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Vision System Testing for Teleoperated Vehicles

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VISION SYSTEM TESTING FOR TELEOPERATED VEHICLES

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ABSTRACT

Teleoperated vehicles separate the human operator from the vicinity of the vehicle. Commands to the vehicle and feedback to the operator regarding the environment and actions of the vehicle are transmitted over a communications link, tieing the vehicle to the operator. Visual information, the primary feedback required by the operator, is provided through closed circuit television. Intelligent allocation of video bandwidth is predicated on determining which video system characteristics contribute the most to driving performance. Factors include such things as camera placement, video resolution, field-of-view, color, steering coupling, and the use of multiple cameras. Sandia National Laboratories has conducted mobility testing to study these effects on off-road, remote driving performance.

This study compared three forward-looking vision systems consisting of a fixed mount, black and white video camera system, a fixed mount, color video camera system and a steering-slaved color video camera system. Subjects were exposed to a variety of objects and obstacles over a marked, off-road, course while either viewing videotape or performing actual teleoperation of the vehicle. The subjects were required to detect and identify those objects which might require action while driving such as slowing down or maneuvering around the object. Subjects also estimated the size, distance, and separation of two obstacles using the same video systems as in the driving task. Two modes of driver interaction were tested: 1) actual remote driving, and 2) noninteractive video simulation. Remote driving has the advantage of realism, but is subject to variability in driving strategies and can be hazardous to equipment. Video simulation provides a more controlled environment in which to compare vision-system parameters, but at the expense of some realism.

Results demonstrated that relative differences in performance among the visual systems are generally consistent in the two test modes of remote driving and simulation. A detection-range metric was found to be sensitive enough to demonstrate performance differences viewing large objects. It was also found that subjects typically overestimated distances, and when in error judging clearance, tended to overestimate the gap between the objects.

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Dan Morrow - Jeep steering control system analysis.
Dave Hubbard - Experimental support and ghost-rider.
Dave Shirey - Experimental support and ghost-rider.

Thanks are due to all the subjects who willingly participated in this experimentation.

This research was supported by the US Army Missile Command (MICOM) through the Teleoperated Mobile All-purpose Platform (TMAP) project.

This work is dedicated to the memory of Linda Giron, who, through her cheerfulness and enthusiasm, made it a pleasure to continue in the face of bad weather, equipment breakdowns, and the other normal problems of coordinating a large experiment.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

VISION SYSTEM TESTING
FOR
TELEOPERATED VEHICLES

INTRODUCTION

Teleoperation provides a capability for humans to work effectively in conditions which are not comfortable or not conducive to long-term performance. The human can be positioned at a control station in a comfortable, safe environment while a mobile platform is remotely driven (teleoperated) to the area of operations. The vehicle, communication link, control station, and human operator form a system which, together, can perform the required function. Such systems have been developed for a variety of applications including those of military and security use [1,2].

In a typical mobile teleoperation system, the operator commands the vehicle through an input device such as a joystick or a steering wheel. Feedback is through a video link, displaying the view from the vehicle at the driving station. From this display, the operator must derive sufficient information to safely maneuver the remote vehicle. This separation of the operator from the world outside the vehicle exacts a significant performance penalty. Experience with several systems [3,4] indicates that expected vehicle performance (speed and course-following accuracy) will be much less than that which would result with an on-board driver. Further, there is significant risk of loss of control or vehicle damage when operating in an off-road environment [5].

Sandia National Laboratories (SNL) has been involved in feasibility studies and technology development of teleoperated vehicle systems for several years. As part of this effort, SNL has been engaged in the development of a portable driving station for use in the Teleoperated Mobile All-Purpose Platform (TMAP) project. This project, supported by the U.S. Army Missile Command (MICOM), is intended to increase survivability of the operator by providing vehicle control from a remote, protected position through a secure, jam-proof command data link. The overall project goal is the development of small, low cost, lightweight robotic systems for a variety of battlefield activities. The anticipated TMAP applications include sentry and scout roles, courier or decoy duty, target designation for longer range weapons, and possibly explosive ordnance disposal. The system was also initially configured to mount, emplace, and operate individual and crew served infantry weapons.

Since the TMAP control unit is limited in size and display complexity, it is important to provide the operator with the best information possible. A program of experimentation in vision systems related to the requirements for vehicle control was therefore planned and executed. The basic test format was structured to investigate several features of video systems which, in SNL experience, had significant impact on control of teleoperated vehicles. Specifically, conditions of color video versus black and white video and camera pointing control (e.g., fixed camera versus panning the camera in connection with vehicle steering inputs) were researched. An additional goal was to develop a test methodology which would allow future testing to be performed in a cost-effective manner.

Results of these experiments have been reported in a series of papers [6,7,8], each addressing one aspect of the experiment. This report provides a summary of all results and, in addition, contains supporting information regarding detailed hardware description, test software specifications, and test protocols. Copies of test documentation are included as well as subject questionnaire responses.

DESCRIPTION OF EXPERIMENT

BACKGROUND

The operator of a teleoperated off-road land vehicle must be able to 1) scan the immediate terrain for obstacles or terrain features that may impede progress or damage equipment, 2) search distant terrain for landmarks which could be used to assist in navigation, 3) monitor pitch and roll attitudes to maintain vehicle stability, and 4) assess size and separation of obstacles to anticipate the clearance of the vehicle in driving between them. Very little work has been done to address these requirements for teleoperated vehicles. Most of the available literature concerns automobile control and visual requirements for driving tasks performed in a well defined roadway environment. Visual tasks of interest in this environment include previewing roadway features, reading highway signs, monitoring vehicular instrumentation, and checking rear-view mirrors. Only limited work has been reported addressing human performance in an off-road driving environment.

Television requirements have been addressed primarily for teleoperation using remote manipulators. Studies in this field have examined the relative benefits of using color, multiple cameras, stereo vision, and different levels of image resolution in tasks involving the remote manipulation of objects in hazardous work environments. In these applications, the work space is in close proximity to the viewing system and is relatively static. The visual requirements for remote, off-road driving tasks appear to have little in common with this type of task except for generalities concerning the inadequacies of television as a substitute for direct viewing.

Experience at SNL has been gained through development and operation of a variety of vehicles. Several observations were derived from this activity. First, color video seemed to have an advantage over black and white for systems of comparable resolution. Second, increasing the accessible horizontal field-of-view by using multiple cameras, or by panning a single camera, seemed to assist local-area navigation and turn negotiation. These two observations were directly relevant to the TMAP requirements for effective vehicle teleoperation but neither reports from the literature nor experimental validation were available to provide confirmation. Accordingly, it was decided to perform experiments designed to systematically investigate these observations.

Military mission scenarios require teleoperated vehicles to be driven from point A to point B quickly and successfully. To compare candidate vision systems, the typical approach has been to have operators remotely drive a course. Data, such as elapsed time, probability of success, or estimates of operator workload, is gathered for analysis. Although this is the most realistic of approaches, it has some inherent drawbacks. First, it is costly, time consuming, and sometimes dangerous. Second, since the drivers' experience, abilities, and strategies play important roles in overall performance, experiments evaluating vision system parameters are susceptible to strong influences from these factors. It was therefore decided to expand the experimental program to attempt to develop a simulation technique which would allow comparable testing of vision systems without the problems of real-time vehicle teleoperation.

As a result of the above considerations, an experiment was developed which allowed two distinct types of testing. First, video display systems were chosen which represented a range of visual conditions. This allowed investigation of the visual requirements for teleoperation. Second, the experiment was repeated with conditions of actual teleoperation of a vehicle and simulated conditions. This provided data regarding the validity and practicality of part-task testing.

EXPERIMENTAL CONDITIONS

Three levels of vision system quality were tested under conditions of remote driving and video simulation. The system which was expected to yield the best performance was a color CCD camera mounted on a panning device that was linked to the vehicle steering. As the vehicle was steered, the camera panned in the direction of the turn (referred to as a steering-slaved system). The system with the worst anticipated performance was a color CCD camera, fixed to the vehicle, with the color turned off at the monitor. Intermediate to these two was a system with the same fixed camera as used in the suspected worst system but with the video presented in color. The video conditions were chosen to allow a series of single variable contrasts to be made. Color could be compared to black and white with the same resolution and field-of-view. Fixed camera position could be compared to steering-slaved camera control with the same resolution and color condition.

Two types of operator involvement were used. In the first type, remote driving, the operator was in control of a teleoperated vehicle. The operator, seated at a control console, gave steering, brake, and throttle commands to the vehicle while viewing progress on a monitor which displayed video from the vehicle. The second type of operator involvement was simulation. The operator was seated at the same console while a video tape was shown on the driving monitor. The video tape was initially recorded under conditions essentially identical to those of remote driving.

In both operator conditions, remote driving and simulation, the task was to detect and identify obstacles while the vehicle traversed a marked off-road course.

A secondary task of instrument monitoring was added to provide additional workload. The subject was instructed to watch simulated gauges presented on a graphics display, if time permitted, and indicate whenever the readings went out of tolerance. The gauges represented vehicle velocity, pitch angle, and roll angle. The gauges presented data which was directly received from the vehicle (during remote driving) or which was recorded at the same time the simulation display tape was generated.

After subjects had completed the driving task, they were tested for distance and clearance judgment under conditions similar to their driving experience. This part of the testing required the subject to view a video tape of the approach to a pair of columns. When motion stopped, the subject was to indicate the distance to the columns and whether the vehicle would fit between the columns.

At the conclusion of the experiment, subjects were asked to respond to a questionnaire regarding their experiences and subjective ratings of the various vision systems.

HARDWARE DESCRIPTION

The basic test hardware utilized a previously developed vehicle and control station. The video system was constructed to allow testing of the specific conditions of black and white versus color video and camera pointing control. A test course was established to expose the vehicle operator to a variety of objects and obstacles. Each of these components is described below.

VIDEO SYSTEM

Two cameras (illustrated in Figure 1) provided the video for the three separate vision conditions. A Sony DXC-101 CCD color camera (capable of 320 lines of resolution) and a Canon CI-10 CCD color camera (300 lines of resolution) were mounted on the vehicle. Both cameras were fitted with Cosmicar 16mm ALC lenses, providing a horizontal field of view of approximately 42 degrees, and automatic iris control which adjusted for changes in lighting conditions. The Canon camera was mounted on a turntable which was controlled such that the camera panned left and right in coordination with the vehicle's steering. The full lock-to-lock, steering-slaved effective horizontal field of view was 102 degrees, with an instantaneous horizontal field of view of 42 degrees. The Sony camera was installed on a fixed Vicon adjustable mount. Both cameras were mounted on the roof of the instrumented vehicle at approximately 6.5 feet above ground level. Both cameras were mounted looking forward, with a 10-11 degree negative pitch putting the aim points at approximately 26 feet in front of the vehicle's front bumper.

Panasonic BT-S1900N 19-inch color monitors (350 lines resolution) were used for all video displays. The black and white video condition was implemented by recording in color and playing back with no color on the monitor. This technique not only obviated the need for a third camera, but also allowed a direct comparison between color and black and white video without any differences in system resolution.

Recordings for the simulation conditions were made using Panasonic PV-4700 VHS video cassette recorders. These same VCR's were used for playback during simulation testing. Video from remote driving was recorded for future analysis and to condition

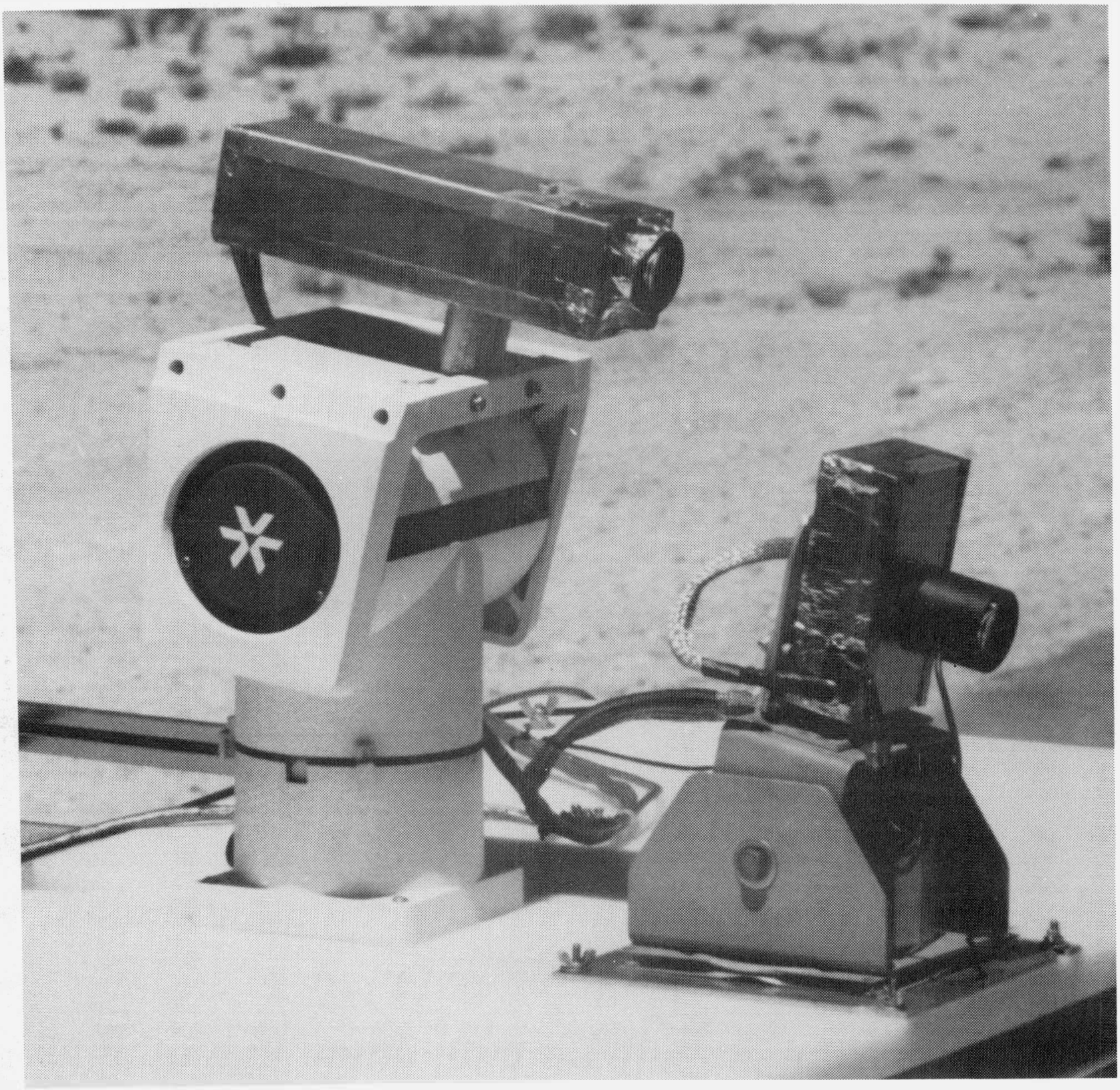

Figure 1 - Experimental System Camera Installation

the signal so that simulation and remote driving video were as similar as possible. The recorders limited the system resolution (whether from videotape or from the live transmission) so that presented video had the same resolution regardless of source. System resolution displayed at the monitor was on the order of 250 lines.

VEHICLE

A 1980 American Motors Corporation Jeep Cherokee was used as the vehicle to be controlled [9]. This vehicle, shown in Figure 2, was equipped with four-wheel drive, a standard six cylinder engine, and automatic transmission. An in-line floor shift was installed in place of the column-mounted gear shift. Electric actuators control the throttle, brake, gear shift, and steering. Actuators are controlled through an on-board 68000 microprocessor.

Sensors have been installed on the Jeep to provide feedback on vehicle status. These sensors include actuator positions, vehicle velocity, distance traveled, inclinometers (to measure pitch and roll), and vehicle heading. Vehicle position information is derived from two of these sensors; steering position, and odometer. Steering position is measured from the position of the vehicle steering gear tie-rod. A linear potentiometer provides steering position accurate to ±2 degrees. The odometer used is a magnetic pulse system mounted on the drive shaft. This device provides distance traveled to a resolution of 0.3 feet. Being mounted on the drive shaft, the odometer effectively averages the distance traveled by both rear wheels. No compensation is added for wheel slip.

A modem allows communications between the on-board system and a remote control station. The vehicle can be operated remotely or in a manually driven mode.

CONTROL CONSOLE

The control station was adapted from an existing system (illustrated in Figure 3). Video from the vehicle is shown on the center monitor while the left monitor displays graphic gauges for tilt, roll, and vehicle speed as shown in Figure 4. The other screens are blank for the TMAP testing.

Driver input to the vehicle is through a steering wheel, throttle pedal and brake pedal. These are mounted on a movable column which can be adjusted for operator comfort.

