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To guide development of a mobility sensor for an unmanned ground vehicle (UGV), a field testing program was established in which alternate mobility viewing system options were objectively compared with regard to their impact on driving under controlled field testing conditions. This report describes the procedures and specific tasks used in making comparisions across the 4 viewing system options that were compared: (1) direct view; (2) direct view 40° × 30°, (3) monoscopic helmet-mounted display (HMD), and (4) stereoscopic HMD. Testing was conducted with two groups of drivers: (1) an "experienced" group who were well practiced on courses run and tested with each of the four alternate viewing system options, and (2) an "inexperienced" group who were unfamiliar with courses and tested with a single mobility sensor system option on a one-time basis. Specific results in terms of relative driving efficiencies on six driving courses are reported and discussed with respect to their general implications for design of the man-machine interface for safe and efficient driving of UGVs in the teleoperated mode.

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OBJECTIVE ASSESSMENTS OF MOBILITY WITH AN EARLY UNMANNED GROUND VEHICLE (UGV) PROTOTYPE VIEWING SYSTEM

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1.0 ABSTRACT

Over the past decade, the Naval Ocean Systems Center's Hawaii Laboratory has engaged in a program to develop unmanned ground vehicles (UGVs) that have been delivered to the United States Marine Corps for field assessments of the applicability and effectiveness of such vehicles for reconnaissance and combat in tactical environments. An essential component of these unmanned ground vehicles is a visual sensor suite and helmet-mounted display that allows an operator to view the remote scene in a familiar, natural fashion well enough to drive the UGV safely and reliably across unfamiliar off-road terrain. To guide the development of this mobility sensor system, a field testing program was established in which alternate mobility viewing system options were objectively compared with regard to their impact on driving under controlled testing conditions.

This report describes the procedures and specific tasks used in making comparisons across the various viewing system options tested. The experiment reported here was run with two groups of drivers; 1) well-practiced civilian personnel who were tested with each of four alternate viewing system options, and 2) unpracticed, enlisted Marine personnel who volunteered to be tested with a single mobility sensor system option on a one-time basis. Specific results in terms of relative driving efficiencies on six driving are reported and discussed with respect to their general implications for design of the man-machine interface for driving remotely operated ground vehicles.

2.0 BACKGROUND

The Ground-Air Telerobotics (GATERS) program was initiated in October 1985 to develop teleoperated vehicle systems for military applications. Three TeleOperated Vehicle (TOV) systems were delivered to the U.S. Marine Corps for field assessments of their operational value in tactical combat environments. Observations derived from initial field assessments of TeleOperated Vehicle (TOV) performance and their implications for future UGV developments are the topic of another paper in this volume of proceedings [1]. A TOV system consists of a remotely-operated, High Mobility Multi-purpose Wheeled Vehicle (HMMWV), a datalink, and a control interface for the human operator. Several alternative mission modules have been developed for the TOV to support a variety of observation and surveillance missions as well as forward target designation and light weapons engagement. A more detailed description of the TOV system including its control system architecture, fiber optic datalink, mobile control station, and various mission modules is available in a recent report [2]. In this paper, I describe results from a series of controlled vehicle mobility studies conducted in late1986 - early 1987 at an outdoor test course with the first operational prototype of the TOV.

2.1 Viewing Options.

In the experimentation described here, the effects of four different viewing options on driving performance were measured and compared. The four viewing options investigated were: 1) unobstructed direct view, 2) direct view with a 40° by 30° field of view, 3) monoscopic helmet-mounted display , and 4) stereoscopic helmet-mounted display Under the first two of these options, drivers viewed test courses directly; that is, they were physically present on the test courses in the vehicle and had a direct line of sight to the vehicle and courses while driving. With the remaining two viewing options, the operators' only view of the vehicle and the test courses was provided indirectly by means of a video system.

More specifically, under the "Direct View" (DV) viewing option, the vehicle operator was physically present in the driver's seat of the HMMWV with a direct, non-restricted, "natural" view of the driving course. This viewing option established a "100% telepresence" performance baseline against which the other three viewing options could be compared. Image resolution, contrast, and color sensitivity were limited only by the visual capabilities of individual drivers. Additionally, the DV option provided "perfect" head motion coupling (i.e., no position errors or motion lags), eye-head coordination, and a "natural" 1:1 spatial correspondence between perceived space and physical space.

Under the "40° by 30° Direct View" (DV 40 x 30) viewing option, the driver's view of the test site was identical in all ways to that of the DV option, except for the fact that his peripheral field of view was restricted. The central 40° by 30° of his normal binocular field was visible. Areas outside this region were occluded and not visible. Thus, the DV 40 x 30 viewing option provided all of the advantages of the DV option, but with a field of view restricted to that available under the two video viewing options described next.

