The disconnects are bundled with the coax cables to ensure correct hookup. Connect the other end of the power cable to the LCC port labeled video. *** Caution: If the quick disconnect line has been removed from the transmitter, ensure that the positive and negative leads are correctly installed at the transmitter base by referring to the +/- labels when reconnecting.
4) Connect the microphone to the mic out port at the rear of the camera housing. Make sure the microphone is switched to the 'on' position.
5) The loader ignition key must be in the 'on' position and the LCC must also be turned on for the cameras to transmit.

B. Viewer hook-up:



1) Ensure that all devices are turned off and the power inverter is not being supplied power (the red light on the inverter indicates it is being powered).

2) Connect the coax cables labeled video and audio at the rear of the viewer base to the connector labeled video in and audio in. Connect the other end of the coax cables to the base of the receiver on the connectors labeled video out and audio out.

3) Connect the two pair wire bundle (brown) to the rear of the viewer at the connectors labeled 12 VDC +/- out. Connect the other end of the bundle to the base of the transmitter to the positions labeled +/- in. Make sure that the leads are of matching polarity at the in/out connectors.

4) Connect the 4 wire pair bundle to the rear base of the viewer at the position labeled R, G, BLU, BLA. Match the corresponding wires of the bundle to the base of the VCR at the same positions.

5) Plug the 120 VAC power lines from the viewer and the VCR into the power strip. As a precaution it is usually best to leave the power strip unplugged from the power inverter.

6) Connect the two leads with the alligator clips to the terminal posts of the battery (Red to positive (+), Black to negative (-)). If the leads are reversed, the internal fuse in the inverter may blow. Make sure that contact is made by listening to the inverter power up with a high pitched whine, a red indicator light will also display. Plug the power strip into the inverter.

7) Turn on the VCR and the viewer. The viewer on/off switch is located below the display. The VCR must be on in order for the viewer to show a picture even when a recording is not being watched.

8) If the power inverter continues to make a high pitched whine during operation, the battery is low and must be charged- do not continue use. The picture in the viewer display may also become black & white indicating a low battery.

C. Troubleshooting

-Poorly fastened connections
-Improperly connected connections
-Power not on
-Battery dead
-Transmitter/receiver blocked (must maintain line-of-sight)

1. Checking the Cameras:
If you believe a problem may exist at the cameras:

1) Manual Iris on camera lens may have vibrated to a closed position. This will cause the image at the viewer to appear very dark for one of the monitors. To adjust the iris, the camera housing must be removed from the camera pod and the manual iris on the lens adjusted (it is best to match the lenses from each cameras to the same positions if you are in doubt)

2) Cameras may not be getting power. To verify that there is power at the cameras, place hand over fan inlet at rear of camera housing. If airflow is detected, power is being supplied. If no airflow is being detected, power may be supplied using a 12 VDC battery instead of from the LCC. To provide power from a battery use a fused lead pair with hookups for the power inlet at the camera housing base. If there is still no power at the cameras, contact Metron Optics.

2. Checking the Transmitter and Receiver:

If you believe a problem may exist with the transmitter or receiver, the RF system may be bypassed. To remove the RF transmitter/receiver from the system, simply hook the audio and visual coax cables directly from the base of the camera housing to the base of the viewer housing. If the problem persists, the problem is not with the transmitter or receiver. If it is solved the transmitter and receiver may need to be repaired. Contact Pelco.