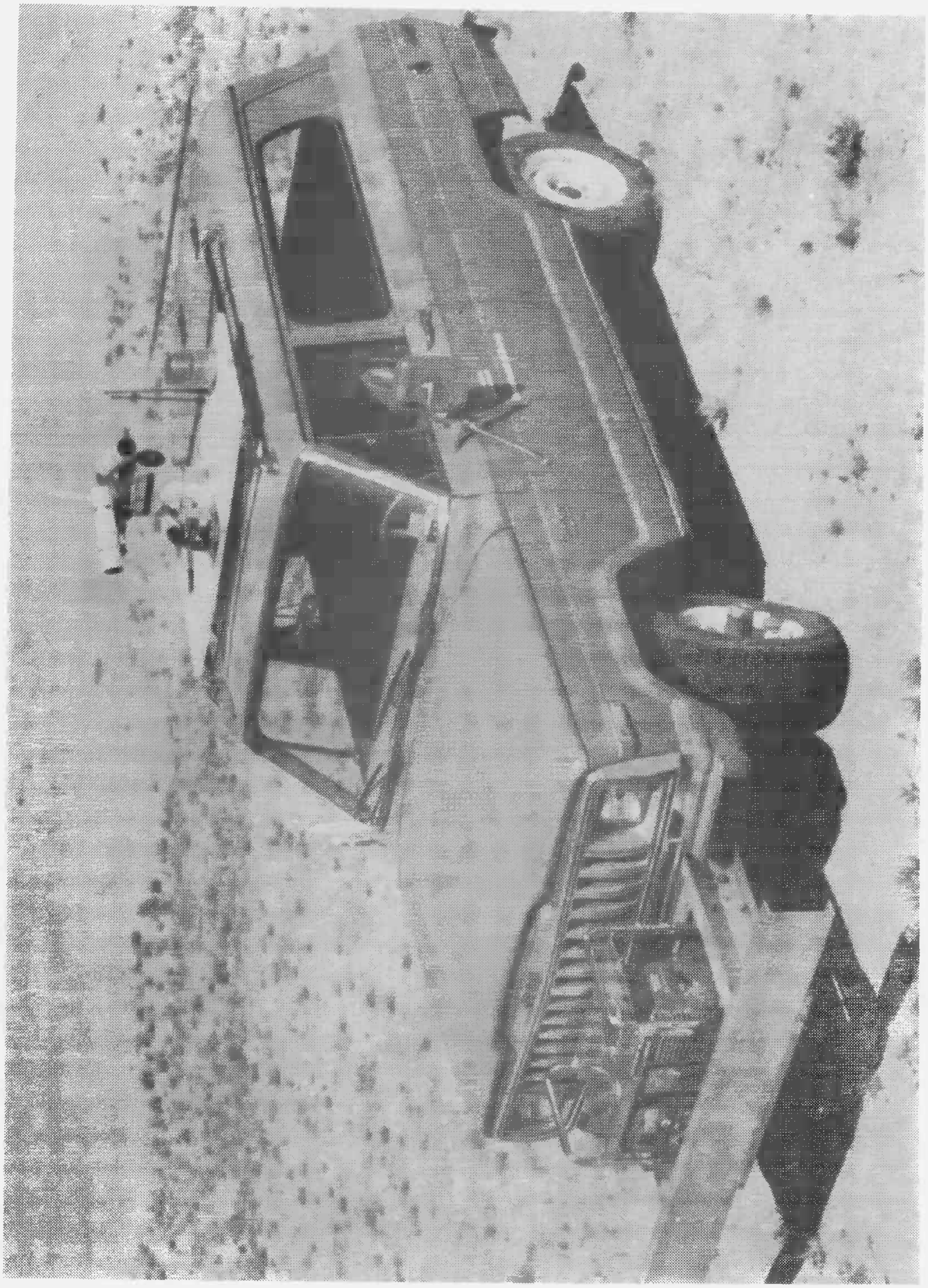

Figure 2 - Jeep Cherokee Test Vehicle

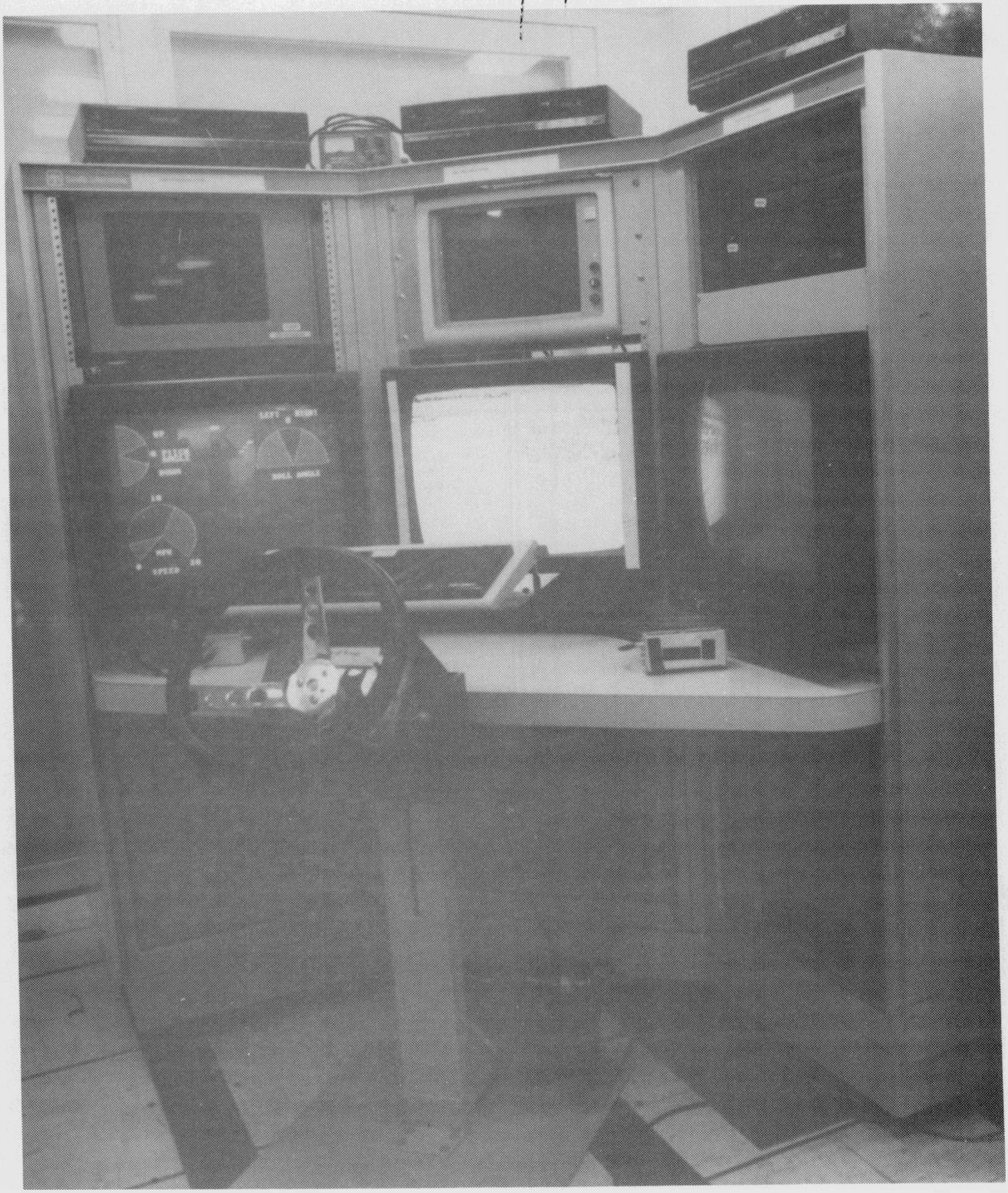

Figure 3 - Control Console

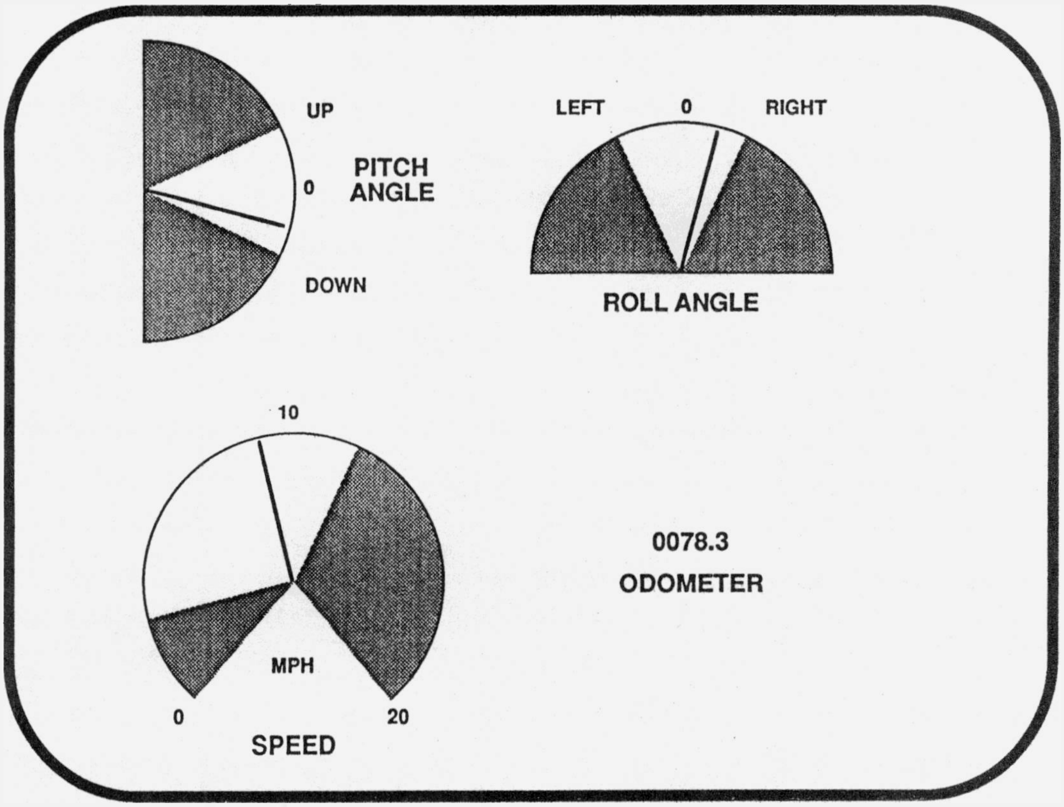

Figure 4 - Simulated Vehicle Gauges

Operator's responses to obstacles were recorded using a computer keyboard mounted in front of the steering wheel. Access was provided to only two keys, the "D" key and the "I" key. These were used by the operator to indicate when an obstacle had been detected ("D") and when it could be identified ("I"). A pushbutton mounted on a box installed next to the keyboard was used in the secondary task to indicate a gauge reading was out of tolerance. The subject was instructed to press the button when the gauge went out of the indicated acceptable range and to hold it down until the gauge returned to "normal".

CONTROL SOFTWARE

There are two major software systems used in controlling the Jeep. The first resides on-board the vehicle and is dedicated to local control. This system is an assembly language program used by the on-board 68000 processor to receive predefined ASCII commands from the remote console. It controls the vehicle driving functions and generates output from vehicle sensor data. Communication to the remote console is through a digital RF modem. Additional details can be found in Reference 9,

The second software system provides the operator interface and experimental data control. This system resides in an IBM/AT mounted in the remote console.

During normal vehicle control (teleoperation), the IBM/AT reads operator inputs from the driving station at the remote console, converts them to the appropriate command characters, and transmits them to Jeep. Data from the Jeep is received, processed, and routed to the display. For testing involving remote driving, both the video display and data display were done in real-time, as they were received from the vehicle.

This system was modified to allow data handling during the simulation experiment. Driving simulation runs were conducted using playback of videotapes made with the same vehicle/camera combination as that used for remote driving of the vehicle. Data displayed for the simulation runs was collected from the vehicle by computer at the same time the videotape was made. This data was synchronized with the videotape by electronic means so that during the test run, the scene viewed matched the data displayed.

Subjects' keyboard and secondary-task responses were recorded on diskette for later analysis and comparison to a set of master datalog files which were generated in exactly the same way.

Simulation: The program used to collect the instrument data and to synchronize it with the videotape made concurrently was called TMAPDATA.BAS. This ran on a portable MS-DOS computer on-board the vehicle as it was manually driven over the test course. The data files that it generated were called TESTRUN?.DAT (where "?" was a number from 1 to 5, the test course segment number). The portable computer was hooked to the Jeep's onboard computer via the serial port. After initializing the Jeep's odometer to zero, the program began looping through a velocity sensor request and an odometer data request, waiting for both of those sensors to indicate movement of the vehicle. As soon as movement of the vehicle was detected, data collection began and a special electronic tone generator tied to the Jeep's on-board computer produced a tone which was recorded on the audio track of the videotape being made from the Jeep's onboard camera. This allowed synchronization of the collected data with the videotape for later playback.

When Jeep movement was detected, the program began to collect velocity, odometer output, pitch angle, and roll angle data, and store it in the computer memory. Table 1 lists the data assignments inside each data segment. The total time to collect the data and the number of data "chunks" collected were also tracked, so that an average "time between successive data chunks" could be computed. This time factor was then used while displaying the data during simulation to keep the data running in real-time and synchronized with the videotape playback (also in real-time).

When the vehicle reached the end of the test run, it was brought to a stop and the data gathering portion of the program was halted. The program then proceeded to copy the contents of memory to diskette, beginning at the first data segment holding sensor data. This resulted in a disk file which contained successive readings from the vehicle's sensors, separated in time by an amount equal to the average of the total elapsed time divided by the number of data segments stored.

TABLE 1
INSTRUMENT DATA RECORDING ASSIGNMENTS
(16 byte segment)

byte	data	type
0,1,2	velocity	binary
3,4,5,6	odometer	binary
7,8,9	pitch angle	hexadecimal
10,11,12	roll angle	hexadecimal
13,14,15	unused	

The program used to test the subjects at the driving console was called TMAPTEST.EXE. This performed the two main functions of data synchronization and display and subject response recording. First, the program loaded the *.DAT file specified from diskette into RAM. Data display then was started upon activation by a special audio detector linked to the videotape's audio output (thereby synchronizing the start of the videotape and data display). While data was being displayed the designated response keys were being strobed to detect test subject responses. Responses were transferred to a diskette file (*.ANS) along with the current odometer reading and timestamp data. That file was converted at a later time to a format readable by humans for interpretation.

<u>Remote Driving:</u> The program used to perform both remote vehicle control and response data collection (*.ANS) was called TMAPJEEP.EXE. This program ran on the driving console computer. The acquisition of data from the Jeep was performed in real-time, and was displayed to the test subject using identical graphic displays as those used for simulation runs. Response keys were strobed in and response files were generated to diskette in exactly the same way as the simulation. The only difference in data handling between simulation and remote driving was that the data in remote driving was not retrieved from diskette storage, but rather was "live" data.

<u>Data Conversion:</u> The program used to convert response (*.ANS) files to a readable format was called TMAPLOG.EXE, and could be run offline from the testing process. The program processed one response (*.ANS) file at a time. The sequence of processing was as follows. 1) Open the *.ANS file specified by the operator and begin to input data, discarding spaces between the data bytes. 2) Determine which key had been pressed (identifying the subject's response), decode and convert the odometer data to feet, decode and convert the time stamp into seconds. 3) Print the results to another diskette file (*.LOG); i.e. "obstacle detected at 1203 feet, time = 107 seconds". Each test run began at zero feet and zero elapsed time, so the *.LOG file gave relative distance and time information specific to each test run.

A set of master log files (*.MAS and mstrlog.*) contained the odometer locations relative to the beginning of the test run for all obstacles and for the points at which any of the graphics data went beyond specified range (the subject's secondary task). This information gives one set of standards to test subject response comparison, and was generated in the same manner as test subject data.

JEEP STEERING CONTROL SYSTEM RESPONSE

The vehicle steering control system was tested to determine the speed and accuracy of response [10]. The system was tested through providing a "step" input at the console steering wheel and measuring the response at the vehicle wheels. Figure 5 shows the typical command/response data. Three parameters are marked: the lag between the beginning of the command and the beginning of the response, the slope of the response curve which represents vehicle turning speed, and the length of time for the command step, "cmnd time". Table 2 lists the values of these three parameters.

TABLE 2
STEERING RESPONSE

	Lag	Slope of Response	Length of "Step" Command
mean	235 msec	23.9 deg/sec	165 msec
std dev	56 msec	1.9 deg/sec	40 msec

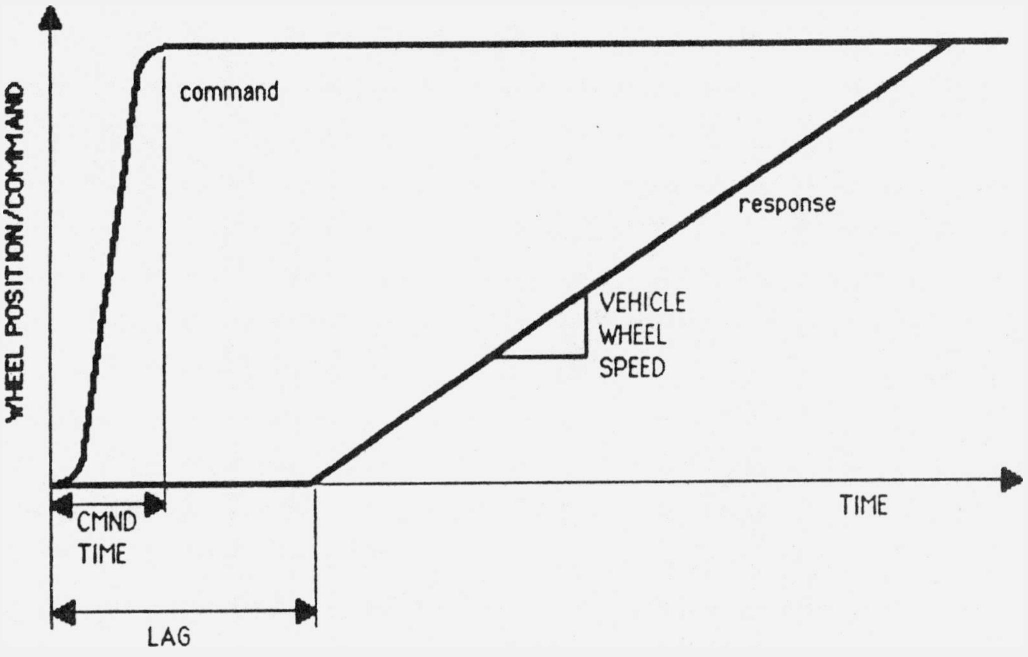

Figure 5 - Jeep Command Response Measurement

Although the input was not a true step, it is noted that the command is finished before the response even begins. The slope of the response is essentially constant, suggesting that the actuator reaches full speed very quickly and stops abruptly when the error signal goes to zero. The lag between the beginning of the command and the beginning of the response is expected in a teleoperated system due to the fact that the control console must communicate with the vehicle. The total time from the beginning of the command (90 deg at steering wheel) to the end of the response (30 deg at vehicle wheels) is approximately 1.5 seconds using the above results.

During the remote driving studies, nearly all of the subjects had difficulty with the steering system. Even though subjects were coached by the experimenters on the best way to control the vehicle steering (gently), the lateral error was usually close to the width of the road (approximately 20 feet) with a vehicle speed of about 5 miles per hour. Increased vehicle speed led to increased lateral error. At the conclusion of experimentation with subjects, the system was disassembled and checked. It was found that the potentiometer hooked to the steering wheel (the input pot) was failing in a way that generated a non-linear response with a significant random component. Replacement of this pot greatly improved the steering control quality. The overall speed of response and lag were not changed.

TEST COURSE

A two-mile long test course was developed which allowed driving over a variety of terrain ranging from graded dirt roads to off-road across the desert. When the course left the established road network, a 24 foot wide path was marked by 28-inch high traffic pylons placed approximately 40 yards apart. Pylons were spaced much closer together in corners in order to adequately define the course. The pylons were covered with white paper since it was found that, in the intended visual field, the normal orange pylons did not provide sufficient contrast to be visible while using black and white video.

Objects were placed on the course as obstacles which must be avoided for safe vehicle operation. These objects included such things as gas cans, fences, sign posts, and oil drums. Other existing natural features such as ditches, trees, bushes and intersecting roads were also included in the course to provide a full range of obstacles as listed in Table 3. Figure 6 presents a map of the course with obstacle locations marked.

TABLE 3
TMAP TEST COURSE OBSTACLES

POINT	OBJECT
	Start of Leg One
1	Road
2	Berm-Leave main road
3	Railroad Tie
4	Tire
5	Cable Spool
6	Post-Buried Cable Marker
7	Gas can
8	Railroad Tie
9	Rocks
10	Barrel (or Drum)
11	Ditch
	End Leg 1 - Start Leg 2
12	Cable Spool
13	Bush
14	Railroad Tie
15	Tire
16	Road
17	Berm - (off of road)
18	Gas Can*
19	Wooden Beams
	End Leg 2 - Start Leg 3
20	Rocks
21	Cable Spool
22	Gas Can*
23	Tire
24	Rocks
25	Road
26	Railroad Tie
27	Barbed Wire Fence
28	Barrel (or Drum)
29	Tree
30	Tree Stump
31	Bush
32	Tire
	End Leg 3 - Start Leg 4
33	Rocks
34	Ditch
35	Railroad Tie
36	Ditch
37	Cactus (Bush)
38	Ditch
39	Rocks
40	Bomb Casing
	End Leg 5 - Start Leg 5
41	Tire
42	Gas Can
43	Rocks
44	Wooden Crate
45	Gas Can
46	Road
	End of Leg 5

46 Obstacles used for Simulation
44 Obstacles used for Remote Driving
(minus 2 Gas Cans*)

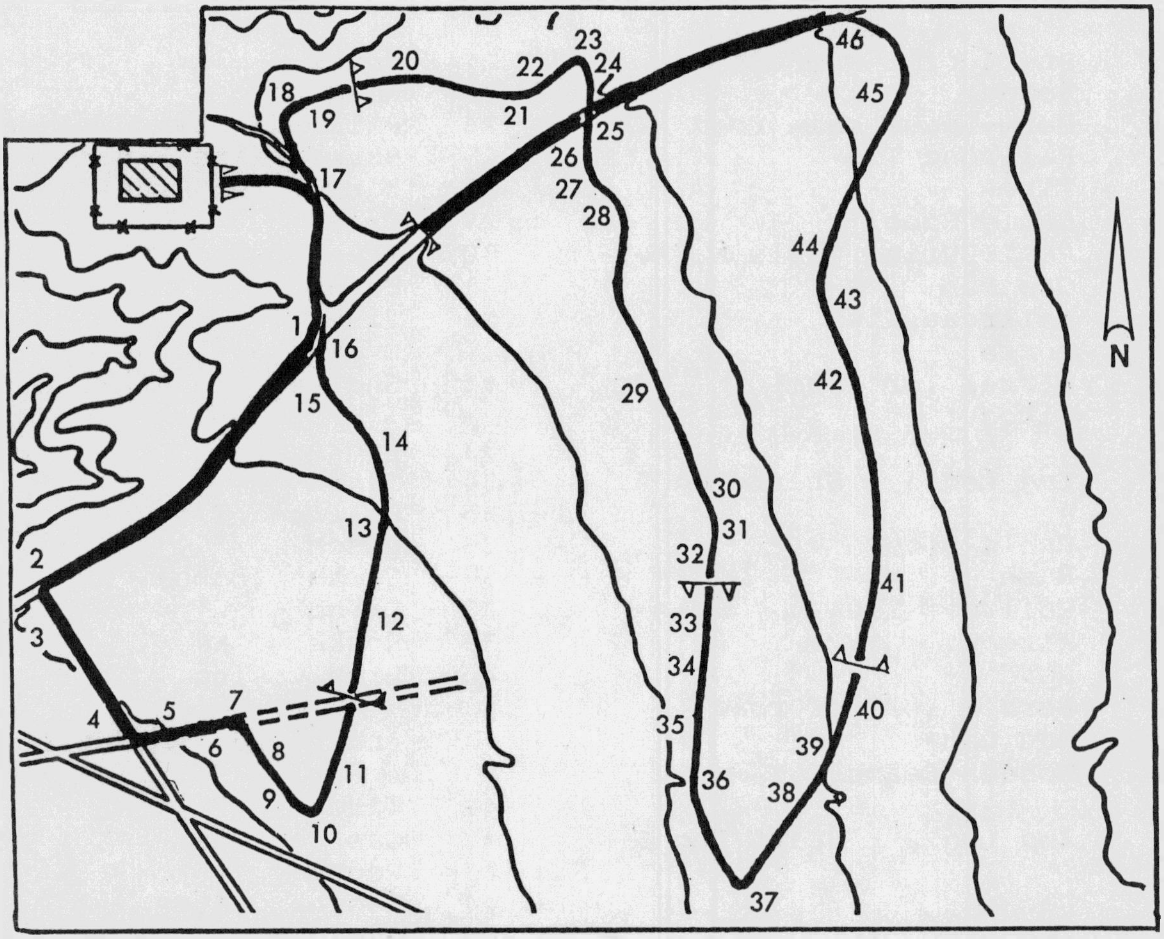

Figure 6 - TMAP Test Course

Object locations were picked to provide several backgrounds (unimproved road and mesa) and both straight approaches and approaches around a curve. Objects were divided randomly among legs so that each leg of the course had approximately equal conditions. Figure 7 shows the road intersection included as object 1. The vehicle entered from the right-hand road, continuing the course onto the larger road. There is a significant ditch between the main road and the intersecting road which required slowing the Jeep. Identification of both the road intersection and the ditch was desired.