Under the two video view options, the driver was also physically present in the driver's seat of the vehicle while driving it, but his only view of the test course was provided indirectly, by means of a video system. A stereoscopic pair of cameras, attached to the top of his helmet, fed a pair of small helmet-mounted CRTs, each of which was visible to only one of the driver's eyes. Opaque tape was used to prevent direct view of the driver's surroundings. The helmet-mounted display (HMD) used in this experimentation was a Honeywell Integrated Head Aimed Display Sighting System (IHADSS) modified to provide two separate video channels for stereo viewing. The HMD system itself weighed slightly less that 2.25 kg and afforded its wearer a 40° horizontal by 30° vertical, fully overlapped, stereoscopic, monochromatic field of view. A stereoscopic (stereo) pair of cameras was mounted atop the HMD with optical axes separated by 65 mm and symmetrically converged on a point approximately 8 meters ahead of the TOV front bumper. This camera pair, it's mounting plate, and attached cables added approximately 1 Kg to the overall weight burden on the operator's head.

Though resolution and contrast were greatly reduced, and color contrast was absent from the video images, it should be noted that both these video view options did provide the driver with a wealth of sensory information not readily available to an operator controlling a UGV from a remote station. Camera slewing was nearly perfectly matched to the operator's head and upper body motions with only very slight lags and distortions in the displayed imagery induced by the video scanning rate. And, except for the mismatch between visual and vestibular stimulation caused by the lack of 1:1 spatial correspondence in the display [system magnification was measured to be ~.77] ; vestibular, kinesthetic, and vibrational information was generated by the physical movement of the vehicle and driver through the courses. This non-visual sensory information provided the driver with immediate feedback regarding body orientation relative to the vehicle and vehicle dynamics with respect to the various courses run.

Under the monoscopic viewing option ("Mono - HMD"), the video signal output by the right camera was split and fed to both IHADSS displays. This provided the operator with a two-dimensional, "flat" view of the scene, though many visual cues to depth and distance were discernable within the "flat" images provided. [3]

Under the "Stereo - HMD" viewing option, images from the left and right cameras were fed to their corresponding IHADSS display units. This viewing option provided the driver with a more accurate three-dimensional view of the test course and vehicle during testing.

Under all four viewing options, drivers were instructed to maintain their upper bodies in a fixed, upright posture, making scanning motions only with movements of their heads. This was done to make scanning of the scene roughly equivalent to the scanning that would occur under teleoperation with a mechanical pan and tilt head. Since there were no external physical constraints placed on drivers other than a lap belt, slight deviations from the instructed posture were observed. However, large deviations from the instructed posture such as "leaning out" the side of the vehicle to better view obstacles in the path of the vehicle did not occur during data collection.

A true Remote View driving condition was not tested in the initial phase of the TOV mobility testing program reported here. However, more recent studies that are beyond the scope of this report have been conducted and are currently being prepared for public release as a NOSC Technical Publication [4].

2.2 Experimental Drivers

Two groups of drivers participated in the experiments. An "experienced" group, consisted of four civilian personnel (mean age = 43 years) who were licensed HMMWV operators and were well-practiced at driving all of the test courses used in the experiment. Under both Direct View and Direct Drive Video View conditions, these drivers were run through each of the courses a minimum of ten times prior to experimental data collection. A graphical analysis of measures taken during these course familiarization runs suggested that all "experienced" drivers had reached stable levels of performance on all measures taken prior to completion of the familiarization runs. Each of the "experienced" drivers was run under all viewing conditions tested (i.e., DV, DV 40° by 30°, Stereo HMD, Mono HMD).

A second, "inexperienced", group of drivers consisted of 4 detachments of 4 Marines each (mean age = 23 years). Each of these drivers was a licensed HMMWV operator and volunteered to serve as an experimental driver during a single test session. All drivers from both the "experienced" and "inexperienced" groups had normal or corrected-to-normal visual acuity as determined by a standard Armed Forces Vision Tester. Prior to experimental data collection, each of the "inexperienced" operators was driven around the entire set of courses by the data collector and instructed in the specific procedures for each of the 6 courses described in detail below. Immediately prior to testing, "inexperienced" drivers were allowed one practice run through each course under DV conditions. These instructional runs were not necessary with the "experienced" drivers due to their high degree of prior familiarity with the courses. "Inexperienced" drivers were used in order to gain an appreciation for the effects of learning and experience on driving performance under the various viewing conditions tested.