3. Checking the Viewer:

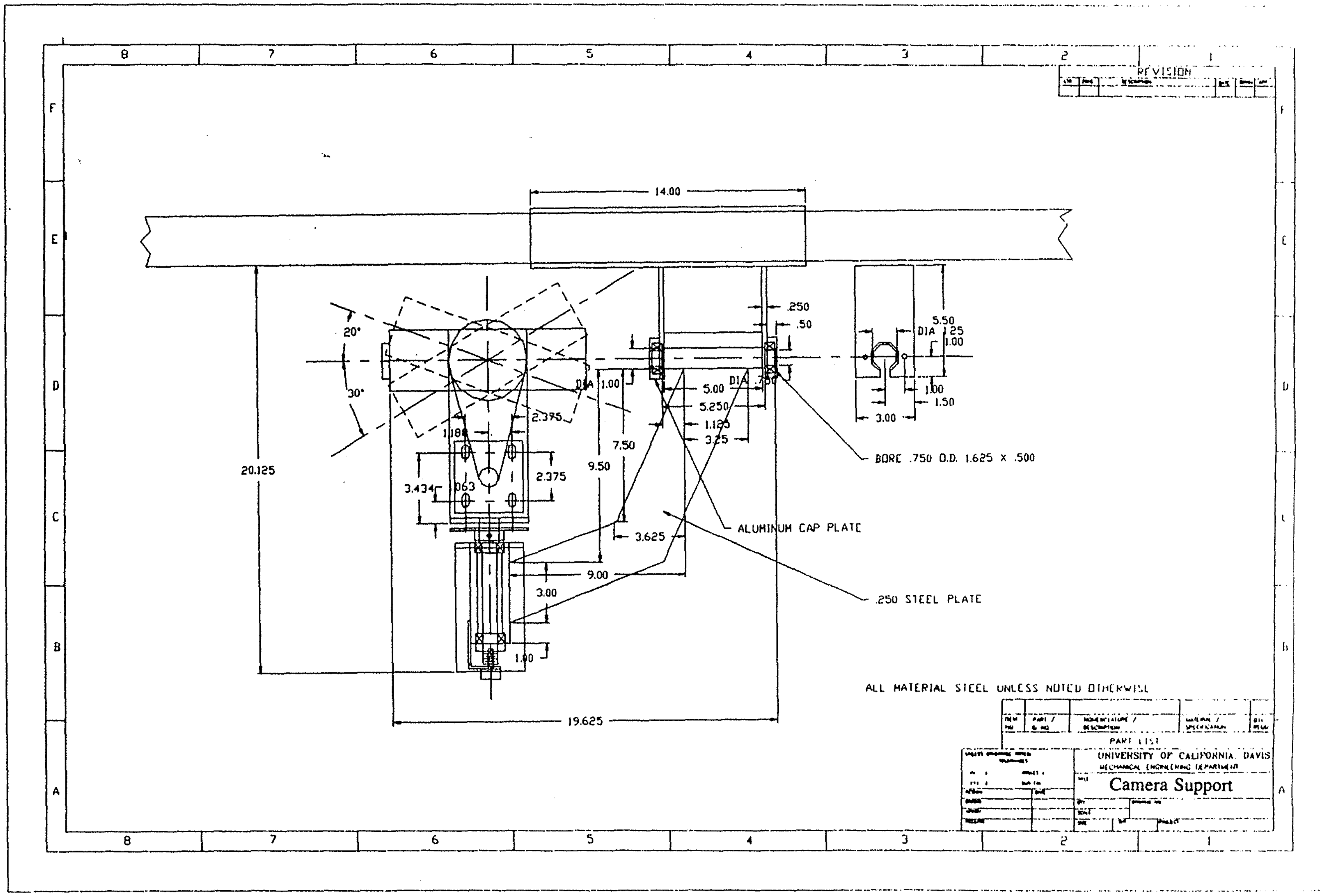
1) A common problem with the viewer is that the monitors may become unmatched. They can be adjusted by using the color and contrast controls for each monitor as described in the instructions provided by Metron Optics.

2) If the display becomes black & white the power supplied by the power inverter may be too low. If this is the case the power inverter may be bypassed by plugging the power strip directly into a 120 VAC outlet.

3) If more serious problems persist contact Metron Optics

Many of the problems that may occur may be troubleshooted using the instructions provided by Metron Optics. The instructions also include all manufactures data for the various remote 3D system components and how they may be contacted in the event of failure.