Figure 8 illustrates an unimproved dirt road and obstacle 3, a railroad tie. Note that the object is clearly in the path of the vehicle requiring some action on the part of the driver to avoid hitting it.

Figure 9 is at the start of Leg 3 with obstacles 20 (rocks) and 21 (cable spool) visible. In this view the rocks are between the pylons which are used to delineate the course and are therefore to be considered obstacles even though the vehicle pathway misses them. The cable spool is not yet clearly identified as on the course.

Object 22, a gas can, is shown on Figure 10. This object is also just off the vehicle pathway but is within the boundary formed by the pylons and should therefore be reported as a valid obstacle.

EXPERIMENTAL METHOD

TEST PROCEDURE

Subjects were instructed to preview the path of the vehicle for obstacles and terrain features which might impede vehicle progress. When an obstacle was first detected, the subject was to press the "D" key on the computer keyboard. When the object became identifiable, the subject pressed the "I" key and verbally identified the object. Revisions to identification were permitted, as the data of interest were maximum distances at which obstacles were correctly identifiable using a given visual system.

To control for variations in the video medium other than the variables of interest, identical video sequences and obstacle orders were used in all six conditions. The two simulation video tapes were recorded simultaneously to ensure that they were identical in terms of lighting conditions, approach angle, speed, and duration. Remote driving was performed over the same course, using the same vehicle and cameras, at approximately the same time of day that the simulation tapes were recorded.

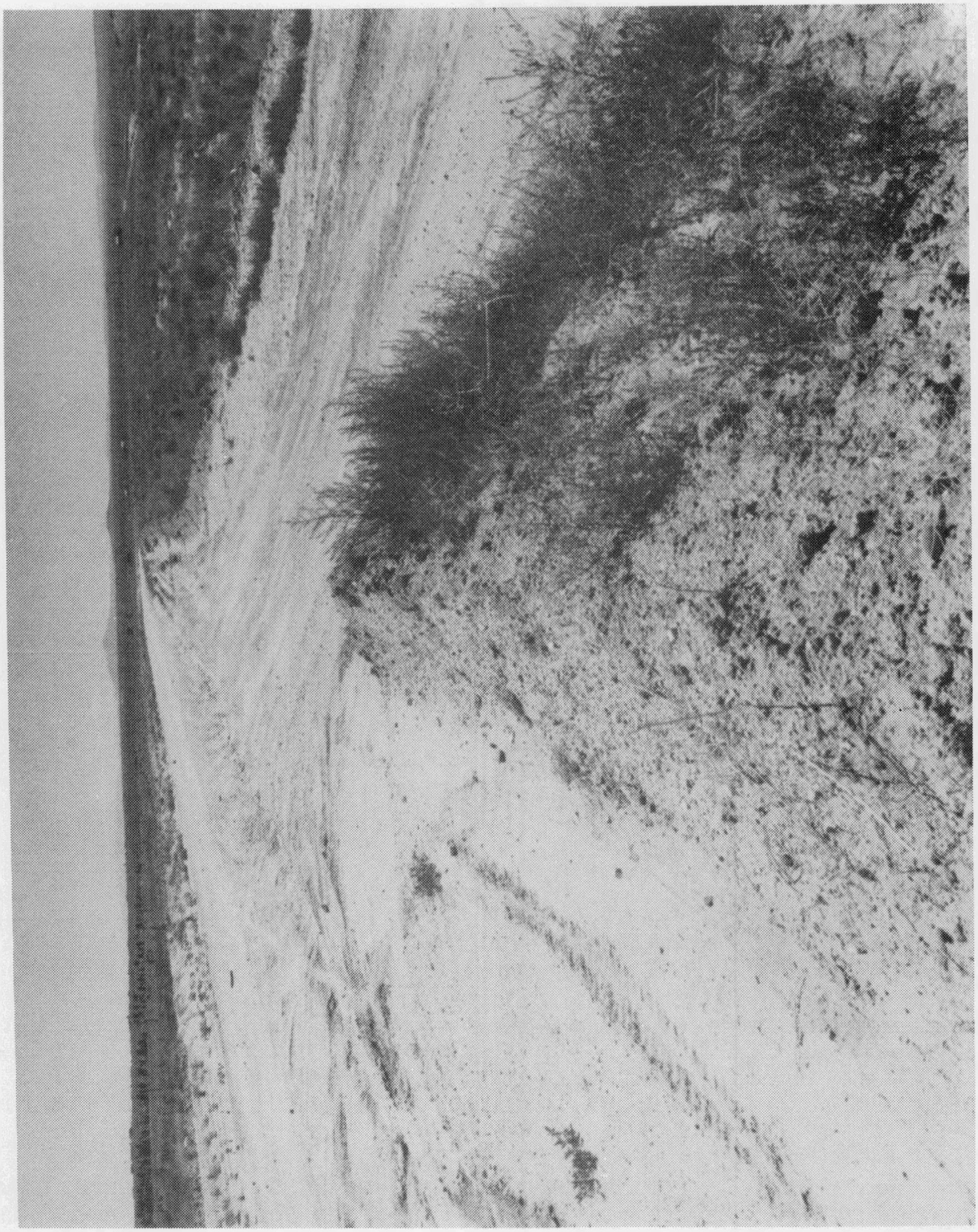

Figure 7 - Test Course; Road Intersection

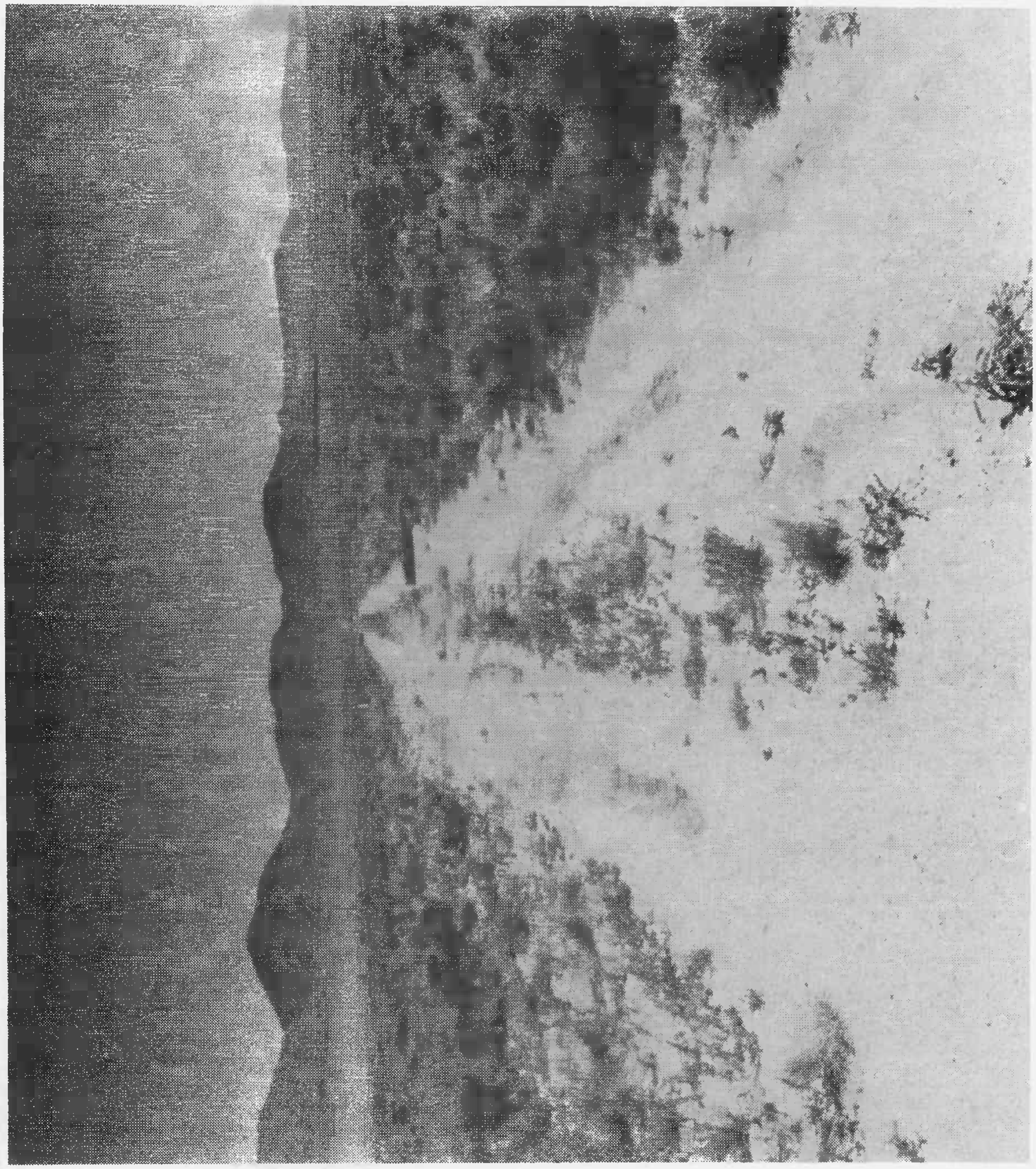

Figure 8 - Test Course; Railroad Tie (Object 3)

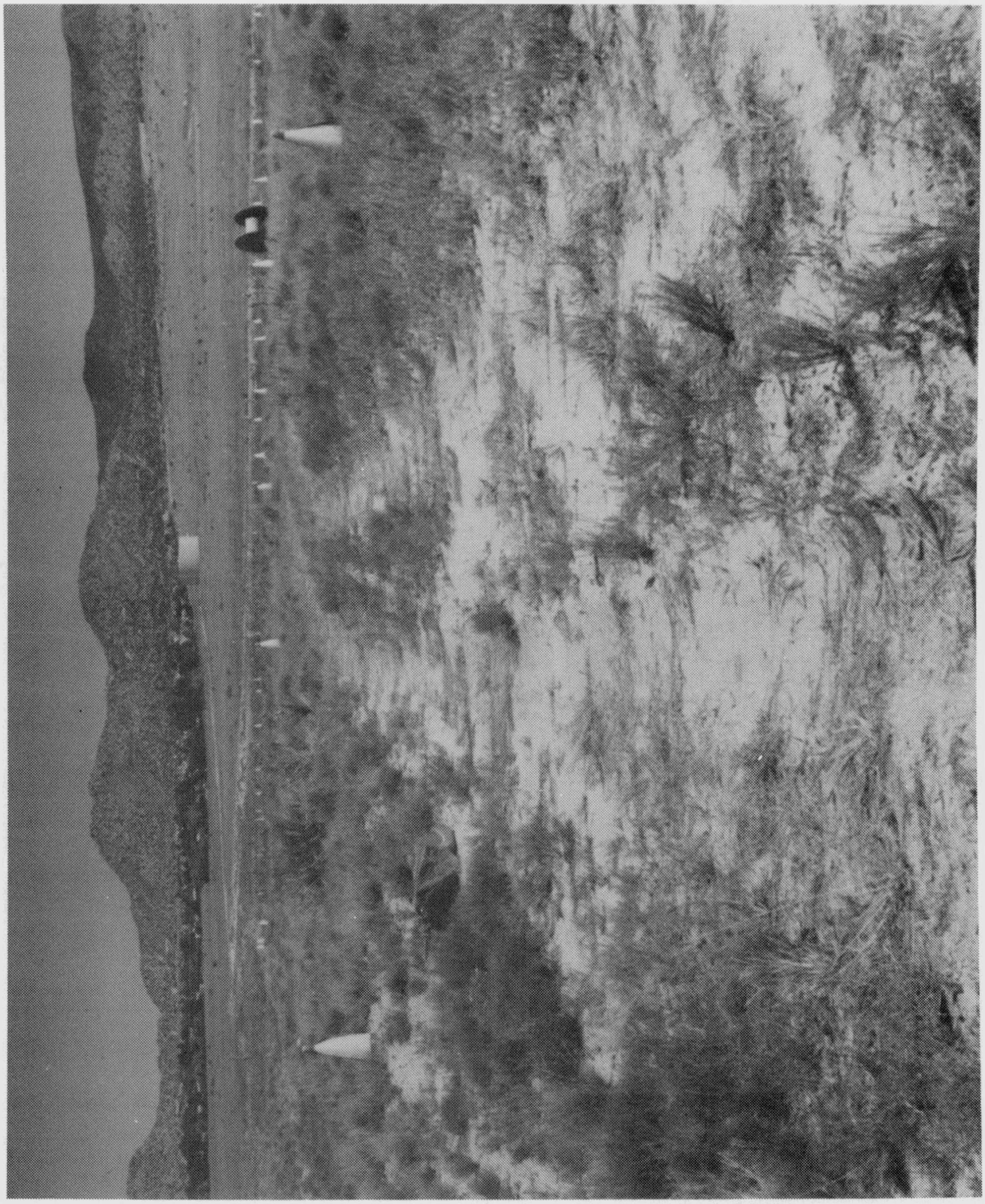

Figure 9 - Test Course; Rocks, Cable Spool (Objects 20 and 21)

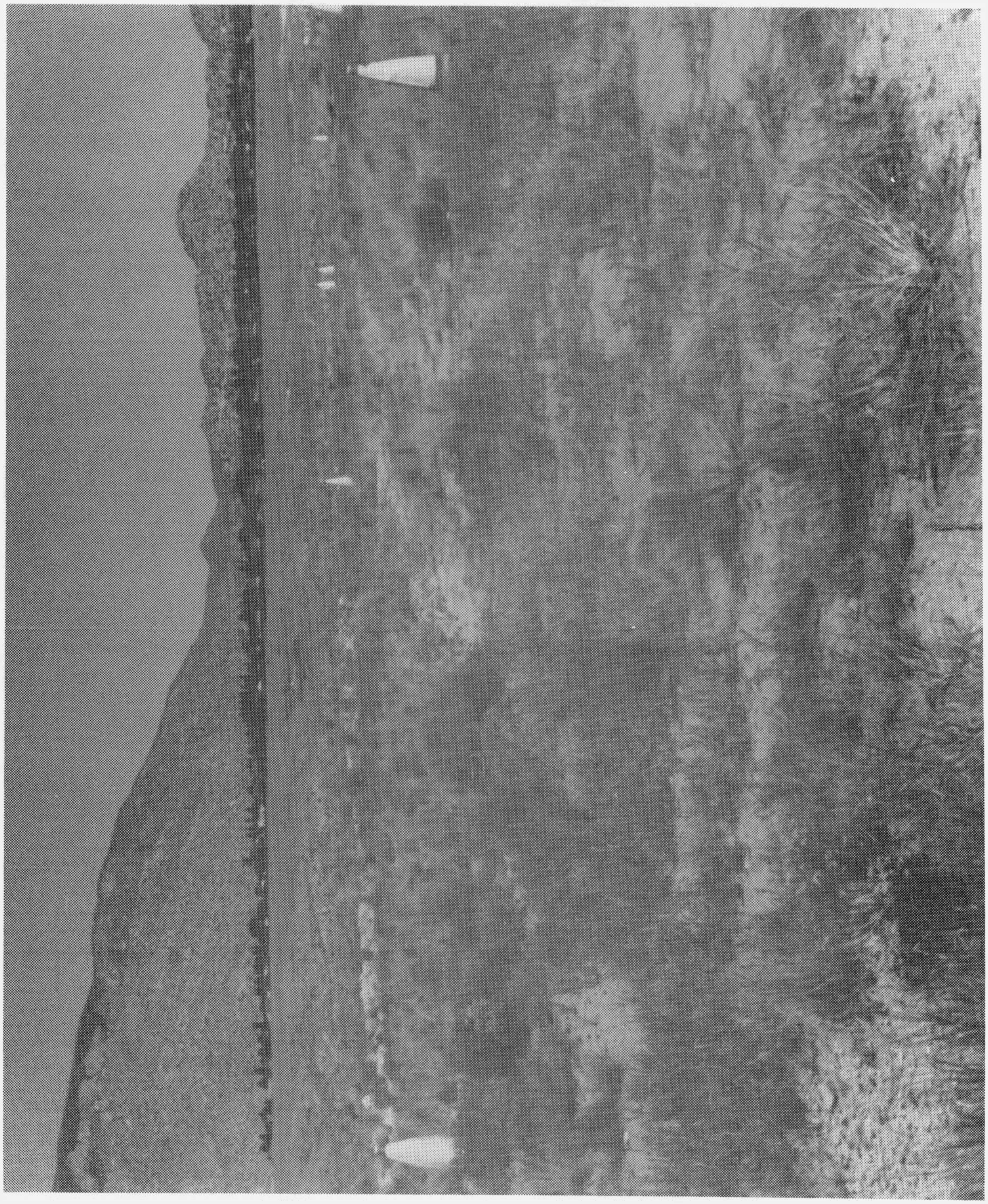

Figure 10 - Test Course; Gas Can (Object 22)

In addition to the obstacle detection task, subjects were asked to perform a secondary task as time permitted. This consisted of visually monitoring three graphic instruments on a second CRT and responding to any one of three variables going out of its acceptable range by holding down a pushbutton for the duration of the excursion. The instruments displayed the actual current speed, pitch, and roll of the vehicle in the remote driving conditions and recorded data in the simulation conditions.

At the conclusion of the obstacle detection task, subjects participated in a distance/clearance estimation study. They were shown a video tape of the approach of the vehicle to two white, vertical columns. When movement had stopped, the subject was to instructed to indicate how far away the columns were and whether the vehicle would fit between them. A series of sixteen conditions were presented with approximately 15 seconds pause between conditions.

Subjects were then shown a video tape composed of short sections of the video simulation tape for each camera condition. After watching the tape, subjects answered a questionnaire which asked for an evaluation of the various video systems.

Testing was concluded after the questionnaire. Subjects were thanked, handed a certificate of participation and told they would receive a report of the results of the study.

SUBJECT INSTRUCTIONS

Subjects were greeted at the test area and handed a sheet of paper which contained a description of the testing to be performed (Appendix A, page A-2). Subject visual acuity was checked using a standard Snellen eye chart. The subject was then seated at the driving console and handed instructions for the obstacle detection part of the test. Two sets of instructions were used, as appropriate, for visual simulation testing (Appendix A, page A-3) or remote driving (Appendix A, page A-5).