2.3 Driving Courses

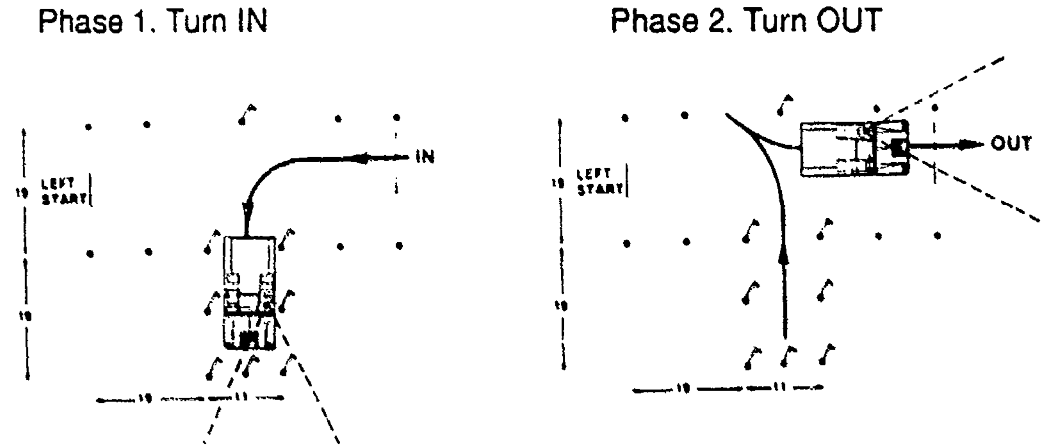
Six driving courses were used in an effort to characterize low-speed mobility on a more or less ideal, paved road surface. The six courses used were originally selected on the basis of a factor analysis of 58 measures of low-speed maneuverability [4] conducted at the University of Michigan's Highway Safety Research Institute (HSRI). This battery of tests was developed to provide a cost-effective, reliable, reasonably sensitive and comprehensive metric against which vehicle control options could be systematically assessed and improved. The testing courses, described in detail below, were surveyed and marked off on a level, asphalt covered test area within 1 kilometer of NOSC-Hawaii's Teleoperator Development Center.

Though the general layout of courses used in this paper was described in the HSRI report, some slight modifications to course configurations and procedures were required for testing with TOV. Bright orange 76.2 cm [30 inch] tall traffic pylons were used to mark off all course boundaries. In certain of these traffic pylons, 1.82 meter [6 foot] long, 2.54 cm [1 inch] diameter white rods were inserted to make them visible over the high hood and rear flatbed of the TOV. Order of administration for the 6 courses was identical for all drivers on all days of testing and followed the order in which they are described below. For all courses, verbal instructions were given which emphasized the importance of accurate, error-free driving and de-emphasized the importance of speed.

2.3.1 Course 1. Right Angle Turn- IN.

The first course run during each test session, the Right Angle Turn- IN, is diagrammed in the left panel of Figure 1. The course is configured as a 3.35 meter (11 feet) wide right angle parking space connected to a perpendicular 5.8 meter (14 feet) wide access lane. The driver's task was to start at one end of the access lane and make a controlled right-angle turn pulling as far into the parking space as possible without touching any of the cones defining the course or touching/toppling the stop cone centered at the end of the parking space with the front bumper of the vehicle. Runs were scored for elapsed time, number of cones touched or toppled during the maneuver, and accuracy of position relative to the parking space endpoint. The Right Angle Turn-IN was executed a total of 6 times per session, 3 times each from right and left START positions.

FIGURE 1. The Right Angle Turn IN/OUT Course.
Note: Distances are expressed in feet.



2.3.2 Course 2. Right Angle Turn- OUT.

As the right panel in Figure1 illustrates, starting from the position in which the vehicle rested following the previous Right Angle Turn-IN run, the vehicle was reversed out of the parking space and across the access lane. It was then put into forward gear and driven out of the access lane in the same direction from which it had been driven in. Runs were scored for elapsed time and number of cones touched or toppled during the maneuver. As with the Right Angle Turn-IN procedure, 6 runs were measured per session; 3 from each START position.

2.3.3 Course 3. Figure-8.

The next course required an operator to negotiate a figure-8 pattern through a sparse set of cone gates (see Figure 2). Spacing between cones comprising the gates was widened from the original HSRI specification in order to accommodate the HMMWV turning radius. A single experimental run of the course consisted of three consecutive circuits through the figure-8 pattern. Runs were scored for elapsed time and number of cones touched or toppled. Two runs were measured per session.

FIGURE 2. The Figure-8 Course.