APPENDIX B



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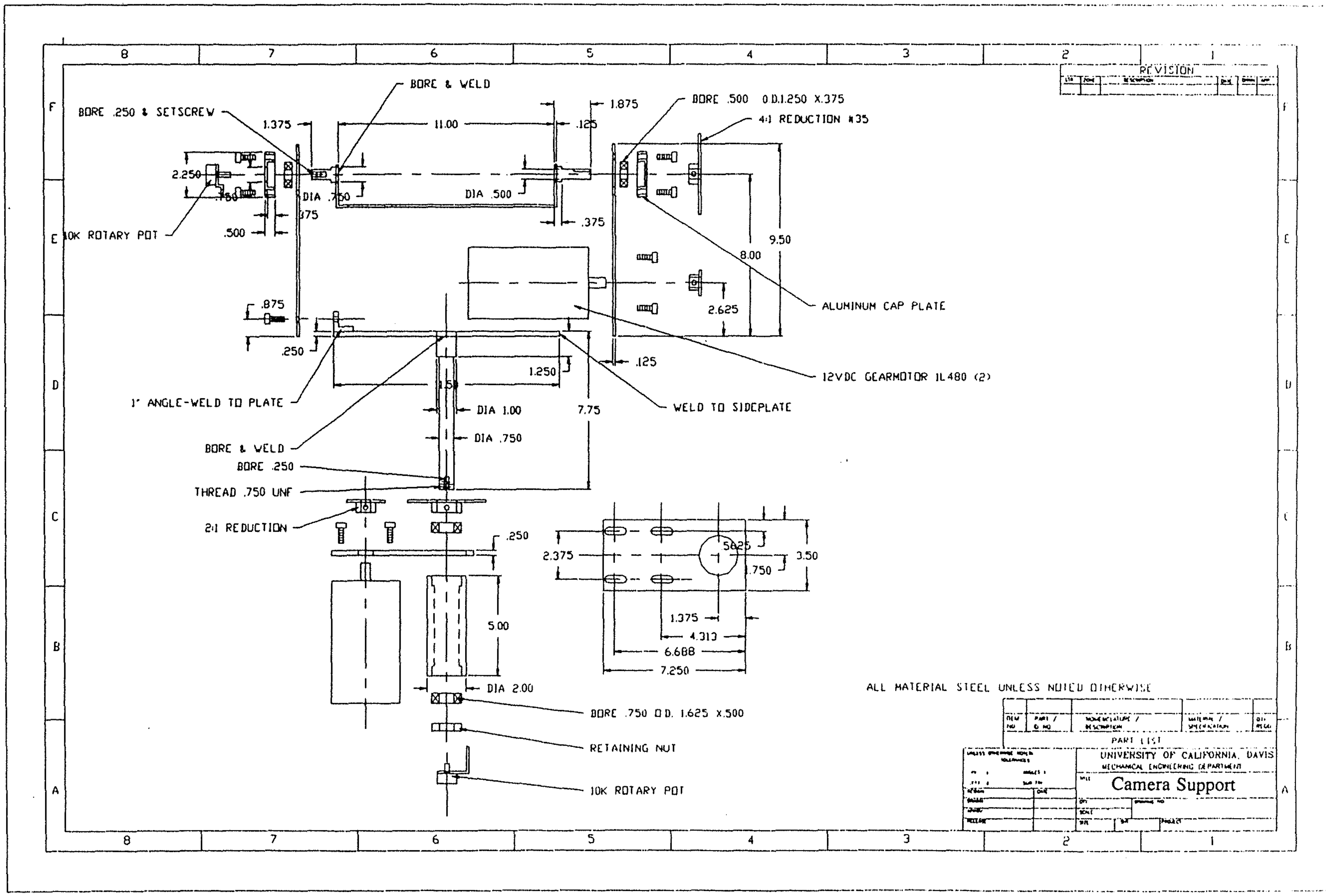
PART LIST
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
Camera Support


BORE & WELD
BORE .250 & SETSCREW
1.375
11.00
1.875
.125
BORE .500 O.D.1.250 X.375
4:1 REDUCTION #35
2.250
DIA .750
DIA .500
.375
10K ROTARY POT
.500
9.50
8.00
ALUMINUM CAP PLATE
.875
2.625
.250
.125
12VDC GEARMOTOR IL480 (2)
1.250
1" ANGLE-WELD TO PLATE
DIA 1.00
7.75
WELD TO SIDEPLATE
DIA .750
BORE & WELD
BORE .250
THREAD .750 UNF
2:1 REDUCTION
.250
2.375
.5625
3.50
.750
5.00
1.375
4.313
6.688
7.250
DIA 2.00
BORE .750 O.D. 1.625 X.500
RETAINING NUT
10K ROTARY POT
ALL MATERIAL STEEL UNLESS NOTED OTHERWISE
REVISION
PART LIST
UNIVERSITY OF CALIFORNIA, DAVIS
MECHANICAL ENGINEERING DEPARTMENT
Camera Support