When this phase of the experiment was concluded, subjects were provided instructions for the distance/clearance estimation test (Appendix A, page A-7), followed by a comparison of video systems (Appendix A, page A-8).

A questionnaire (Appendix A, page A-9) was then administered. At the conclusion of testing a final set of instructions (Appendix A, page A-11) thanked the subject for his cooperation and requested that the test not be discussed with other participants prior to their testing.

TEST PROTOCOLS

Specific protocols were developed to guide the experimenters through equipment set-up and collection. These were determined to be necessary due to the complexity of the equipment involved and the need for safe operation, particularly in the remote driving testing.

Simulation: Simulation testing required coordination among four different systems; the Jeep video display system, response recording system, driving station recording system and the computer monitoring system. The Jeep video display system consisted of a video cassette recorder and monitor used to display scenes recorded while the Jeep negotiated the planned course. This system was used in playback only.

The response recording system was a VCR coupled to the computer CRT. Secondary task information (gauge monitoring) was drawn from the stored data in the computer and displayed to the subject. The response recording system copied this information and also contained an audio track which recorded subject comments.

The driving station recording system was a video camera, microphone, and VCR set to record a view of the subject, vehicle controls, and video displays. The tape from this system was saved for any interpretation of subject actions which might be necessary at a later time.

The computer monitoring system provided the data for the secondary task and storage for subject responses using the "D" and "I" keys.

The detailed protocol for the visual simulation testing is included as Appendix B.

Remote Driving: The protocol for remote driving testing (Appendix C) is generally similar to that for visual simulation except that data is generated live from the Jeep which the subject is controlling. The Jeep video display system presented live data which was recorded for future analysis.

The response recording system functioned the same as in visual simulation except that an additional audio signal was superimposed when identified obstacles passed from the scene. During analysis, the tone provided a marker for relative vehicle location, referenced to the obstacle. This was done to provide more accurate distance measurement than would have been possible using the vehicle odometer referenced to the beginning of each leg.

The driving station recording system setup was identical to simulation testing.

The computer monitoring system provided the control program for Jeep teleoperation and recorded all incoming data. This included the vehicle conditions used for the secondary task (speed, etc.) as well as the subject responses.

An analog data tape was initially part of the setup to record steering wheel position during Jeep driving. The degradation of the steering potentiometer discussed above rendered these data unusable.

EXPERIMENTAL RESULTS

A 3x2 factorial design was selected in which three levels of vision system quality were tested under both remote driving and video simulation. Thirty-six subjects participated, divided into the conditions shown in Table 4. All subjects were screened for average driving experience, corrected 20/20 vision, absence of bifocal or trifocal corrective lenses, and absence of major color-vision anomalies.

At the conclusion of the data-gathering portion of the experiment, a variety of approaches were taken to analyze the results. These included analysis of obstacle detection and identification data (from the simulation and remote driving tasks), comparisons of simulation and remote driving performance, determining the quality of distance/clearance estimation (from the videotape clips of the vertical columns), and finally, reviewing the questionnaire data. Each of these is presented below.

TABLE 4
EXPERIMENTAL DESIGN

CAMERA	REMOTE DRIVING	SIMULATION
Steering-Slaved, Color	6 Subjects	7 Subjects
Fixed, Color	6 Subjects	6 Subjects
Black & White	6 Subjects	5 Subjects

OBSTACLE DETECTION/IDENTIFICATION

Runs two through five were analyzed for obstacle detection and identification for both simulation and remote driving groups. (Run one was treated as a training period.) Overall, subjects correctly detected 75 percent of the 35 obstacles, and correctly identified 63 percent (Figure 11). Subjects reported an average of five false alarms (objects, real or imagined, that were not considered to be obstacles by the researchers) per session. No differences were found among the six experimental conditions based on any of these indices of performance. The search performance metrics did not appear to be sensitive to the vision-system differences used in this study.

In contrast to the search performance metrics, the detection-range measurements proved to be sensitive to differences in performance among the six experimental conditions. Detection range is the distance from the obstacle at which the subject detected its presence and pressed the response key. As could be expected with such a wide variety of visual targets, detection range performance varied greatly across obstacles. Mean detection ranges across all conditions ranged from 17 feet for a pile of rocks to 194 feet for the ten-foot tall cholla cactus. The grand mean detection range for all obstacles was 57 feet. Variability among subjects was also large. For example, subjects' detection ranges for the large cactus ranged from 31 to 321 feet.

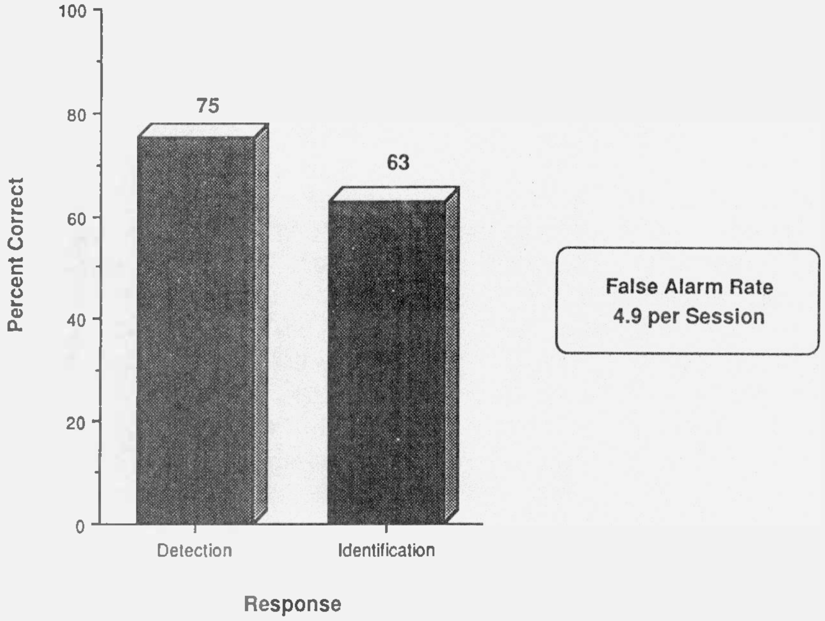

Figure 11 - Search Performance

Typically, the standard deviation for detection ranges of a given obstacle was about 50 percent of the mean. The large variability in detection range data made analysis using parametric techniques somewhat difficult, and the fixed effects of camera and technique somewhat inconsistent.

The frequency histograms of the detection range data show positively skewed distributions, that is, the majority of the responses fell in the short distances (from 0 to 50 feet) with decreasing numbers of responses at longer distances (see Figure 12).

A logarithmic transformation of these data decreases the impact of the few, very long detection ranges on central-tendency statistics (such as the mean), stabilizes the variance, and results in producing a frequency histogram that is more normally distributed (see Figure 13). Both of these effects improve the validity of parametric inferential statistics such as an analysis of variance (ANOVA). Several of the results reported below are based on transformed detection range data.

Analyzing the effect of camera used on obstacle detection performance, inconsistencies in individual obstacle data become evident. For example, the big cactus demonstrated large camera effects in one direction (black and white=150 feet, color=190 feet, steering slaved color=242 feet), while a cable spool showed a modest increase in detection range for color over black and white (103 feet vs. 85 feet), but no benefit for steering-slaved color (90 feet). This may be due to the fact that the cactus was at a location on the course where the approach was curved enough for the steering-slaved camera to have a beneficial effect and the spool was not. However, when obstacles were divided on the basis of straight or curved approach, no consistent steering slaved advantage was found for obstacles on curved approaches.

When data from all 35 obstacles were combined, the large inconsistencies tended to neutralize each other, but the small differences in the same directions tended to accumulate. A two-factor ANOVA using ln(detection range) data showed a nearly significant difference due to camera (F=2.83, p=.07). Most of this effect was attributable to the difference between black and white (51.4 feet) and the two color conditions, color (59.9 feet) and steering-slaved color (60.3 feet), as shown in Figure 14. When data from both color conditions are combined, the black and white versus color difference becomes statistically significant (F=5.66, p=.02), demonstrating an average advantage of about 9 feet for color cameras.

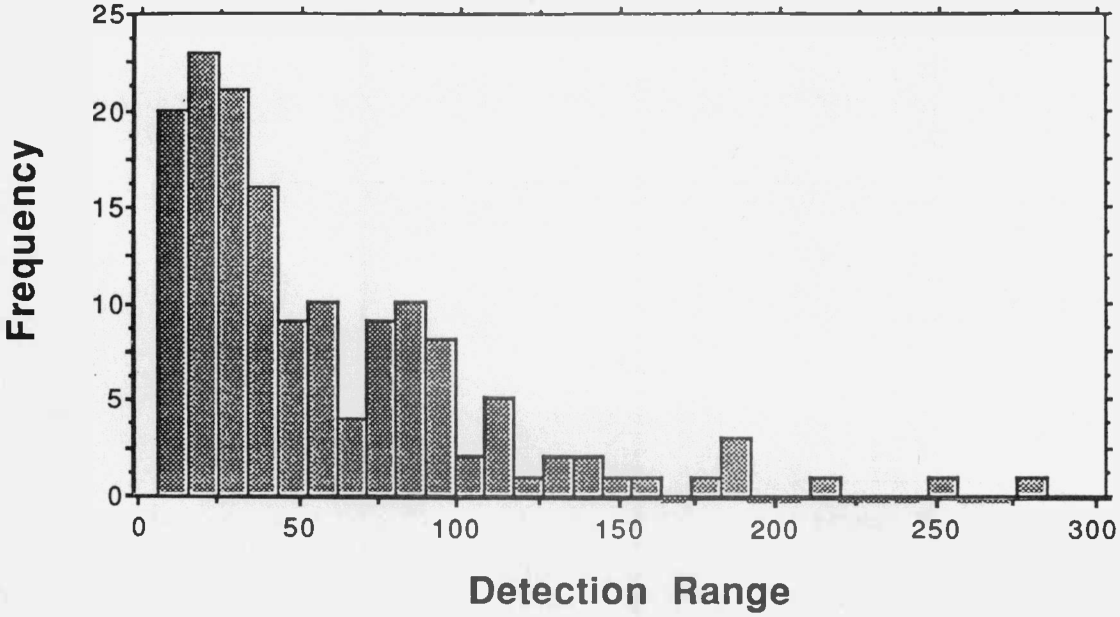

Figure 12 - Detection Range; Remote Driving, B&W Video

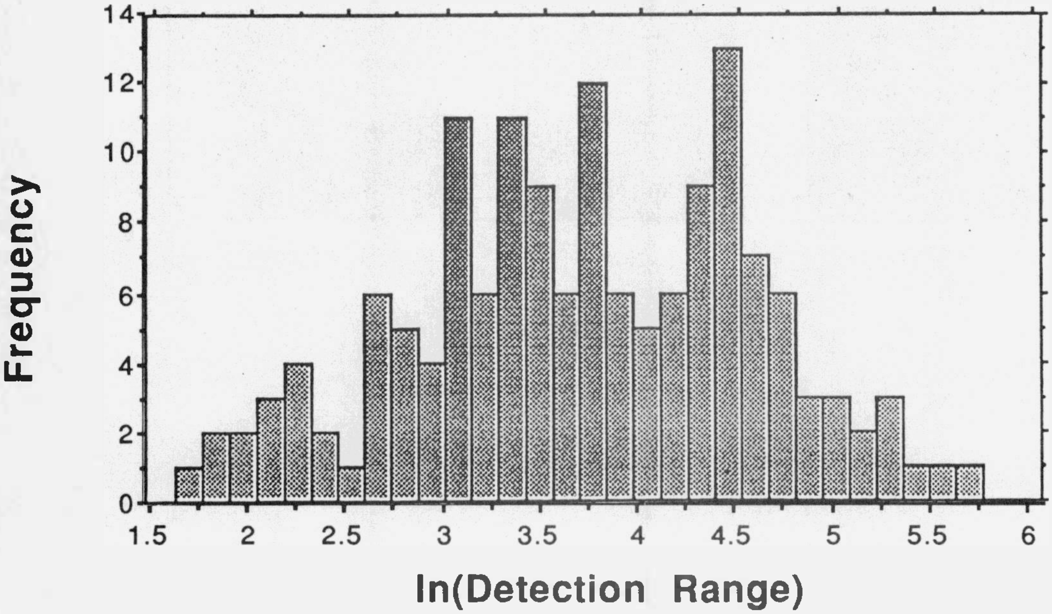

Figure 13 - ln(Detection Range); Remote Driving, B&W Video

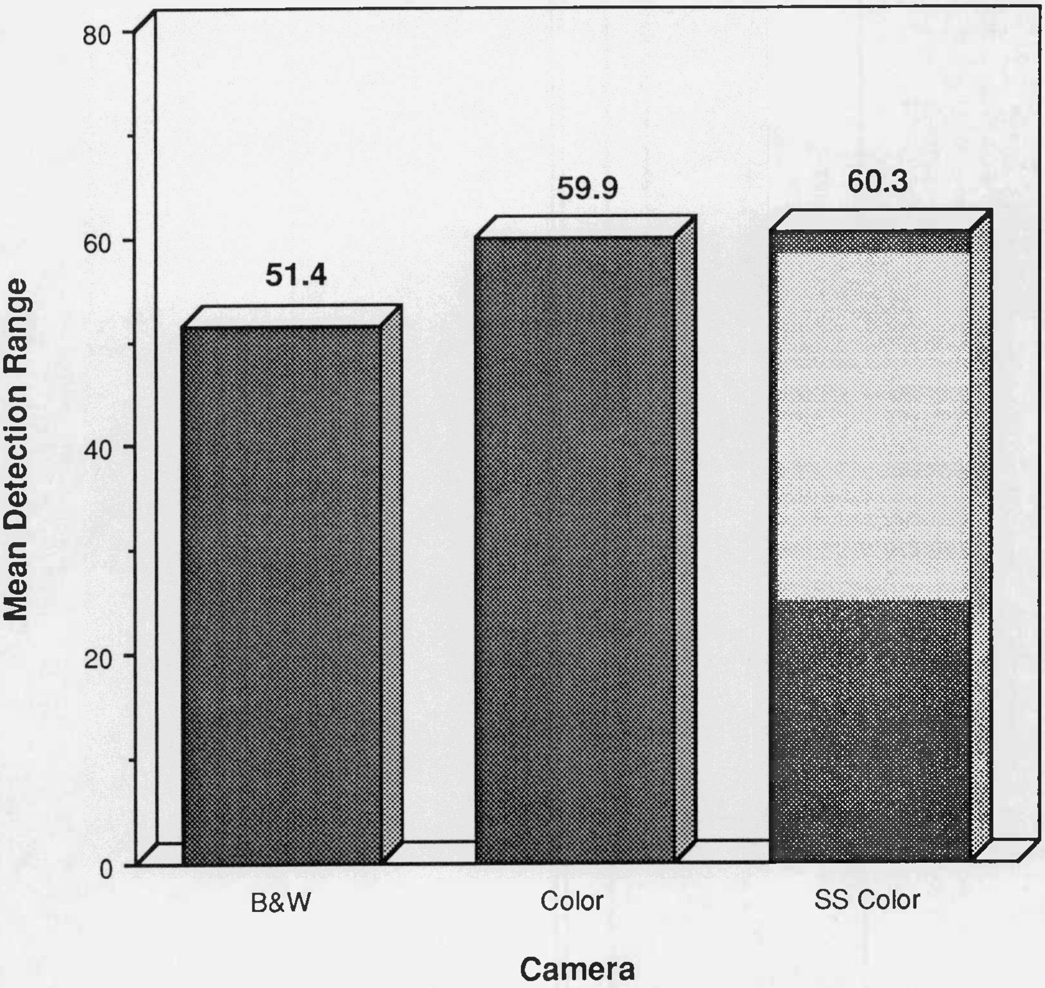

Figure 14 - Mean Detection Range; by Video System

Comparing overall means of detection range in the six experimental conditions, there was some indication of an interaction taking place between technique (simulation vs. remote driving) and camera (F=1.74, p=.2). This is shown in Figure 15. In simulation conditions, the camera effect monotonically increases from black and white (45.4 feet), to color (58.3 feet), to steering slaved color (63.6 feet). However, in the remote driving conditions, black and white (56.4 feet) and steering-slaved color (56.5 feet) are nearly identical, with color slightly better at 61.5 feet. The consistent color advantage confirmed apriori expectations, but the lack of a steering-slaved advantage was surprising. In retrospect, the mounting hardware for the steering-slaved camera introduced some jitter to the video image. As remote driving testing continued, the equipment acquired additional wear, and consequently, more jitter. This may explain the lower mean detection range for the remote-driving steering-slaved color condition, and hence the apparent interaction.

As expected, large obstacles were detected at longer mean detection ranges (90 feet) than smaller obstacles (40 feet), (F=186.7, p=.0001). The color advantage ranged from an average of less than 5 feet for smaller obstacles to an average of about 22 feet for large obstacles. Analyzing performance on large obstacles only, a significant camera effect was attained (F=3.52, p=.04) as shown in Figure 16. These results suggest that for subtle differences in vision systems, the use of large obstacles will provide the most sensitive comparisons.

This study did not validate the initial hypotheses that color video and steering-slaved camera control would be much better than either of the other test setups. In fact, the only conditions which showed a consistent, significant difference between any of the camera types and camera mount setups was for detection range of large objects. In that case, color allowed detection at a further distance (earlier while driving) but there was no significant difference between fixed mount color and steering-slaved color. For all other conditions, including target detection probability, location of objects around corners, sorting objects into specific type (rocks, gas cans, etc.) or into man-made versus natural objects, little difference was seen.