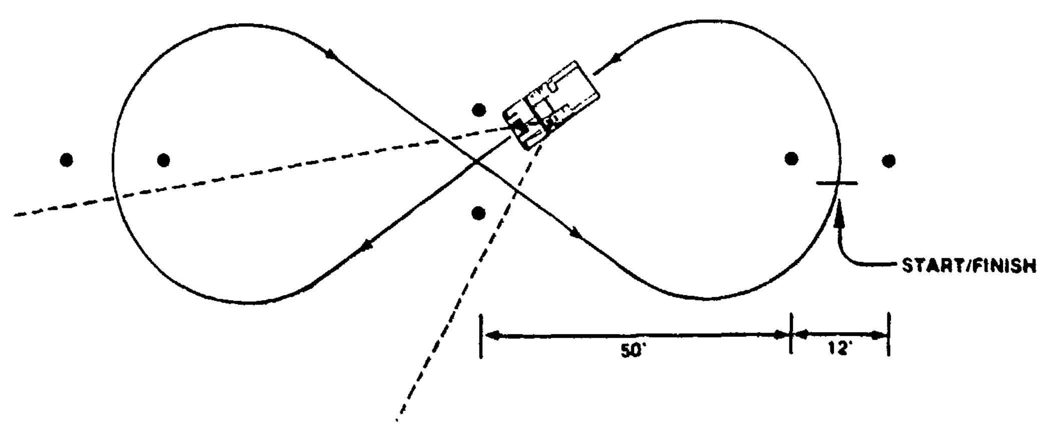
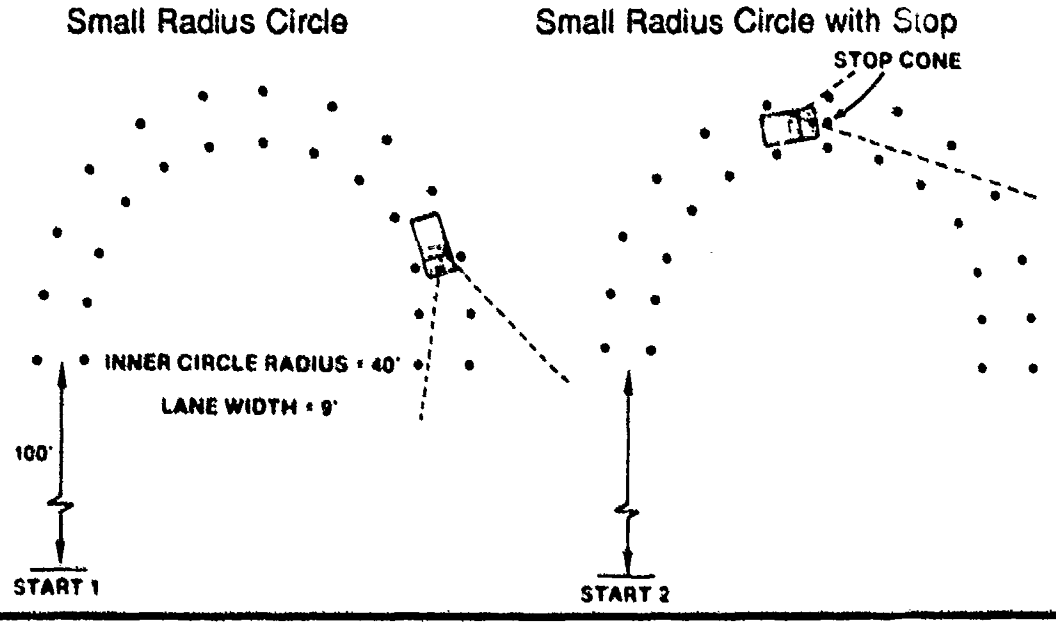


FIGURE 3. The Small Radius Circle Courses.



2.3.4 Course 4. Small Radius Circle.

The Small Radius Circle course is depicted in the left panel of Figure 3. The START position for this course was 30.48 meters [100 feet] from the first cone gate. During a testing session operators drove the course twice from each of the START positions depicted in the figure. Runs were scored for elapsed time and number of cones defining the curved alleyway touched or toppled.

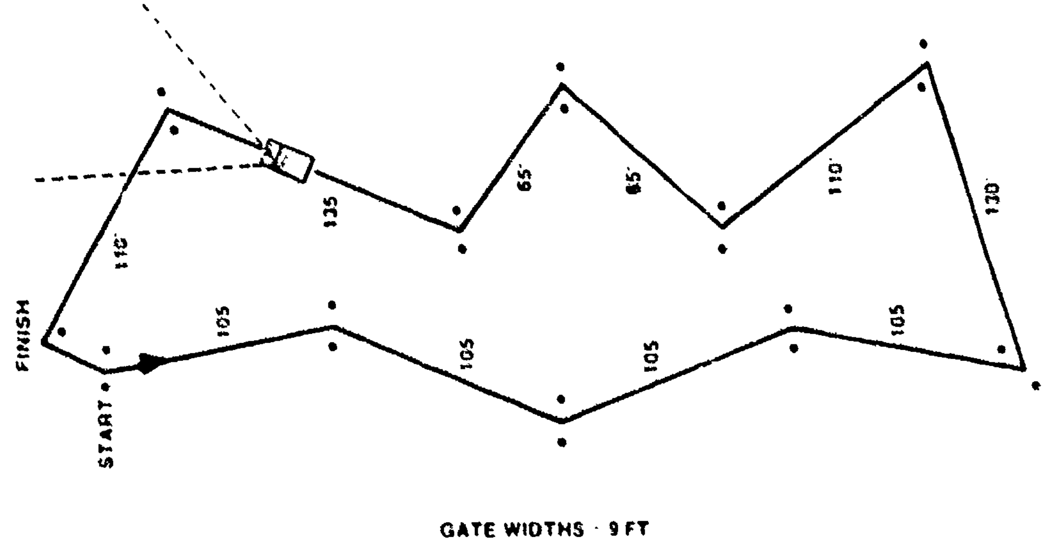
2.3.5 Course 5. Small Radius Circle with Stop.

The Small Radius Circle with Stop course is depicted in the right panel of Figure 3. The layout of this course identical to that of the Small Radius Circle with the addition of a stop cone at the apex of the arc. Drivers were instructed to position the front of the vehicle as close to the stop cone as possible without touching it. During a test session the course was run twice from each of the two START positions depicted in Figure 3. Runs were scored for elapsed time, number of cones defining the curved alleyway touched or toppled, and accuracy of position relative to the stop cone endpoint.

2.3.6 Course 6. Gymkhana.

The gymkhana course was a large, oval-shaped slalom course depicted in Figure 4. Cone separation for each of the 10 cone gates was 2.75 meters [9 feet]. Three separate runs through the course were undertaken in each session. Runs were scored for elapsed time and number of cones touched or toppled.

FIGURE 4. The Gymkhana Course.



3.0 RESULTS

3.1 Statistical Procedures Used

Performance metrics from each of the driving courses were compiled and subjected to separate analyses of variance (ANOVAs) with comparisons across the four viewing options (DV, DV 40 x 30, Stereo-HMD, and Mono-HMD) being the effect of paramount interest in each analysis. A Type-I error level of .05 for statistical significance was set prior to analysis. Repeated-measures ANOVAs were run on the results from the "experienced" drivers and between-groups ANOVAs were run on the measures from "inexperienced" drivers. Findings are presented below from all courses run across four design topic areas.

3.2 Direct Viewing Versus HMD Viewing

Not surprisingly, all statistically significant differences that were found favored the combined Direct View (i.e., DV & DV 40 x 30) conditions over the combined Video View (i.e., Mono - HMD & Stereo - HMD) conditions. The overall pattern of results that emerged from mean comparisons subsequent to the ANOVAs is presented in Table 1.

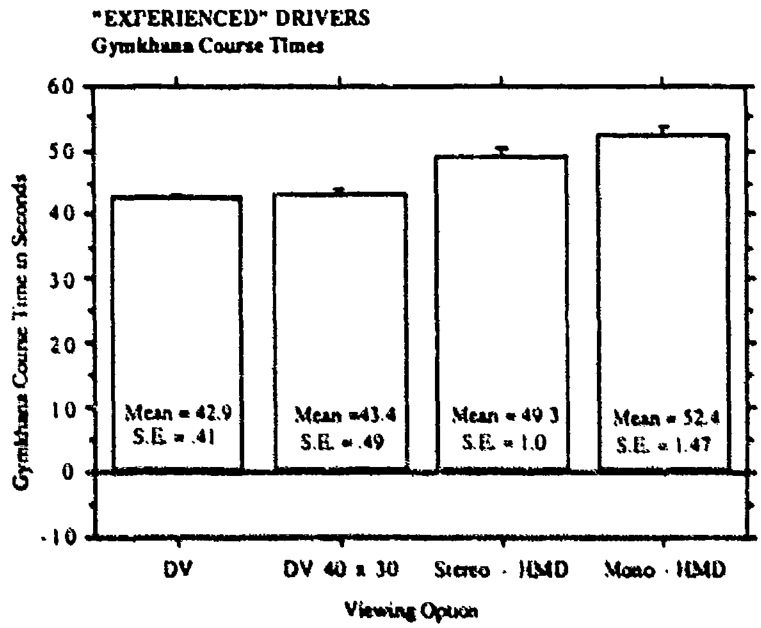
TABLE 1. Summary of Statistically Significant Advantages for Combined Direct View over Combined Video View Conditions.