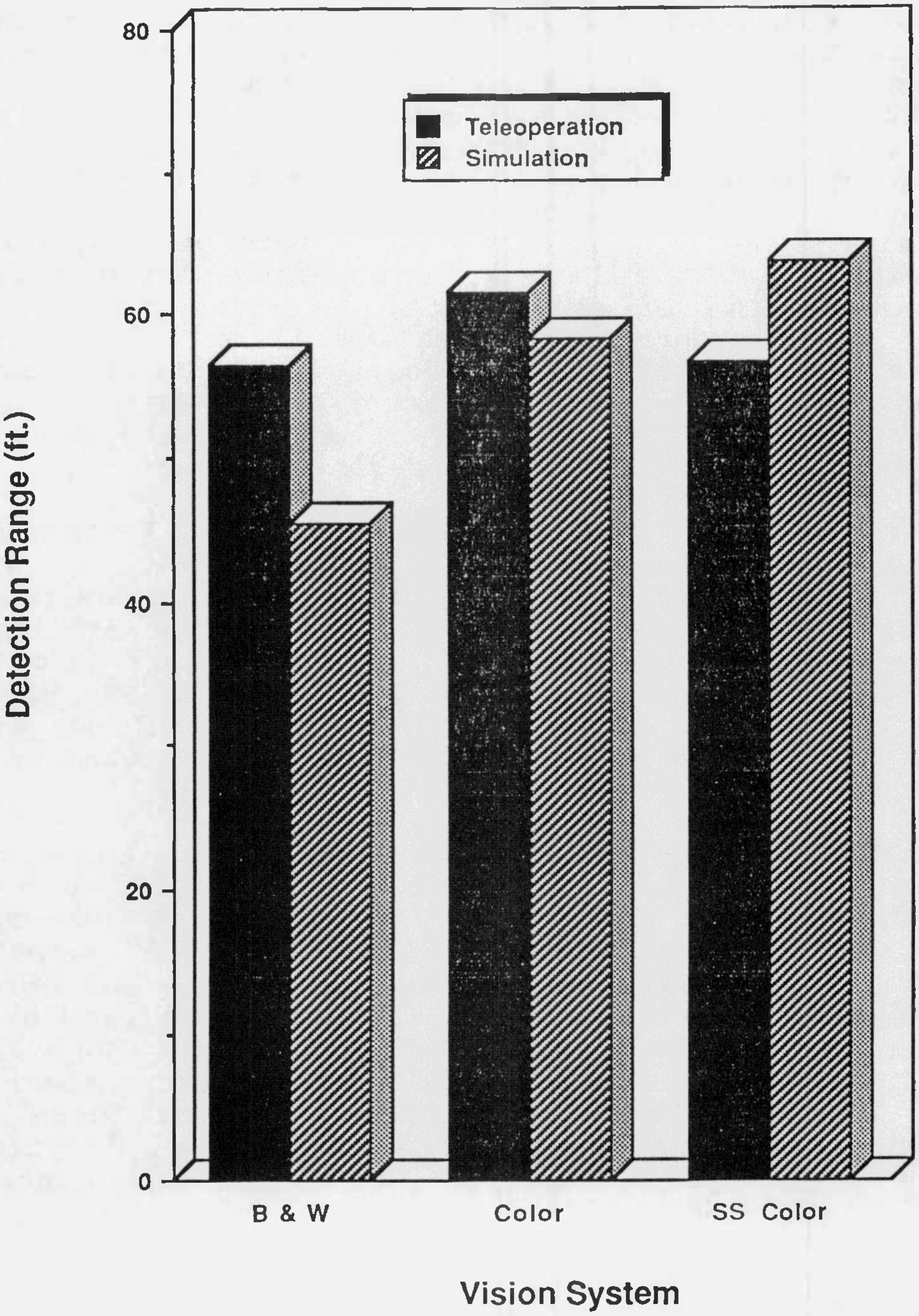

Figure 15 - Mean Detection Range; by Experimental Condition

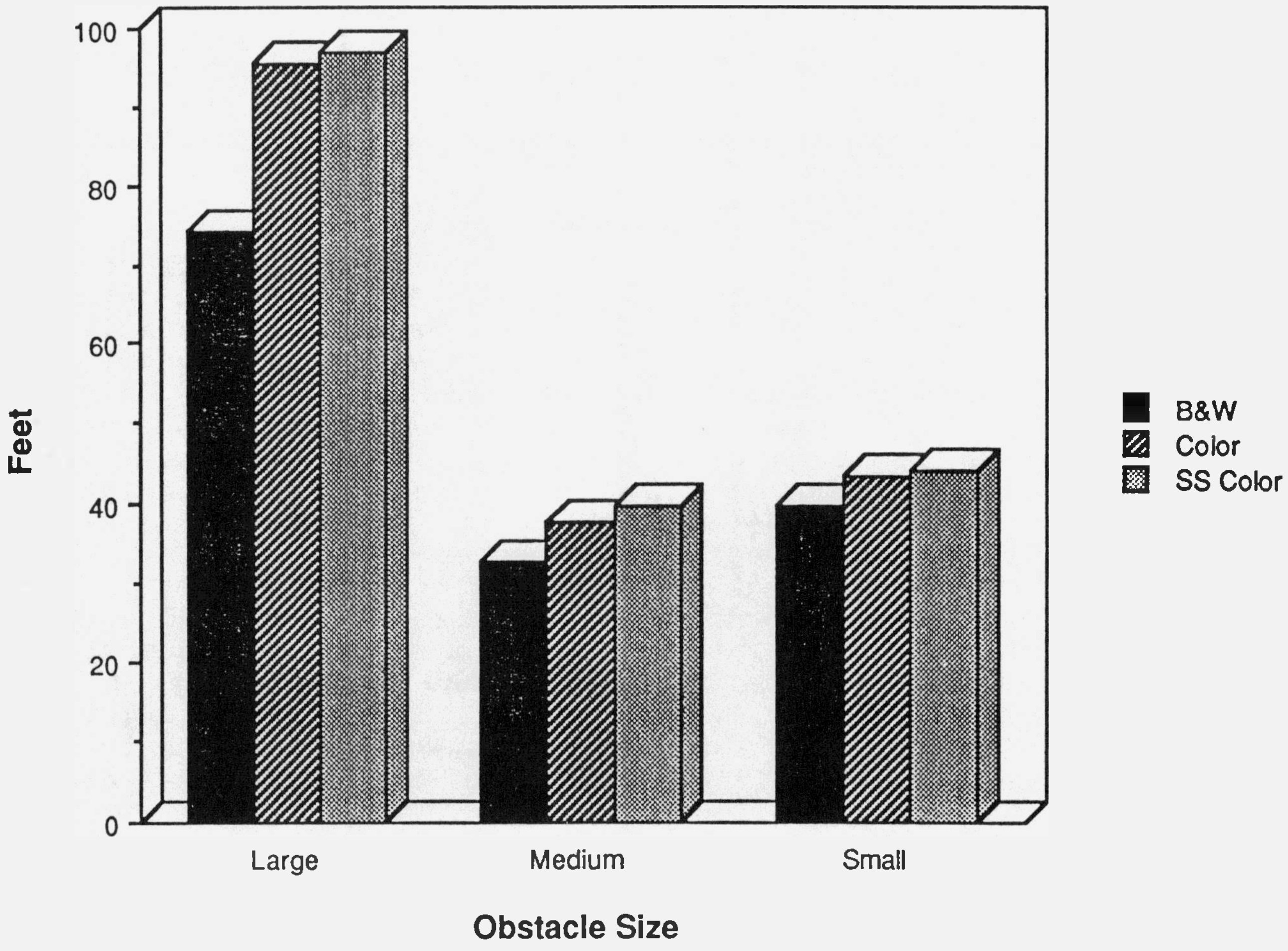

Figure 16 - Camera Effect; by Obstacle Size

REMOTE DRIVING/SIMULATION

As discussed above, the probability of obstacle detection showed no significant difference among any of the experimental conditions including simulation and teleoperation.

Investigating individual obstacles for differences in detection range between simulation and teleoperation shows mixed results. For example, the large cactus showed an advantage for remote driving (231 feet versus 161 feet for simulation). A large cable spool had similar results (155 feet versus 112 feet). The opposite result was shown by a large tire (66 feet detection range for teleoperation versus 110 feet for simulation). For the remaining obstacles, differences in technique were much smaller and had no apparent pattern in direction. It is not clear what caused these inconsistencies.

When data from all 35 obstacles were combined, the differences canceled each other, producing a mean of 57 feet (simulation) and 58 feet (remote driving). A two-factor analysis of variance using the logarithm of detection range yielded no significant difference between simulation and teleoperation (F=.375, p=.5). The similarity of performance in the simulation and teleoperation conditions, both in terms of probability of detection and mean detection distance, suggests that the noninteractive simulation technique can realistically measure visual performance on tasks associated with off-road vehicle teleoperation. It appears that the secondary task imposed on all subjects contributed to the success of the method by helping to equalize the workload across the simulation and teleoperation conditions. The mean number of responses (indicating that the operator had noticed that an instrument was out of range) was 19.4 per session for simulation conditions. For teleoperation, more attention was devoted to the driving operation and the instrument out-of-range responses dropped to less than 1 per session.

Based on the experimental results of this study, it can be concluded that the purely visual tasks of obstacle detection and identification can be extracted from the interactive driving activity and analyzed in a laboratory-based, noninteractive video simulation. Data gathered in this way have been shown to have a reasonable amount of validity when compared to data obtained from actual teleoperation.

The benefit of being able to gather data through simulation is the significant reduction in the amount of field testing required. The extent of this benefit is demonstrated by reviewing the time and effort necessary to gather the data for this study.

The testing discussed above was divided into two distinct phases. The simulation testing required less than two weeks to complete. A total of 21 subjects were tested (data from three of the subjects could not be used and was discarded prior to the analysis above). A single experimenter was required to interact with the subjects, run the testing, and collect data. Very few problems were encountered from equipment, procedures, or outside influences.

The relative lack of difficulty in performing the simulation testing contrasted markedly with the problems of teleoperation. Six weeks were required to test 18 subjects (with an additional two weeks of detailed preparation after conclusion of simulation but prior to the first subject.) A minimum of three people were required to run the tests. The experimenter worked directly with the subjects and collected data as before. The Jeep required a rider to monitor system status and to prevent damage to the vehicle. A range safety officer was necessary to insure overall safe operation.

During the six weeks of actual testing, problems with the vehicle included: failure of power steering hoses, vapor lock (requiring installation of an electric fuel pump), theft of gasoline, carburetor maintenance as a result of dirt in fuel lines, air conditioner failure (the air conditioner was required for onboard control electronics), and introduction of significant quantities of dust and dirt into the vehicle. Other problems included theft of some obstacles (over a weekend, in the middle of testing), growth of weeds and ground cover (which slightly modified the look of the course), fading of paint on obstacles, and displacement of course-marking cones due to wind and other traffic.

When problems of personnel availability, vehicle maintenance requirements, and ability to schedule subjects at a time when the Jeep and the weather would cooperate are included, field operations involving teleoperated vehicles are seen to be very costly compared to simulation.

DISTANCE/CLEARANCE ESTIMATION

Figure 17 illustrates the test columns in a typical placement. The columns are 8 inches in diameter and 54 inches high. Spacing between columns was 3, 5, 7, or 9 feet. This corresponded to two conditions which would block vehicle passage between the columns (3 and 5 feet) and two conditions allowing vehicle passage (7 and 9 feet). Sections of video tape were recorded using the Jeep approaching the columns and stopping at set distances of 2, 4, 6, and 8 vehicle lengths from the columns. All 16 combinations of spacing and distance were taped. Measurements were made

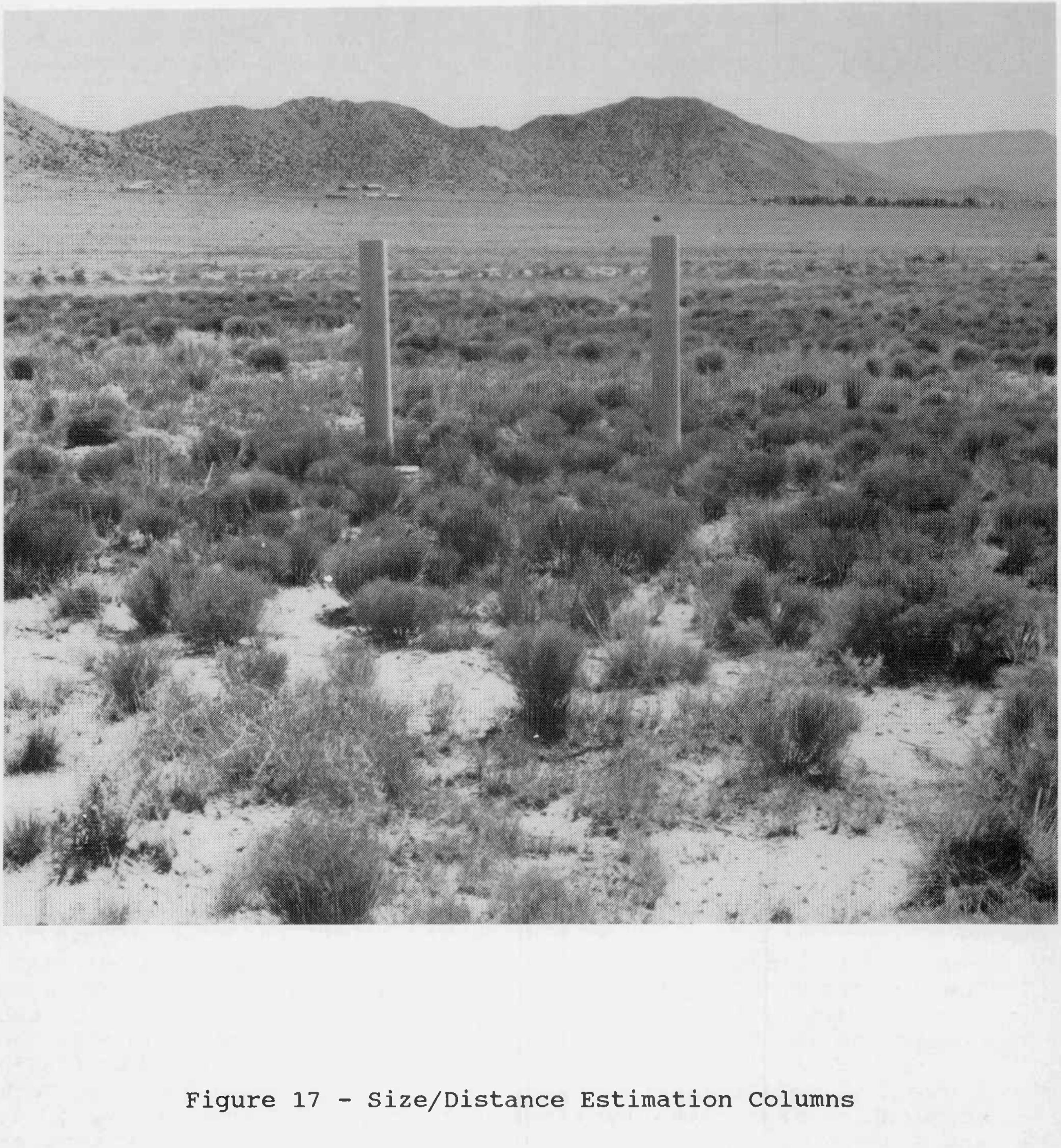

Figure 17 - Size/Distance Estimation Columns

in vehicle lengths (15 feet for the Jeep) since it was anticipated that subjects would have difficulty judging distances in feet or yards.

Thirteen subjects participated in the black and white condition, while 25 experienced color video, for a total of 38 subjects. A between-subject design was used as a carry-over from the obstacle-avoidance part of the study. The imbalance in group size resulted from combining two of the three groups who participated in the obstacle-avoidance tasks.

Distance estimates ranged from 1 to 50 vehicle lengths over the various conditions and subjects. Mean distance estimates were longer than actual distances, and the amount of overestimation increased with distance (Figure 18). Mean distance estimates and inter-subject variability were larger in the color condition than in the black and white condition at all four distances. Due to heterogeneous variance between conditions and positively skewed frequency distributions of distance estimates (Figure 19), a logarithmic transformation was performed on the data (Figure 20) to better satisfy the assumptions underlying an ANOVA. A one-factor ANOVA found significant differences between the means of transformed distance estimates for the two video conditions of black and white and color (F(1,36)=4.3, p<.05). When considering the four distances individually, statistically significant differences were attained only at the 2-vehicle length

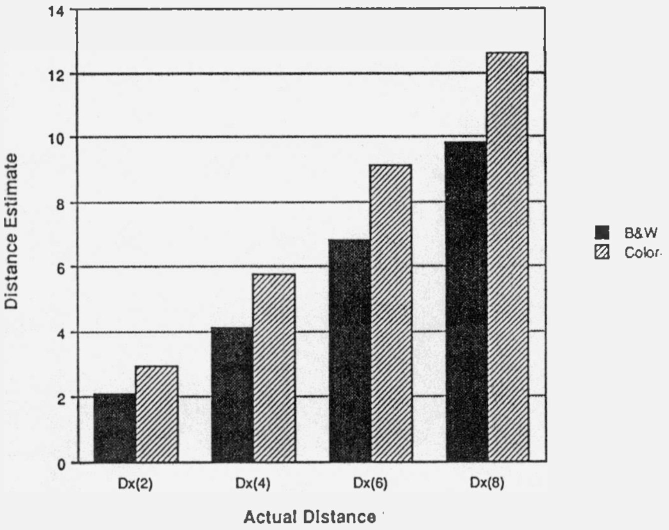

Figure 18 - Mean Distance Estimates

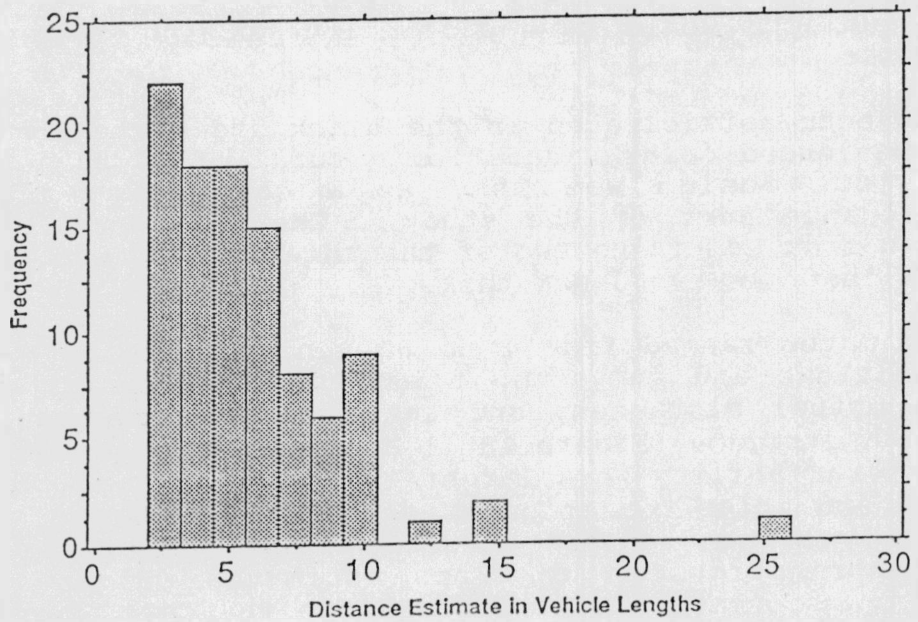

Figure 19 - Distance Estimates; Color, 4 Vehicle Lengths

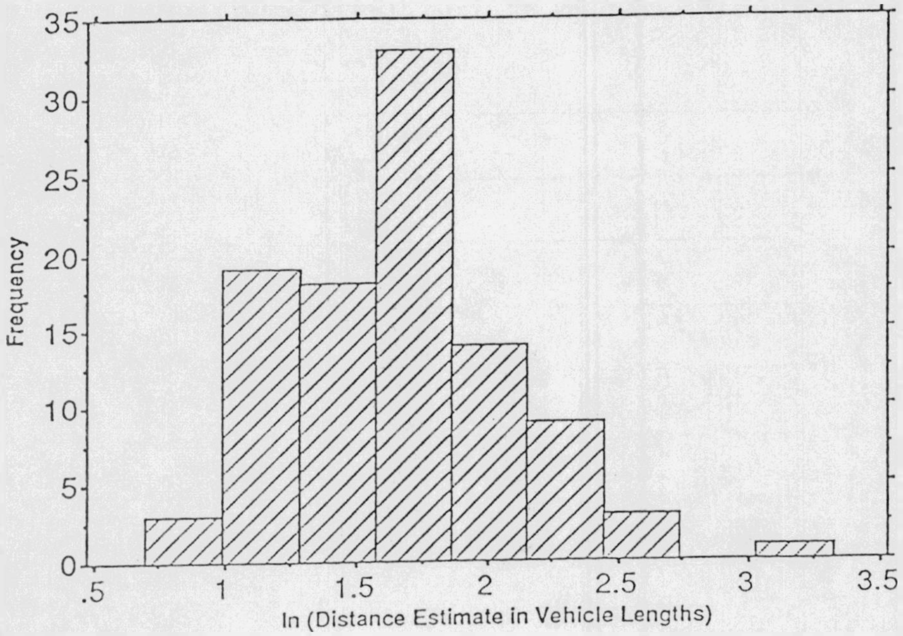

Figure 20 - ln(Distance Estimates); Color, 4 Vehicle Lengths

(F(1,36)=7.2, p=.01), and 4-vehicle length distances (F(1,36)= 4.8, p<.05). Response variability increased with actual distance, precluding significant differences at the two longer distances.

Because several subjects gave unusually long distance estimates, which might exert undue influence on the summary data, responses were categorized as correct estimates, underestimates, or overestimates for further analysis. Overall percentage correct was low (21%) since subjects had to estimate the exact number of vehicle lengths to be scored as correct. Even though responses were in 15-foot increments (the given vehicle length), one out of five correct is an indication of the difficulty of the distance-estimation task. Overestimates were the predominating responses, representing 58%, while underestimates accounted for the remaining 21%. When responses for all four distances were combined, subjects in the color condition evidenced a greater tendency to overestimate distances. Figures 21 and 22 show the distributions across subjects of percent overestimates. The graphs demonstrate how subjects in the color condition tended to make more errors overestimating distance than their black and white counterparts, though there was a great deal of variability within both groups. The overall percentage of responses that were overestimates was greater in the color condition (64.5%) than in the black and white condition (45.9%).

Since clearance estimates were simple binary judgments, more correct responses were made while estimating clearance (81.3%) than in estimating distance. Very few errors (underestimates) were made at the 9-foot separation (4 out of 151, for 2.6%). More underestimates (21) were made at the 7-foot separation (13.8%). A comparable number of overestimates were made at the 3-foot separation (15, for 9.8%). Most of the clearance judgment errors (overestimates) were made at the 5-foot separation (74, for 48.7%). Clearance estimation errors increased with distance from the columns as shown in Figure 23. The color condition again showed a greater percentage of errors as overestimates (89.6%) than the black and white (54%).