	"Experienced" Drivers		"Inexperienced" Drivers	
	Time	Errors	Time	Errors
Right-Angle Turn-IN	~60% faster**	~72% fewer*	n.s.d.	n.s.d.
Right-Angle Turn - OUT	~34% faster**	n.s.d.	n.s.d.	n.s.d.
Figure -8	~31% faster*	n.s.d.	n.s.d.	~65% fewer**
Small Radius Circle	~25% faster*	n.s.d.	n.s.d.	n.s.d.
Small Radius Circle - Stop	~13% faster*	n.s.d.	n.s.d.	n.s.d.
Gymkhana	~15% faster**	n.s.d.	n.s.d.	~50% fewer*

Key:
* Type-I error probability < .05
** Type-I error probability < .01
n.s.d. = no significant difference found

In summary, statistically significant differences in driving performance measures were found for each of the six measures taken in the mobility test battery. All of these differences showed performance under the direct viewing conditions to be superior to that under the video viewing conditions tested. Differences were notably inconsistent between the two driver groups."Inexperienced" drivers produced higher rates of errors on error measures with no significant differences for the time measures. The pattern of results suggests that "inexperienced" drivers attempted to drive the vehicle at equal speeds under direct view and video view options. "Experienced" drivers drove the time-scored courses faster under direct view conditions while maintaining consistent error rates across the viewing options tested. As one example of significant performance effects revealed by the set of analyses conducted, the effect of viewing system option on Gymkhana course times for the "experienced" group of drivers is graphed in Figure 5. While maintaining essentially equivalent error rates for all conditions tested, the performance graphed in the figure is nearly identical for the two direct view conditions, whereas times are slower under the Stereo-HMD option and even slower under the Mono-HMD option. Overall, driving time under the direct view options was approximately 15% faster than driving time under video view options.

FIGURE 5. Effect of Viewing Option on Gymkhana Course Times for the Experienced Group of Drivers.



Note: the error bars graphed in this figure and subsequent figures represent standard errors defining the upper bound of the 95% confidence interval.

3.3 Unobstructed Versus Masked Video Viewing

Given the richly detailed visual information provided under both direct view options, no reliable performance difference was found between the unoccluded DV option and the peripherally occluded DV 40 x 30 option. Though error rates were consistently observed to be slightly elevated for the DV 40 x 30 option versus the DV option for both driver groups on all driving courses tested, none of these error rate differences were found to be statistically significant. This outcome of the analysis suggests that if sufficient image resolution, contrast, color, head motion coupling, and accurate feedback of vehicle dynamics are provided to a driver, a 40° by 30°, 1:1 field of view is sufficiently wide enough for low-speed mobility within the scope of fundamental driving tasks tested in this study. However, the consistency of the pattern of slightly elevated error rates for the DV 40 x 30 option versus the DV option does suggest that some capability is lost by restricting a driver's peripheral field of view. Whether this effect is stronger for driving over more challenging terrain remains to be determined and should be investigated.

3.4 Stereoscopic Versus Monoscopic Video Viewing

Measures were taken with the same IHADSS helmet-mounted display on identical driving courses under two viewing options; monoscopic and stereoscopic. An earlier, preliminary analysis of this data [4] revealed no significant differences between the Mono-HMD and Stereo-HMD viewing options on any of the courses tested for either operator group. The more refined analysis conducted for this paper in which the two driver groups were analyzed separately, contradicted the findings of the previous analysis by revealing statistically significant, but modest, performance advantages for use of a stereoscopic display on several of the courses tested. Table 2 summarizes these significant effects.

TABLE 2. Summary of Statistically Significant Advantages for Stereo-HMD Over Mono-HMD Viewing Options.

	"Experienced" Drivers		"Inexperienced" Drivers	
	Time	Errors	Time	Errors
Right-Angle Turn - IN	n.s.d.	n.s.d.	~36% slower*	n.s.d.
Figure-8	n.s.d.	n.s.d.	~30% slower*	n.s.d.
Small Radius Circle	~13% faster*	n.s.d.	n.s.d.	~61% fewer*
Small Radius Circle - Stop	~15% slower*	n.s.d.	n.s.d.	n.s.d.
Gymkhana	~06% faster*	n.s.d.	n.s.d.	n.s.d

Key:
* Type-I error probability < .05
n.s.d. = no significant difference found between Stereo-HMD and Mono-HMD

With regard to vehicle speeds, it appears that the Stereo-HMD option allows "experienced" drivers to maintain faster speeds than the Mono-HMD on several of the courses without a corresponding penalty in error rates. This pattern is apparent in Figure 6, a graph of the effect of viewing option on course times on the Small Radius Circle course for the "experienced" group of drivers. A possible benefit of Stereo-HMD for the "inexperienced" group may be that it imparts a more accurate sense of space, and that this, in turn, motivates them to slow down and make fewer errors when given a video view of a relatively unfamiliar driving situation. This conclusion is suggested by the patterns of performance graphed in Figures 7 and 8. The pattern of results graphed in Figure 7 shows that "inexperienced" drivers tended to drive significantly faster under the Mono-HMD versus the Stereo-HMD viewing option. A similar pattern (not graphed) was found for "inexperienced" drivers on the Figure-8 course. The "staircase" pattern of results graphed in Figure 8 was apparent in the data from a majority of courses from both driver groups, though it only reached statistical significance in one instance (i.e., Small Radius Circle course errors for the "inexperienced" group) probably owing to the small size of the sample of drivers tested.

FIGURE 6. Effect of Viewing Option on Small Radius Circle Times for the "Experienced" Group of Drivers.

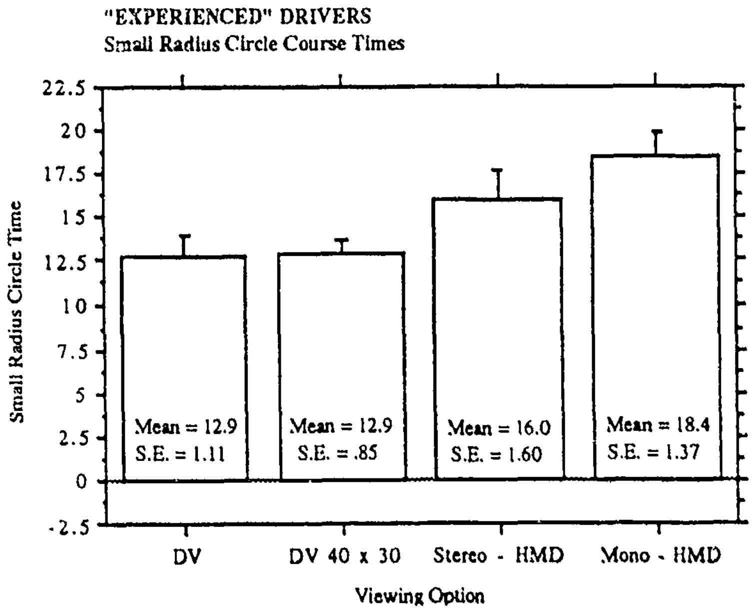


FIGURE 7. Effect of Viewing Option on Right Angle IN Course Times for the "Inexperienced" Group of Drivers.

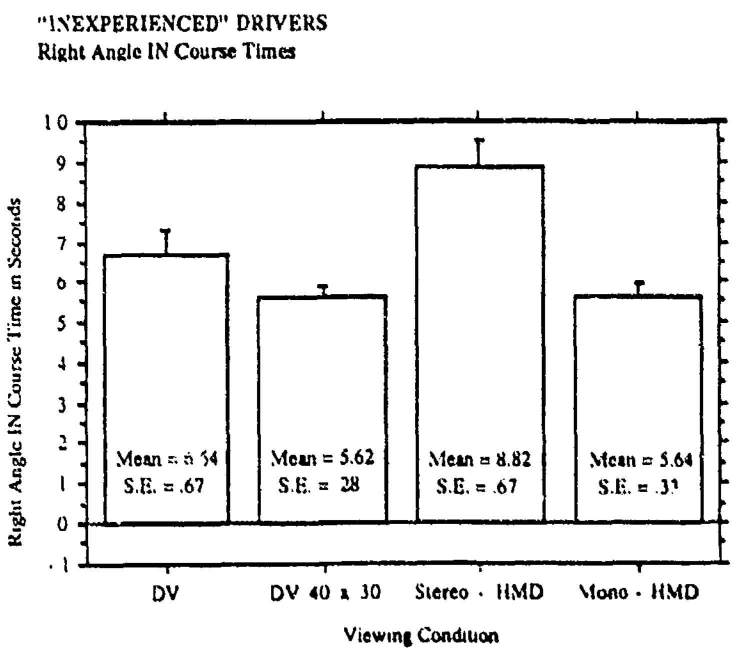
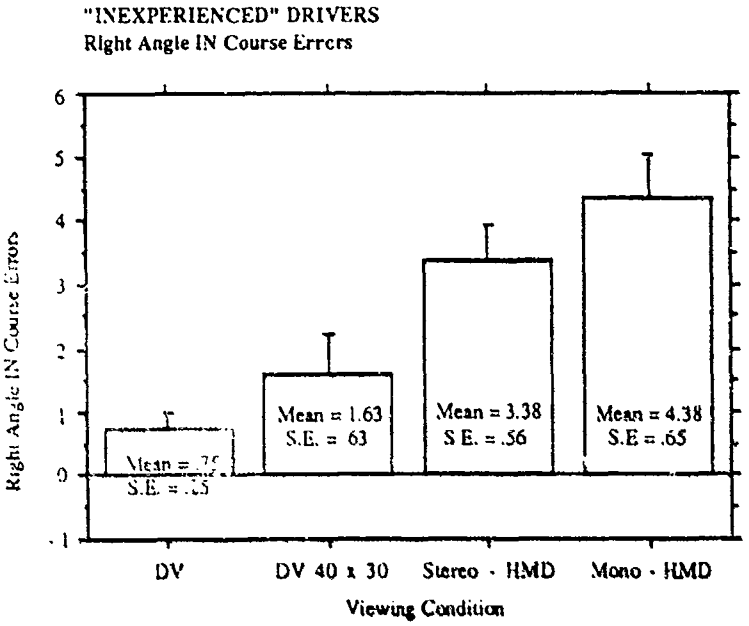