Column height estimates ranged from 3 to 12 feet, and averaged 5.8 feet. Mean height estimates for subjects in the color condition (6.3 feet) were significantly larger than those in the black and white condition (5.0 feet), (F(1,35)=4.79, p<.05). Diameter estimates ranged from 4 to 18 inches, and averaged 10 inches. Unlike the height estimates, there was no difference in mean diameter estimates for the two conditions. Size estimates correlated positively with distance and clearance biases, the strongest of which was the correlation between subjects column-height estimates and their net sum of clearance overestimates (R^2=.439), as shown in Figure 24.

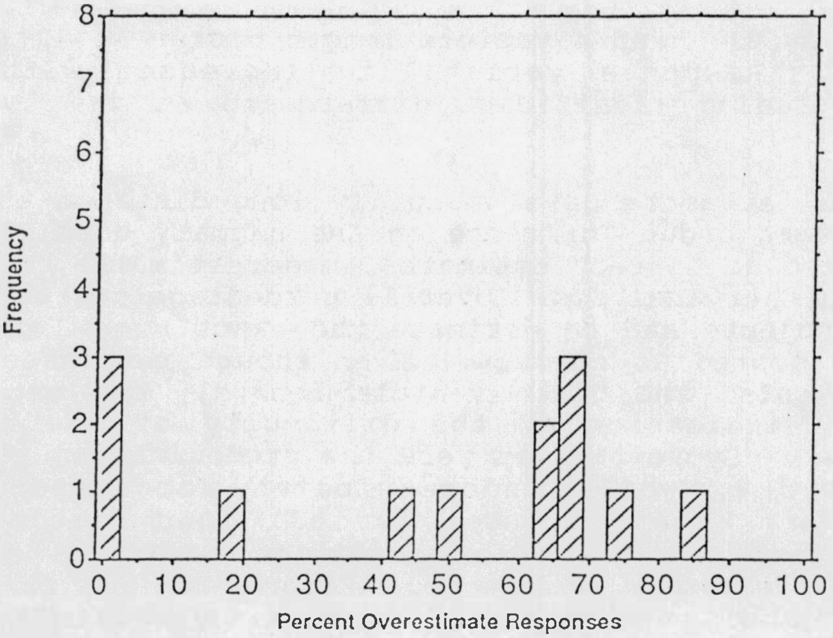

Figure 21 - Percent Overestimates; 13 Subjects, B&W Video

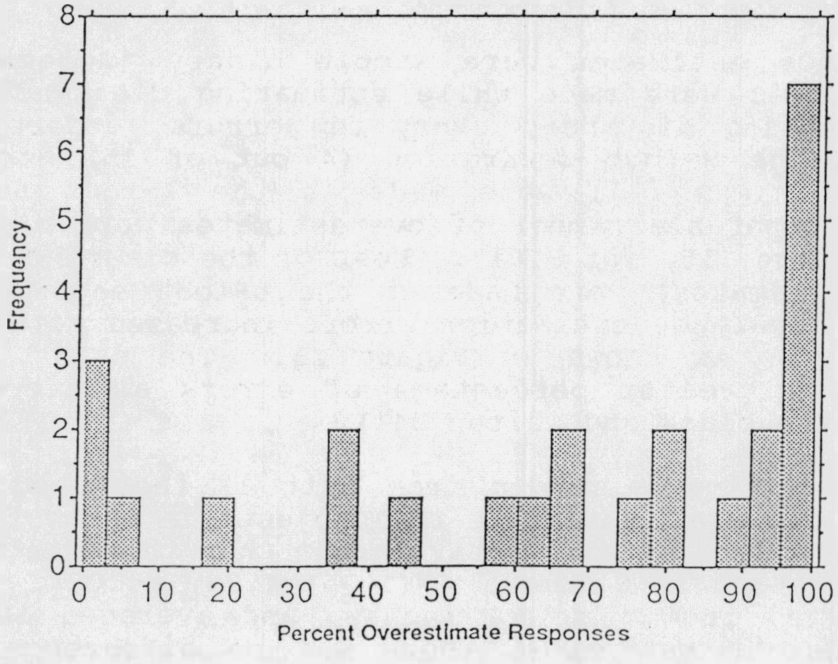

Figure 22 - Percent Overestimates; 25 Subjects, Color Video

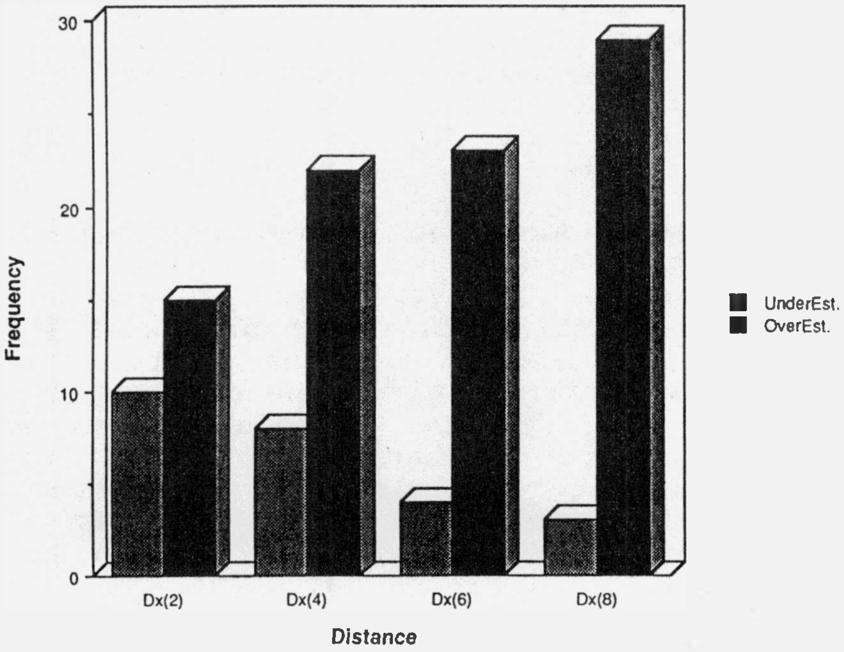

Figure 23 - Clearance Judgment Errors

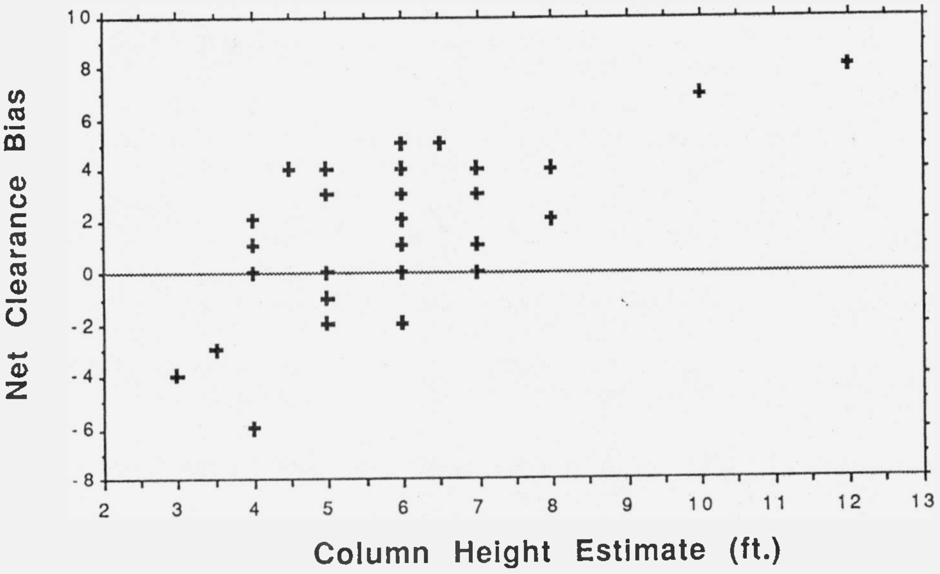

Figure 24 - Clearance Bias and Column-Height Estimates

The preponderance of overestimates in all three data categories, and their positive correlations among subjects, demonstrated a constancy in the perception of the columns using the video system. That is, if the columns are perceived as being larger than truth, their separation will likewise seem larger, and given their projected size on the CRT, they must be farther away (than truth) to look so small.

Distance and clearance estimation performance degraded as a function of increasing distance from the columns. As distance increased, the magnitude of overestimating distance increased, suggesting a power-function relationship between actual distance and perceived distance with an exponent greater than 1.0. These results were not surprising, given the documented phenomenon of minification when judging sizes and distances using video systems. Another contributing factor may be that most people no longer drive "full sized" vehicles, and that their true, internal, vehicle length response unit is shorter than 15 feet, causing them to overestimate the number of vehicle lengths between them and the columns. A similar argument can be made for the high number of overestimates of clearance at the 5-foot separation. The gap can either be perceived as larger, or the requirement for clearance can be perceived as being smaller, as when driving a subcompact automobile.

The differences in performance between subjects using black and white and those using color video were internally consistent, in some cases statistically significant, and surprising. Color video elicited longer distance estimates, higher percentages of clearance overestimates, and larger column-height estimates. This was investigated in another study [11] which looked at differing foreground characteristics. A different video system was used (higher resolution and slightly narrower field of view) with foregrounds of mesa (similar to that for the testing reported above), grass, and freshly graded, smooth dirt. Color, in the more recent study, was not a strong influential factor in distance estimation. Color estimates were slightly longer than black and white in the mesa condition but the differences were small. There were several other findings regarding clearance estimation, distance judgment, column size estimation, and absolute (direct, without CCTV) performance which tended to contradict the results of the study being reported here. The magnitude of the effects was small, however.

The results of this part of the study may have considerable impact on the design of teleoperated land vehicles. When remote drivers overestimate distances and clearances, they will tend to drive "nearsighted", that is, get too close to obstacles before correcting their route, and attempt to drive through gaps that are too narrow for passage.

QUESTIONNAIRE DATA

The questionnaire (Appendix A, pages A-9 and A-10) provided subjective data regarding the video systems, remote driving, and the test procedures. The data from the questionnaires was generally consistent regarding the desirability of visual system features. When asked to rate the three cameras on a scale of 1-10, subjects in both the simulation and remote driving conditions gave higher ratings for color (6.6) and steering slaved color (6.1) than for black and white (4.2), (F=20.4, p=.0001). Since there was no difference between the ratings for color and steering-slaved color, the effect can be attributed solely to the presence of color.

Independent evaluations of the features of color and steering-slaving resulted in the judgments that color was a more desirable feature (Chi Squared=15.7, p<.002). No differences were found to exist between simulation and remote driving groups. Figure 25 illustrates this, showing the frequency subjects responded that color or steering-slaved mounting was {unnecessary, desirable, highly desirable, or necessary}.

The preference for color was consistent with the experimenters' expectations. The limited perceived value of the steering-slaving feature was surprising. Previous experience at Sandia had suggested that the steering-slaved camera would be a significant improvement over a fixed camera in remote driving applications. Two factors may have contributed to this outcome. First, the mounting hardware for the steering-slaved camera introduced some jitter to the video image. Second, the subjects were asked to evaluate the two features in the context of searching for potential obstacles. It is likely that higher ratings would have resulted if subjects operated and were asked about this feature in a context stressing vehicle maneuverability.

When asked if they would prefer to have a wider or a more narrow angled lens on the camera, remote-driving subjects responded wider, and simulation subjects responded narrower on a 10-point scale (F=7.6, p<.001), as shown in Figure 26. There was also a nearly significant indication that subjects in the steering-slaved-color condition preferred a narrower lens, while those in the fixed-camera conditions indicated a preference for a slightly wider lens (F=2.7, p=.1). These results make logical sense in that subjects who actually performed remote driving would be more sensitized to problems associated with navigating through the course, while simulation subjects would be more concerned with the visibility of detail and hence the magnification of potential obstacles. Likewise, subjects using the steering-slaved camera

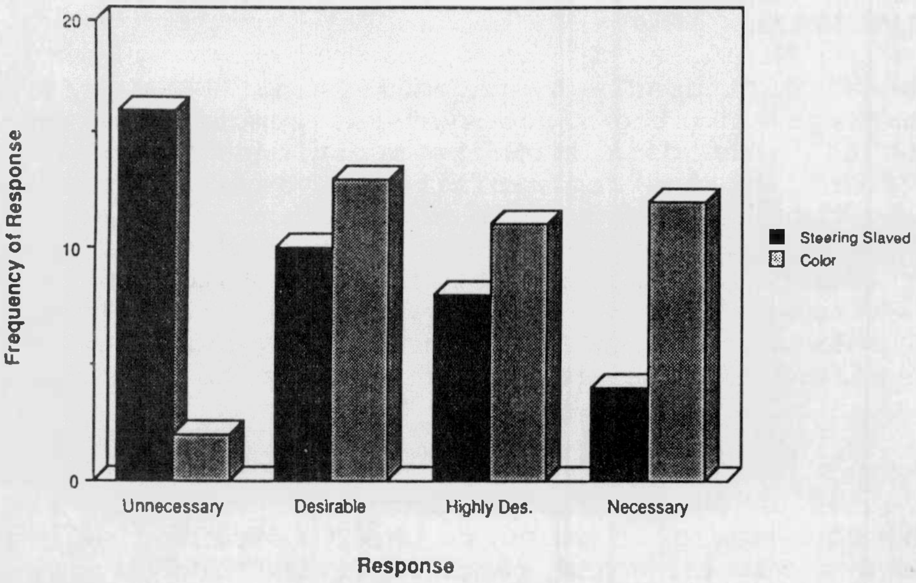

Figure 25 - Feature Desirability

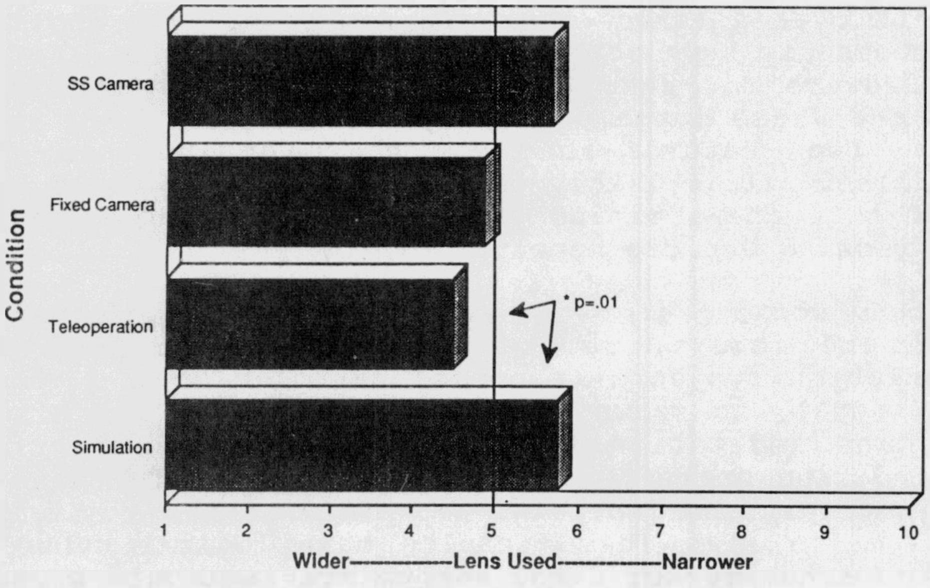

Figure 26 - Subject Lens Preference

might feel that the effective horizontal field of view was adequate, whereas those using fixed cameras might prefer a wider view of the terrain than that provided in the study.

A series of subjective questions were included on the questionnaire to gather information on which objects were perceived to be the easiest to see, the objects which were the most difficult to see, whether the subject felt any motion sickness, etc. Detailed response data are included in Appendix D.

The cable spools, railroad ties, tires and other large or man-made obstacles were indicated as the easiest to identify. Rocks were almost universally chosen as the most difficult objects to identify. This is telling in that artificial foam rocks were used to prevent vehicle damage. Interestingly, railroad ties, tires, and ditches appeared on both lists.

Most subjects indicated that the restriction in field of view and the rate at which the camera panned over the terrain resulted in some difficulties during turns. Not being able to see into the turns was cited as a problem a number of times. The slow steering response of the Jeep was referenced as a problem a number of times by subjects performing the remote driving task.

Very few subjects responded that they had experienced any motion sickness during the testing. Only one subject responded that any discomfort was felt during the simulation testing. Five remote driving subjects indicated some level of motion sickness. (No one was observed to be getting sick by the experimenters.)

When asked for recommendations on additional feedback, sound was a very frequent response. This was suggested as useful to convey information on vehicular status, engine sound for acceleration and deceleration, suspension noise, tire noise, and the clunking sound of rocks being hit.

More or better video was suggested almost as often as sound. Suggestions included more cameras, a selection of lenses, higher resolution, and better color.

Motion or force feedback from the vehicle was identified as a possible improvement by five subjects. Chairs that replicated vehicle motion, force feedback for the steering, and pedals with proper resistance to motion were all suggested.

Additional comments on the experiment itself included requests for additional training, relocation of controls and displays, and improvement in video and control quality. In general, the experiment was well received by the subjects. Several requested the opportunity to participate again, if possible.

CONCLUSIONS AND DISCUSSION

This study did not support some of the initial hypothesis regarding the relative quality of the three chosen vision systems. Further, the magnitude of differences seen between systems was smaller than the differences between subjects. Each subject was, however, internally consistent. That is, the pattern of answers from any single subject remained roughly the same throughout the testing. If subjects under-estimated some distances, most distances were under-estimated. The variability between subjects was typically more than the variability of any one subject's range of answers. This indicates that operator training could be a powerful aid in remote-driving performance.

The study did validate the notion that purely visual tasks can be extracted from the interactive driving activity and analyzed in a laboratory-based, noninteractive simulation. With some modifications and refinements, the simulation approach could be a very cost-effective method for future evaluations of numerous parameters of vision systems for teleoperated off-road vehicles.

Object and obstacle detection was not sensitive to camera differences. That is, the probability that an object would be seen was independent of the video system being used. This did not support the initial hypotheses that color and steering-slaved camera control would result in superior operation. Objects were detected as well with a fixed, black and white camera.

Range data were sensitive to camera differences. When objects were detected, they were detected at a greater range when color was used. Color provided a fairly consistent 5 to 20 foot range advantage when compared to black and white video.

There was no experimental evidence that steering-slaved camera mounting provided any benefit to the subject. This is in direct contradiction to the subjective results of a considerable amount of remote driving experience. The explanation may lie in several different areas. The steering-slaved system used on the Jeep for this testing introduced some jitter into the video, reducing the quality of the displayed video. This may have reduced the anticipated advantage of steering-slaved mounting. The camera was mounted higher than on the system that has provided most of the experience in remote driving. This combined with different steering ratios and different driving requirements (terrain and path marking) may have affected the utility of steering-slaved mounting. Finally, object detection is just one part of the overall activity involved in remote driving, so a lack of demonstrated advantage in object detection does not establish that there are no other benefits.

Simulation and remote driving results were similar enough to establish the utility of using video-tape based, part-task modeling in system development testing. The use of this type of simulation can significantly reduce the time and complexity of performing experimentation on vision systems.

Subject appraisals of the vision systems agree with the performance data and can be useful in evaluating various aspects of video performance. Subjects had a strong preference for color, which is reflected in the increased detection range. Steering-slaving was not considered necessary and the data show little advantage.

In conclusion, the results of this study need to be interpreted as one part of the overall task of remote driving. Operators of remotely driven vehicles need to detect and identify obstacles, as tested in this study, but also must be able to perform avoidance maneuvers, alter routes, make judgments regarding vehicle speed and operational limits, and perform useful mission-related activities. Lack of strong effects of color or black and white video or camera mounting type in the object detection task does not establish that there will not be effects on one of the other driving requirements. The absence of strong effects, and the large subject variability, does, however, indicate a need to continue research so that system design choices are made based on firm system performance requirements and not just on subjective judgments.

REFERENCES

1. H. B. Meieran, "A Compendium on Mobile Robots Used in Hazardous Environments", EPRI NP-5060, prepared for Electric Power Research Institute, 3412 Hillview Avenue, Palo Alto, California, by HB Meieran Associates, 458 South Dallas Avenue, Pittsburgh, Pennsylvania, May, 1987.

2. D. E. McGovern, "Advanced Technology Mobile Robotics Vehicle Fleet", SAND87-0033, Sandia National Laboratories, Albuquerque, New Mexico, March, 1987.

3. R. L. Pepper, "Human Factors in Remote Vehicle Control", 1986 Annual Meeting of the Human Factors Society, September 29-October 3, 1986, Dayton, Ohio.

4. E. H. Spain, "Assessments of Maneuverability with the Teleoperated Vehicle (TOV)", Fourteenth Annual Symposium of the Association for Unmanned Vehicle Systems, July 19-21, 1987, Washington, D.C.

5. D. E. McGovern, "Human Interfaces in Remote Driving", SAND88-0562, Sandia National Laboratories, Albuquerque, New Mexico, March, 1988.

6. D. P. Miller, "Evaluation of Vision Systems for Teleoperated Land Vehicles", <u>IEEE Control Systems Magazine</u>, 1988, <u>vol. 8</u>, no. 2, pp.37-41.

7. D. P. Miller and D. E. McGovern, "A Laboratory-Simulation Approach to the Evaluation of Vision Systems for Teleoperated Vehicles", <u>Proceedings of the Ergonomics Society's International Symposium on Teleoperation and Control</u>, Bristol, England, July 1988.

8. D. P. Miller, "Distance and Clearance Perception Using Forward-Looking, Vehicular Television Systems", <u>Proceedings of the Human Factors Society, 32nd Annual Meeting</u>, Santa Monica, California, October, 1988.

9. D. P. Jones, "Jeep Cherokee Mobile Robotics Testbed Vehicle", SAND87-0394, Sandia National Laboratories, Albuquerque, New Mexico, 1987.

10. J. D. Morrow, "Measurements of Jeep Steering Control System", memo to internal distribution, Sandia National Labs, Albuquerque, New Mexico, November 12, 1987.

11. C. U. Smith and D. P. Miller, "Evaluation of Foreground Effects on Video Spatial Perception", SAND88-2596, Sandia National Laboratories, Albuquerque, New Mexico, in press.

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APPENDIX A

SUBJECT INSTRUCTIONS

SESSION INTRODUCTION

You are participating in a study designed to compare video systems for remote driving. As you know from experience with driving street vehicles, good vision is important for safe, efficient navigation. Although you will be using only one video system, your results will be compared with results obtained from other people using different video systems. These comparisons will help us determine how video system characteristics influence remote driving performance.

Your one-hour session today will consist of the following segments: First, we will verify your visual acuity with a standard eye test. Next, we'll go over to the driving station and get oriented to the controls and displays. You will then be shown some written instructions, and start a training run. After that, you will do four test runs with two-minute breaks between them. Next, you will observe some short video segments and make some distance and quality judgments. Finally, we will ask you to answer a brief questionnaire concerning your impressions of the tasks in the study.

Any questions? In order that your results compare realistically with others, we ask that you try your best throughout this session.

[please stop here and wait for the experimenter]

SESSION INSTRUCTIONS
for Simulation Conditions

In a few minutes you will be watching some video tape recorded from a camera mounted on the top of a vehicle travelling off-road. Each simulated driving run will last about 5 minutes and there will be 2-minute breaks between runs. Your primary task is to detect and identify large objects in the path of the vehicle which must be avoided in order to continue safely. Since the vehicle has a ground clearance of only 5 inches, anything larger than that, such as rocks, bushes, trees, and man-made objects, should be considered as an obstacle, and be reported. Also report any terrain features such as ditches, holes, intersecting roads, and ridges which may impede or slow down the progress of your vehicle. Do not bother reporting tall, flimsy objects such as weeds, as they would not impede your vehicle's progress. You will be able to anticipate which objects may be in the path of your vehicle by noting if they fall within the lane markers (white traffic cones). If an obstacle lies inside of the lane markers report it--if it lies outside the lane markers, don't report it.

Report when you detect (first see) what appears to be an obstacle within the lane by pressing the D key once. When you get close enough to identify the obstacle by name, say what it is out loud and press the I key to record your response. If you wish to correct an early identification that is incorrect, press the I key again and revise your description of the obstacle. Since the data of interest are the maximum distances at which you can detect and identify obstacles, be sure to hit the D key as soon as each obstacle becomes visible in the lane. Similarly, as soon as you can identify the obstacle, hit the I key and say out loud what it is.

If time permits, there is a secondary task to be performed simultaneously with detecting and identifying obstacles. Monitor the vehicle performance gauges on the left-hand CRT to determine if any value displayed exceeds its acceptable range (goes into the gray region). If you see any value of PITCH, ROLL, or SPEED outside its acceptable range, hold down the Black Button (found next to the steering wheel) until the value returns to the acceptable range.

To review responses:

Detect obstacle	D key
Identify obstacle	I key
Detect gauge reading out of tolerance	Black Button (hold until value returns to acceptable range)

Remember that your performance is based on your ability to see obstacles and out-of-tolerance gauge indications. Pay close attention to the driving video, since in a real remote driving situation a missed obstacle may defeat your mission.

Good Luck!

[please stop here and wait for the experimenter]

SESSION INSTRUCTIONS
for Remote Driving Conditions

In a few minutes you will be driving an off-road vehicle remotely by means of the controls at this driving station. Each driving run will last about 5 minutes and there will be 2-minute breaks between runs. The vehicle will be controlled by conventional means using pedals for acceleration and braking, and a wheel for steering. You will be able to navigate across the terrain by watching the video picture shot from a camera mounted on the top of the vehicle.

In addition to driving the vehicle safely through the course which is identified by white traffic cones on both sides, your primary task is to detect and identify large objects in the path of the vehicle which must be avoided in order to continue safely. Since the vehicle has a ground clearance of only 5 inches, anything larger than that, such as rocks, bushes, trees, and man-made objects, should be considered as an obstacle, and be reported. Also report any terrain features such as ditches, holes, intersecting roads, and ridges which may impede or slow down the progress of your vehicle. Do not bother reporting tall, flimsy objects such as weeds, as they would not impede your vehicle's progress. You will be able to anticipate which objects may be in the path of your vehicle by noting if they fall within the lane markers. If an obstacle lies inside of the lane markers report it--if it lies outside the lane markers, don't report it.

Report when you <u>detect</u> (first see) what appears to be an obstacle within the lane by pressing the <u>D key</u> once. When you get close enough to <u>identify</u> the obstacle by name, say what it is out loud and press the <u>I key</u> to record your response. If you wish to correct an early identification that is incorrect, press the I key again and revise your description of the obstacle. Since the data of interest are the maximum distances at which you can detect and identify obstacles, be sure to hit the D key <u>as soon as each obstacle becomes visible</u> in the lane. Similarly, <u>as soon as you can identify</u> the obstacle, hit the I key and say out loud what it is.

If time permits, there is a secondary task to be performed simultaneously with detecting and identifying obstacles. Monitor the vehicle performance gauges on the left-hand CRT to determine if any value displayed exceeds its acceptable range (goes into the gray region). If you see any value of PITCH, ROLL, or SPEED outside its acceptable range, hold down the <u>Black Button</u> (found next to the steering wheel) until the value returns to the acceptable range.

To review responses:

Detect obstacle	D key
Identify obstacle	I key
Detect gauge reading out of tolerance	Black Button (hold until value returns to acceptable range)

Remember that your performance is based on your ability to see and avoid obstacles and notice any out-of-tolerance gauge indications. Pay close attention to the driving video, since a missed obstacle may defeat your mission. Your speed is not critical, but try to keep moving at a pace you feel comfortable with.

Good Luck!

[please stop here and wait for the experimenter]

SIZE/DISTANCE ESTIMATION INSTRUCTIONS

Successful off-road navigation depends not only on avoiding obstacles, but also being able to judge distance and clearances between obstacles. This part of the study will evaluate your ability to judge distances using the same video system that you used earlier.

Each video clip will show the driving approach to two white vertical columns. At some point distant from the columns, the vehicle will stop. Your task is to judge the distance to the columns, and whether or not your vehicle could drive between the columns. Your vehicle is an old-style Jeep Cherokee, which is about 6 feet wide, and about 15 feet long. Since estimating distances in feet or yards is difficult, make your verbal responses in <u>vehicle lengths</u>. Be sure to respond quickly, as the next video clip will begin about 5 seconds after the vehicle stops. A total of 16 clips will be shown.

To review responses:

Distance to columns	Say "X" car lengths (where X is a single integer)
Clearance estimation	Say "Yes" or "No"

If you have any questions, ask the experimenter before you begin.

[please stop here and wait for the experimenter]

VIDEO SYSTEM COMPARISONS

Next, you will be seeing three segments of video tape, recorded using three different video cameras. One of these will look familiar since you used it earlier in the session. Each segment will last about one minute. During that minute, study the quality of the video as it applies to the remote driving task. Be sure to evaluate both the clarity of detail as it pertains to identifying objects, and the overall scene as it applies to navigating across the landscape. This is the final video task you will be performing. A short questionnaire will follow, which among other things, will ask you to comparatively evaluate the three video systems.

[please stop here and wait for the experimenter]

QUESTIONNAIRE

Name____ Date____________

Years experience in driving automobiles_____ Off-road driving___

Remote driving/flying experience________________________________

Do you wear corrective lenses?____ Prescription/Acuity score____

Do you have any color vision impairment?________________________

Evaluate each of the three video systems on overall quality for remote driving by circling the number corresponding to its quality level:

	Poor	Adequate	Excellent
B&W Fixed	1---2---3---4---5---6---7---8---9---10		
Color Fixed	1---2---3---4---5---6---7---8---9---10		
Color Slaved	1---2---3---4---5---6---7---8---9---10		

The width of the video scene or the angle of the horizontal field of view is determined by the lens on the camera. As you know, wide-angle lenses have a greater field of view than narrow-angle or telephoto lenses-but don't have as much magnification for detail. In relation to the lens used in the experiment, how could remote driving be made easier by picking a wider/narrower angle lens?

Much wider angle lens	lens used |	much narrower angle lens
1---2---3---4---5---6---7---8---9---10		

Fill in the blank by circling one of the choices:

Color video is_____________________ for off-road, remote driving.
[unnecessary, desirable, highly desirable, necessary]

A steering-slaved camera is________ for off-road, remote driving.
[unnecessary, desirable, highly desirable, necessary]

Which obstacles were easiest to identify?____________________

Which obstacles were most difficult?________________________

Explain any difficulties you may have had in the turns.__________

Did you experience any motion sickness during your session? If so, when?____________________________________

What additional feedback (such as sound, motion, more vision) would you recommend to improve off-road remote driving performance?____________________________________

What can we do to improve our experiment?____________________

Other comments?____

DEBRIEFING STATEMENT

Thank you for helping us with our study. We regret that we cannot give you any meaningful feedback on how well you did, or how your assigned video system compared with the other systems. When a Sandia Report gets written describing the study and its conclusions, we will put all of the participants on distribution.

It is important that our future participants perform the same tasks that you performed without the foreknowledge of what obstacles they might see. Therefore, we would appreciate it if you would not discuss the obstacles you saw with anyone that plans to be a participant in this study.

Thanks once again for your cooperation and support.

APPENDIX B

VISUAL SIMULATION TEST PROTOCOL

TMAP MOBILITY TESTING
VISUAL SIMULATION TEST PROTOCOL

INTRODUCTION

This test protocol applies to the mobility testing being performed by Division 5267 and Division 7223 under the TMAP program. The goal of this testing is to gain an understanding of how various CCTV hardware parameters affect remote driving performance. The approach is to gather data on the visual performance of operators while observing pre-recorded video scenes and while driving a vehicle from a remote driving station.

Testing is divided into two major categories: visual simulation and remote driving. The protocol for visual simulation testing is described below.

In this testing, subjects (S's) will be seated at a console, viewing videotapes. These display tapes will replicate the view provided from the Jeep Cherokee as it negotiates preplanned paths. The S will observe the video screen in order to identify obstacles. While performing this task, the S will also monitor vehicle performance measurements shown on a separate video screen. The S is to indicate when any of these measurements deviate from a defined range. The S's responses will be recorded on a subject response recording system. This system will directly record the computer monitor graphics on a videotape. An audio track will record operator verbal responses concurrently on the videotape. Keyboard responses will initiate a sequence of digital data recordings onto diskette for later analysis.

TEST SETUP

Subject (S) watches display on center monitor. Display is provided by the Jeep video display VCR (in center on top of console - set to PLAY). Vehicle status information (tilt, roll, speed and odometer) is displayed on the left CCTV monitor. Vehicle status information is directly recorded onto the subject response recording system (VCR on top of console on left side - set to RECORD). This VCR also records audio (subject comments). Subject button pressing responses are recorded in the computer.

TEST INTERFACES - VISUAL SIMULATION

Jeep video display system.

This video cassette recorder displays scenes recorded while the Jeep negotiates a planned path. Various conditions and paths will be used. This tape is used to PLAYBACK only. Speed is set at SP.

Response recording system.

This video cassette recorder copies information directly from the computer CRT. The audio track records subject verbal responses. Comparing the responses with the odometer data allows determination of the distance at which the subject identifies obstacles. This tape is used to RECORD. Speed is set at SLP.

Driving station recording system

This video cassette recorder is linked to a video camera. The camera is mounted such that the subject and driving station are in view. This tape is used to RECORD. Speed is set at SLP. Tape from this system will be saved if anything out of the ordinary happens. Otherwise, it will be reused during a later test session.

Computer monitoring system

The computer system provides two functions. First, it is the source of vehicle data corresponding to the conditions when the display videotape was made. This data is contained on the computer hard-disk. The computer must be instructed which data to use for each display videotape. No other handling is necessary.

Second, the computer stores the subject responses. This data is derived from the subject pressing specific buttons to mark distances at which obstacles are noticed and identified, and to record when vehicle status readings go out of range. It is automatically stored on the computer hard disk at the time of generation. At the end of each day's test session, this data is dumped to floppy diskette for later processing.

REQUIRED DOCUMENTATION

Visual Simulation Test Protocol
Subject Instructions - Visual Simulation
Object Identification Sheet
Size/Distance Estimation Response Chart
Questionnaire
Certificate of Appreciation
Test Log Book

PRELIMINARY SETUP - VISUAL SIMULATION

Review test schedule for conditions to be tested.

Power up the console.
Move the toggle switch at lower left (on the front panel, under the tabletop) to the "up" position. A set of time-delayed power relays will apply 110 Vac power to each of the three rack units which make up the console. This may take several seconds.

Inspect operator controls.
Make sure that the special "panic button" box is plugged in to the power supply, the power supply is turned on, and the control cable from the box is plugged into the special receptacle located under the tabletop. Note that visual simulation does not use the connector from the driving fixture. Make sure that the "Out of Range" label on the driving fixture is covered and the "Out of Range" label on the keyboard cover is exposed.

Reboot the computer.
Press <CNTRL>, <ALT>, and <DEL> simultaneously immediately before starting the lab simulation software. This is especially important if there has been any remote driving done on the system that same day, because a special configuration inside the computer is required for each of the two tasks (driving and simulation), and the ONLY way to be ABSOLUTELY SURE that the correct configuration exists is to restart or reboot the computer before attempting to load the software.

Start the computer.
After making sure the computer is ready, type <tmaptest> and press < ENTER > to start the lab simulation software.

Load blank videotape into response recording VCR.
Make sure the left VCR is ON. Load blank videotape into the left VCR and rewind to beginning. Set the VCR to RECORD and then put it in PAUSE. Zero the tape counter.

Check response recording VCR microphone.
Check the placement of the microphone. Make sure that the microphone power supply is turned on. Talk from the position of the subject, giving date, time, and experimental conditions (fixed color, fixed black and white, or steered color camera). Make sure that an audio signal is being received at the VCR. Set the response recording VCR to STOP.

Select, verify and load proper Jeep video display videotape.
Make sure the center VCR is ON. Load the videotape and rewind. Zero the counter.

Measure resolution.
Set the display VCR (center) to PLAY. Observe and record the resolution. Put the VCR on STOP.

Load blank videotape into driving station recording system.
Make sure the right VCR is ON. Load blank videotape into the right VCR and rewind to beginning. Set the VCR to RECORD and then put it in PAUSE. Check the camera aim. STOP the VCR. Zero the tape counter.

Review subject protocol.
Make sure that copies of instructions, questionnaires, and distance estimation score sheets are available.

CONDUCT OF THE EXPERIMENT - VISUAL SIMULATION

Greet S and read short explanation of experiment.

Perform visual acuity test.
Have S stand at place marked on the floor and read the eye chart. S should cover one eye and read the lowest line. Repeat for the other eye. Record the number of the line of the smallest figures read with one or less errors. If score is worse than 20/30 with either eye, worse than 20/20 with both eyes, or S has bifocals, reject. Thank S, give him a certificate and send him home.

Seat S at console.
Make sure S is seated correctly for visual distance criterion.

Have S read instructions.

Answer any questions.

Identify the test and subject.
At the computer's prompt ("Please input the realtime sensor data filename?"), type the filename to be used for the test run and press < ENTER >. Note that testdata filenames for these tests are (in order): TESTRUN1, TESTRUN2, TESTRUN3, TESTRUN4, TESTRUN5. Then at the prompt ("Please input the subject's name and number") type the test subject's initials and run number and press < ENTER >.

Start response recording system.
Set the left VCR to RECORD. This VCR should record continuously until the end of the simulation runs. Audibly identify the subject and test run (e.g., "Begin test PRK1").

Start driving station recording system.
Set the right VCR to RECORD. This VCR should record continuously until the end of the simulation runs.

Start Jeep display system.
Set the center VCR to PLAY.

Start test run.
The software and hardware should now be ready for a test. The computer should display: "Press <F1> to begin test...be sure to start the videotape at the same time." Press the "PLAY" button on the VCR FIRST...and verify that the tape is running and a picture appears. Press <F1> to start the software. Close the keyboard cover. The test run will begin when vehicle movement on the videotape is detected by the software.

Write down S responses.
Keep a log of object identifications using supplied form.

Perform 5 test runs.
At the end of each run, the computer will prompt "You have reached the end of the data....Press <ESC> to exit program; or press <Return> to restart". Stop the Jeep display system (center VCR). The response file will be saved to disk automatically. If more data is to be taken, select restart. You will be prompted for another data filename. Also, audibly identify the test subject, test conditions and run number for the response recording system. Allow 2 minutes break between runs.

In case of trouble, restart
If data and displayed video do not start at the same time, stop the test run. Rewind the Jeep video display tape (using the rewind while play) to find the start of the specific test session that did not start correctly. Restart the computer using <R>. This will restart the program using the previous subject identifications and filenames.

Stop response recording system.

Stop Jeep display system.
Rewind tape and remove from center VCR.

Stop driving station recording system.

Have S read instructions and perform distance-estimation run.
Insert Size/Distance Estimation videotape in center VCR. Rewind. When S has completed reading instructions, set VCR to PLAY. Record responses on form (supplied). Do not let S see form since it has the answers on it. Stop tape at end of 16th response. Ask S what size poles are. Record this on the response form.

Have S read instructions and view different vision conditions.
When S has completed reading, set VCR to play. One minute sections of video are recorded after the last distance estimation test. The visual conditions are, in order: fixed color camera, fixed black and white camera, steering slaved color camera. After last section (steering slaved), rewind tape and remove from VCR.

Give S subjective questionnaire.

Read S debrief statement and present certificate.

POST EXPERIMENT CLEAN-UP - VISUAL SIMULATION

Record any observations, comments, etc.

Rewind all videotapes and remove from VCR's.

Label response recording system video tape.

Label driving station video tape.

Exit from computer test program.
Exit the software program at the prompt (at the end of the last test run) by pressing < ESC >.

Store response data files (after last run of the day).
Reboot the computer by pressing < CNTRL >, < ALT >, and < DEL > at the same time. The computer will then restart. When the computer has finished the bootup process, the prompt " D> " will appear. Insert a blank, formatted diskette into drive A (the floppy drive on the LEFT), type "tmapbkup" and then press <ENTER>, to begin a datafile backup procedure. This will copy the data response files (used in reducing the test data) to a floppy disk in drive A. When the backup procedure is complete, remove the floppy disk, label it "TMAP backup disk:" and put the date on it (ALWAYS write on the label sticker BEFORE sticking it to the diskette), and store it in one of the diskette flip-files on the desk next to the driving station.