FIGURE 8. Effect of Viewing Option on Right Angle IN Course Errors for the "Inexperienced" Group of Drivers.



In attempting to generalize these findings of a stereoscopic advantage to more rigorous and challenging UGV driving conditions, one must keep in mind that past research and hands-on field experience has shown that the performance advantages which stereoscopic imagery provides are most pronounced in unfamiliar, visually cluttered, and visually degraded images. Stereo imagery is also known to be useful in judging the relative distances and orientations of objects and terrain surface features - all of which are invaluable to an operator when evaluating the composition and topography of terrain before attempting to traverse it. The results of this study are strongly suggestive of potential performance advantages to be derived by using stereoscopic imagery in UGV display systems. A more relevant, systematic, controlled comparison of UGV performance with stereoscopic and monoscopic imagery is recommended.

3.5 "Experienced" Versus "Inexperienced" Drivers

The observed effect of operator experience on driving the TOV through the test courses used in this experiment can be summarized quite simply. The "experienced" group tended to drive more conservatively than the "inexperienced" group. Under video viewing conditions, "experienced" drivers slowed down and made fewer errors on all the driving courses tested than their "inexperienced" counterparts. The "inexperienced" group tended to drive the TOV at speeds approximating those achieved under the two direct viewing conditions, but in doing so they committed many more errors than the "experienced" group. Perhaps the observed difference in performance is really just a difference in risk-taking between the two groups. The "experienced" group was considerably older and more technically astute than the "inexperienced" group. Overall, this pattern of results suggests that, given several hours of experience in driving the TOV, drivers became more cautious and lowered their driving speed to better correspond to their degraded view of the courses.

4.0 IMPLICATIONS FOR UGV DEVELOPMENT & DESIGN

Even while driving under the simplified, relatively undemanding, and benign course conditions investigated in this early study, a large performance gap was documented between direct view and video view driving. These observed differences in performance are directly attributable to parameters of the viewing systems used to view the driving situation since other aspects of the driving situation (i.e., steering controls and forces fed back through them to the driver, acoustic feedback, the dynamics of sensor aiming, and body motion senses) were generally equivalent under all viewing options tested. The findings suggest that considerable thought and effort will be required to devise UGV viewing system hardware that will overcome the technological limitations inherent in available video displays and provide a reasonable approximation to the level of performance achievable under direct drive conditions. Several obvious discrepancies between direct viewing and video viewing merit further systematic investigation. These include system magnification, spatial resolution, and image contrast. The best way to gauge the effects of these and other viewing system parameters on UGV driving is by systematic, controlled comparisons of objective performance measures.

Field of view is a fundamental parameter of any UGV viewing system. Results of this investigation suggest that a 40° horizontal by 30° vertical field of view with high fidelity head movement coupling of camera aim can provide a close approximation to the level of driving performance achievable with a full, unoccluded field of view for the type of low-speed mobility measured here. However, it should be noted that this conclusion is here only validated for a situation in which other important system parameters such as image resolution, image contrast, and system magnification are equivalent to those under direct viewing conditions. An objective study of the effects of a fixed sensor field of view on remote driving performance is currently underway at the US Army's Human Engineering Laboratory. The results of this study should hold important implications for selection of an appropriate field of view for future UGV systems.

Use of an easily implemented stereoscopic video display improved driving performance significantly, though modestly, on several of the courses tested. By providing the driver with a more accurate internal spatial representation of the driving course and his vehicle's movements within that course, the driver was perhaps able to make better decisions regarding speed and steering of the vehicle. For drivers who are highly experienced at performing a particular driving task, the additional information may allow them to drive faster while maintaining an acceptable, stable risk of erring. For drivers unpracticed at performing the particular driving task demanded by a driving course, the additional information provided by a stereoscopic display may increase their awareness of the limitations of their view and control over the vehicle and may subsequently encourage them to reduce speeds and drive more conservatively in unfamiliar situations.

The results presented in this report point very consistently to the general conclusion that providing the UGV driver with a display that more closely approximates the "full telepresence" viewing condition is a successful approach to improving driving performance as measured by systematic, objective test procedures.

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