Power down the system (after last run of the day).
Flip the console power switch located at lower left (on the front panel, under the tabletop) to the "down" position. This will cut all power to the console.

Collect, verify labels, and file check lists, questionnaire and notes.

APPENDIX C

REMOTE DRIVING TEST PROTOCOL

TMAP MOBILITY TESTING
REMOTE DRIVING TEST PROTOCOL

INTRODUCTION

This test protocol applies to the mobility testing being performed by Division 5267 and Division 7223 under the TMAP program. The goal of this testing is to gain an understanding of how various CCTV hardware parameters affect remote driving performance. The approach is to gather data on the visual performance of operators while observing pre-recorded video scenes and while driving a vehicle from a remote driving station.

Testing is divided into two major categories: visual simulation and remote driving. The protocol for testing in each of these categories is described below.

This protocol supplements SOP 49600 8608 ("Safe Operating Procedure for Remote Controlled Vehicle Fleet (Range Safety)") and SOP 49300 8608 ("Safe Operating Procedure for Jeep Cherokee"). In cases of conflict, the appropriate SOP shall be followed

TEST SETUP

Subject (S) controls vehicle using steering wheel, brake and throttle pedals on the special driving fixture. S watches video from Jeep displayed on center monitor. Video is ported through Jeep video display VCR (in center on top of console - set to RECORD). Vehicle status information (tilt, roll and odometer) is displayed on left video monitor. Vehicle status information is directly recorded onto subject response recording system (VCR on top of console on left side - set to RECORD). This VCR also records audio (subject comments). Subject button pressing responses are recorded in the computer. Steering inputs are recorded on an analog data tape. An overall view of the driving station is recorded on the driving station recording VCR (VCR on top of console on right side - set to RECORD).

Since this testing requires remote operation of the Jeep, safety is paramount. A range safety officer will be positioned near the driving station. Barricades will be erected on the main dirt road through the area. Radio contact will be maintained between the range safety officer and the rider in the Jeep. No vehicle traffic will be allowed during Jeep teleoperation.

TEST INTERFACES - TELEOPERATION

Jeep video display system.

This videocassette recorder (center on top of console) displays and records scenes while the Jeep negotiates a planned path. Various conditions and paths will be used. This tape is used to RECORD. The audio track records subject verbal responses. Speed is set at SLP. This VCR is also used in the size/distance estimation tasks. For this, it is set to PLAY, using a prerecorded tape.

Response recording system.

This videocassette recorder (left on top of console) copies information directly from the computer CRT. The audio track records a signal indicating when obstacles reach the lower edge of the screen. This allows determination of true position of detection and identification. Comparing the responses with the odometer data allows determination of the distance at which the subject identifies obstacles. This tape is used to RECORD. Speed is set at SLP.

Driving station recording system.

This videocassette recorder (right on top of console) is linked to a video camera. The camera is mounted such that the subject and driving station are in view. The audio track records subject verbal responses. This tape is used to RECORD. Speed is set at SLP.

Analog data tape.

The steering wheel angle is recorded on the analog data recording system (to the right of the console). The resulting tape is stored for further analysis.

Computer monitoring system.

The computer system provides two functions. First, it is the source of the vehicle control program. This program converts operator inputs to vehicle commands and vehicle responses to operator displays. Displayed data includes pitch, roll, speed and odometer data. Second, the computer stores the subject responses. This data is derived from the subject pressing specific buttons to mark distances at which obstacles are detected and identified, and to record when vehicle status readings go out of range. It is automatically stored on the computer hard disk at the time of generation. At the end of each day’s test session, this data is dumped to floppy diskette for later processing.

REQUIRED DOCUMENTATION

Teleoperation Test Protocol
Subject Instructions - Teleoperation
Object Identification Sheet
Size/Distance Estimation Response Chart
Questionnaire
Certificate of Appreciation
Test Log Book

PRELIMINARY SETUP - TELEOPERATION - CONTROL STATION

Review test schedule for conditions to be tested.

Power up the console.
Move the toggle switch at lower left (on the front panel, under the tabletop) to the "up" position. A set of time-delayed power relays will apply 110 Vac power to each of the three rack units which make up the console. This may take several seconds.

Inspect operator controls.
Make sure that the special driving fixture (a portable pedestal with steering wheel and control pedals) is located in front of the tabletop and that it is plugged into the special receptacle located under the tabletop. The special "panic button" box used in visual simulation is not used for teleoperation and should be removed. Make sure that the "Out of Range" label on the driving fixture is covered and the "Out of Range" label on the keyboard cover is obscured.

Reboot the computer.
Press <CNTRL>, <ALT>, and <DEL> simultaneously immediately before starting the software. This is especially important if there has been any other testing done on the system that same day, because a special configuration inside the computer is required for each of the two tasks (driving and simulation), and the ONLY way to be ABSOLUTELY SURE that the correct configuration exists is to restart or reboot the computer before attempting to load the software.

Load blank videotape into response recording system.
Make sure the left VCR is ON. Check that speed is set at SLP. Load blank videotape into the left VCR and rewind it to the beginning. Set the VCR to RECORD, and then put it in PAUSE. Zero the tape counter.

Check response recording VCR microphone.
Make sure that the microphone power supply is turned on. Talk from the position of the subject, giving date, time, and experimental conditions (fixed color, fixed black and white, or steered color camera). Make sure that an audio signal is being received at the VCR. Set the response recording VCR to STOP.

Load blank videotape into Jeep video display system.
Make sure the center VCR is ON. Check that speed is set at SLP. Load blank videotape into the center VCR and rewind it to the beginning. Zero the tape counter.

Load blank videotape into driving station recording system.

Make sure that the right VCR is ON. Check that speed is set at SLP. Load the videotape into the right VCR, set it to RECORD, and then put it on PAUSE. Check the camera aim. Stop the VCR. Zero the tape counter.

Set-up data recorder

Turn on the analog recorder power. Load tape into the analog recorder. Zero the counter (only on the first setup) or note the tape counter reading in the log book. Check switches for proper set-up. Tape speed should first be moved to "load" followed by 15/16 ips. The input cable should be plugged into the channel corresponding to the test (Channels 1 and 3 can not be used). Subject 1 uses channel 2, subject 2 uses channel 4, subject 3 uses channel 5, subject 6 uses channel 7, etc. Note the channel number in the logbook. Input range for the selected channel should be set at 10 volts. Setting on the other channels (not in use) is not important. Meter slide switch should be on Rec. for the channel being used. Verify operation by moving the steering wheel while recording. Note: To start recording, press the play button (>) while holding the RECORD button down. Watch the meter while turning the steering wheel to make sure signals are present. Stop the recorder.

Verify voice link between control station and Jeep.

Check status of Jeep preparation.

The Jeep must be ready for remote driving prior to proceeding beyond this step.

Remind Jeep rider of set-up.

Engine running.
Computer running.
Strobe ON.
4WD engaged.
Emergency brake OFF.
Generator running.
Video xmitter powered.
Fuel pumps ON.
Hubs Locked.
Helmet on.
Clip board available (to record observations during rests).

Measure Jeep video resolution and camera angle.

Observe and record the resolution from the Jeep CCTV camera. Observe the camera pointing angle to make sure it is centered (side to side) down the center of the Jeep hood. Check to make sure that the correct camera is connected to video xmitter.

Review subject protocol.

PRELIMINARY SETUP - TELEOPERATION - FIELD

Review test schedule for conditions to be tested.

Set-up and inspect Jeep (according to SOP) for safety and operation.

Verify position of marker barricades.
Barricades (signs with prominent arrows) should be placed at the road intersections to direct the S as he is driving.

Erect barricades on main dirt road.
Barricades with warning signs should be placed on the main road, beyond the range of Jeep operations.

Verify voice link between control station and Jeep.

Verify 2-way data communication with Jeep and driving station.

Position Jeep for start of first run.

Initialize Jeep control program.

Report readiness to control station.
Engine running.
Computer running.
Strobe ON.
4WD engaged.
Emergency brake OFF.
Clip board available (to record observations during rests).
Generator running.
Video xmitter powered.
Fuel pumps ON.
Hubs Locked.
Helmet on.

Measure and record Jeep video camera resolution.
Observe and record the resolution from the Jeep CCTV camera. Observe the camera pointing angle to make sure it is centered (side to side) down the center of the Jeep hood. Check to make sure that the correct camera is connected to video xmitter.

CONDUCT OF THE EXPERIMENT - TELEOPERATION

Greet S and read short explanation of experiment and session.

Perform visual acuity test.

Have S stand at place marked on the floor and read the eye chart. S should cover one eye and read the lowest line. Repeat for the other eye. Record the number of the line of the smallest figures read with one or less errors. If score is worse than 20/30 with either eye, worse than 20/20 with both eyes at the same time or S has bifocals, reject. Thank S, give him a certificate and send him home.

Seat S at console.

Make sure S is seated correctly for visual distance criterion.

Have S read instructions.

Answer any questions.

Range safety officer to close range.

Barricades erected.

Verify with range safety officer that range is clear.

Start response recording system.

Shut off PAUSE on left VCR. Make sure it is in RECORD and the tape is running.

Start Jeep video display system.

Shut off PAUSE on center VCR. Make sure it is in RECORD and the tape is running.

Start driving station recording system.

Shut off PAUSE on right VCR. Make sure it is in RECORD and the tape is running.

Start analog data recording system.

Hold the record button and press play (>).

Identify the test and subject.

Audibly identify the subject and test run (e.g., "Begin test PRK1").

Start the computer.

After making sure that the computer is ready, type <tmapjeep> and press <ENTER>. The remote driving software will be loaded and initialized.

Identify the test and subject.

At the computer's prompt, enter the test subject's initials) and test run number (i.e. PRK2, DEM1, etc.). Be sure to enter the following data into the test logbook: Test subject name and run number, date, videotape numbers/names and tape counter readings at the beginning of the test run (this will allow data reduction personnel to find the appropriate spot on the correct tape for each subject's run). Calibrate the steering and brake/throttle pedals according to the instructions on the computer.

Verify radio modem communications.

A graphics display should appear on the computer monitor, signifying that the software is now running. Verify that the radio modem (located at the console's extreme bottom right, near the floor) has all of the red lights on the front lit up. You may notice that the TD and RD lights are blinking rapidly--this is normal. If all of the lights are not lit, this indicates a problem, and the software may have to be aborted and restarted. To abort the program and restart the computer press the <CTRL>, <ALT>, and <DEL> keys simultaneously. In order for the RD and TD lights to be blinking, the Jeep must have already been set-up and initialized. If the CD light is blinking or flickering, it means that there is a problem with radio communication between the Jeep and the control station. In this case DO NOT ATTEMPT TO DRIVE THE JEEP BY REMOTE CONTROL, because there is a distinct possibility that the vehicle's radios or computers are malfunctioning.

Cover computer controls.

Ensure that the special keyboard mask is in place on the computer's keyboard.

Verify Jeep rider is ready (radio).

Perform 5 test runs (allow 2 minutes break between runs).

Restart software by exiting using < F2 >. This saves the data to disk. Reboot computer and restart program for each run.

Write down S responses and log obstacles.

Keep a log of object identifications using supplied form. Watch the video images. As the object the S is referring to just leaves the scene, press the marker button to indicate true position. Obstacle position is the odometer reading at that point plus 7 feet.

Range safety officer observes range during testing.
Use the range camera pan and tilt controls to keep the Jeep in view on the range monitor. This is important since it also keeps the television antenna aligned.

After last test, inform Jeep rider that testing is complete.

Stop response recording system.

Stop Jeep video recording system.
Remove tape to prepare VCR for size/distance estimation test.

Stop driving station video system.

Stop analog data recording system.

Verify status of Jeep shutdown.
When testing is done, the vehicle must be shut down and secured BEFORE shutting down the driving station. This is because of certain safety features in the hardware and software which will activate when the Jeep is still running under computer control and the driving station is deactivated. For shutdown, the order of procedures is: brake/throttle actuator at null, steering drive sprocket set screw accessible, operate/override switch to override, control console to off.

Range safety officer to open range.

Have S read instructions and perform distance estimation run
Insert size/distance estimation videotape in center VCR. Set center monitor to correct condition (color or black and white). Rewind, When S has completed reading instructions, set VCR to PLAY. Record responses on form (supplied). Do not let S see form since it has the answers on it. Stop tape at end of 16th response. Ask S what size poles are. Record this on the response form.

Have S read instructions and view different vision conditions.
Check to make sure center monitor is displaying in color. When S has completed reading, set VCR to play. One minute sections of video are recorded after the last distance estimation test. The visual conditions are, in order: fixed color camera, fixed black and white camera, steering slaved color camera. After last section (steering slaved) rewind tape and remove from VCR.

Give S subjective questionnaire.

Read S debrief statement and escort from lab.

POST EXPERIMENT CLEAN-UP - TELEOPERATION - CONTROL STATION

Record any observations, comments, etc.

Rewind all videotapes and remove form VCR's

Label response recording system videotape.

Label Jeep video display videotape.

Label driving station recording system videotape.

Note tape counter number from analog tape recorder.

Exit from computer test program.
Exit the software program by pressing < F2 >.

Store response data files (after last run of the day).
Reboot the computer by pressing < CNTRL >, < ALT >, and < DEL > at the same time. The computer will then restart. When the computer has finished the bootup process, the prompt " D> " will appear. Insert a blank, formatted diskette into drive A (the floppy drive on the LEFT), type "tmapbkup" and then press <ENTER>, to begin a datafile backup procedure. This will copy the data response files (used in reducing the test data) to a floppy disk in drive A. When the backup procedure is complete, remove the floppy disk, label it "TMAP backup disk:" and put the date on it (ALWAYS write on the label sticker BEFORE sticking it to the diskette), and store it in one of the diskette flip-files on the desk next to the driving station.

Power down the system (after last run of the day).
Flip the console power switch located at lower left (on the front panel, under the tabletop) to the "down" position. This will cut all power to the console.

Collect, verify labels, and file check lists, questionnaire and notes.

POST EXPERIMENT CLEAN-UP - TELEOPERATION - JEEP

Remove barricades on dirt road.

Return radios to charging stations.

Record any observations, comments, etc.

APPENDIX D

SUBJECTIVE RESPONSES FROM QUESTIONNAIRE

QUESTIONNAIRE RESPONSES

The following is a verbatim listing of the written responses from the questionnaire. Questions have been re-stated for convenience. Responses are organized in groups related to the conditions experienced by the subject during the obstacle detection and identification testing. More subjects were tested than are represented in the objective test data discussed elsewhere. Not all subjects answered all questions.

Which obstacles were easiest to identify?

Simulation - Fixed, Black and White Video.
- Spools.
- Railroad ties.
- Tires, railroad ties.
- Tires.
- Railroad ties, 55 gal. drums.
- Ditches.
- Angular or man-made.

Simulation - Fixed, Color Video.
- Tires, trees.
- Tires.
- Big, logs, dark.
- Tire, barrel, ditch.
- Spools.
- Tires, spools.

Simulation - Steering Slaved, Color Video.
- Barrels (stumpy and black).
- Logs, tires, wire spools.
- Logs.
- Large regularly shaped objects.
- Logs. railroad ties.
- Logs, barrels.
- Tires (circular).

Remote Driving - Fixed, Black and White Video.
- Tires.
- Dark, man-made.
- 55 gal. drums and cable spools.
- Tires and spools.
- Man made (tires, barrel, etc.).
- Wire spools.

Remote Driving - Fixed, Color Video.
- Spool, tire.
- Tires.
- Tires, spools.
- Posts, tires.
- Drums, tires.
- Tall items, cactus, tires also because of color contrast.

Remote Driving - Steering Slaved, Color Video.
- Tires.
- Bright-colored, tires.
- Man-made (spools, drums, tires).
- Tires.
- Tire, rabbit, can.

<u>Which obstacles were most difficult?</u>

Simulation - Fixed, Black and White Video.
- Rocks.
- Rocks.
- Rocks - They blend in with dirt.
- Metal and rocks.
- Rocks.
- Rocks.
- Rocks, brush, debris.

Simulation - Fixed, Color Video.
- Rocks, washes (slight).
- Rocks.
- Rocks, ones colored the same as scenery.
- Stones, railroad tie.
- Rocks.
- Logs.

Simulation - Steering Slaved, Color Video.
- Low boxes and piles of rock (often looked like shadows).
- Rock.
- Rocks.
- Peripheral objects.
- Tires.
- Rocks (large) and small items.
- Low colored stones.

Remote Driving - Fixed, Black and White Video.
- Weeds.
- Low, natural.
- Rocks and bushes.

- Rocks.
- Ditches except at road junctions.
- Oil cans, other mechanical junk.

Remote Driving - Fixed, Color Video.
- Railroad ties, gas cans.
- Obstacles which blended into color.
- Gas cans.
- Rocks.
- Rocks.
- Rocks and ditches.

Remote Driving - Steering Slaved, Color Video.
- Rocks.
- Similar to surroundings.
- Rocks.
- Cactus.
- Rock, Wood.

Explain any difficulties you may have had in the turns.

Simulation - Fixed, Black and White Video.
- Without steering slave, I did not know what to expect coming through turns. With steering slave, camera would turn away too soon.
- Not being able to see what you are turning into.
- Obstacles came up quickly.
- Had none.
- Nothing noticeable.
- In turns, when you came upon any obstacle, you could not see far enough ahead.
- None.

Simulation - Fixed, Color Video.
- I was trying to look into the turn more than the fixed camera allowed.
- Wide angle lens would be useful in turns only.
- No peripheral vision.
- Couldn't see path of vehicle.
- Objects sweep into view (less preview time).

Simulation - Steering Slaved, Color Video.
- I forgot to identify crossroads and bumps (during the whole run). Since I was using the slaved camera, I had little difficulty in the turns.
- None.

- Smaller objects that were driven around were often hard to identify as the camera did not fix on them long enough.
- Sometimes you couldn't see if something might have been in the way right after you made the turn.
- Not clear, hazy, too jumpy.

Remote Driving - Fixed, Black and White Video.
- Turned too sharp at first.
- Vehicle response is difficult to determine by visual means alone. Also vehicle bump-steer caused tracking problems.
- Lag-time in steering response. I couldn't see what I was turning into. The slave camera eliminates this.
- None.
- Over-steering was a problem.
- I didn't find the turns difficult.

Remote Driving - Fixed, Color Video.
- Could not see "around corner". Steering lag nearly makes vehicle uncontrollable; especially at higher speeds.
- Oversteering.
- Steering.
- The steering lags too much and is too sensitive (for me).
- Loss of view in turning direction due to fixed camera.
- During very sharp turns the field of view could have been larger but for majority of the course it was fine.

Remote Driving - Steering Slaved, Color Video.
- Too much lag.
- Turns were not too difficult at slow speeds.
- Could not see enough of terrain in direction of turn.
- Would have preferred fixed camera.
- Lag time between steering and response. Not being able to see around corner.

<u>Did you experience any motion sickness during your session? If so, when?</u>

Simulation - Fixed, Black and White Video.
- No (7 subjects' response).

Simulation - Fixed, Color Video.
- No (5 subjects' response).
- No - maybe for the slaved.

Simulation - Steering Slaved, Color Video.
- No (5 subjects response).
- Yes. Black and white picture.
- No, but the films were frustrating.

Remote Driving - Fixed, Black and White Video.
- No (4 subjects' response).
- A little near the end of the course.
- Yes. In the last test (#5) and watching the other videos.

Remote Driving - Fixed, Color Video.
- No (4 subjects' response).
- Fatigue (during the last run). No motion sickness.
- Just a very slight amount at the end when I was not driving.

Remote Driving - Steering Slaved, Color Video.
- No (4 subjects' response).
- Yes, 1/2 way through.
- Yes, most of the time.

<u>What additional feedback (such as sound, motion, more vision) would you recommend to improve off-road driving performance?</u>

Simulation - Fixed, Black and White Video.
- Have the ability to zoom in on desired objects. Sound.
- More vision.
- Something to mitigate the vertical movement of the camera.
- Move gauges below screen (as in real car). Early morning and late evening shadows will be difficult (especially in black and white).
- Sound engine RPM, suspension noise to correct for too much speed.
- Selection of normal lens with wide vision controlled as needed.
- Sound would be useful for vehicular status.

Simulation - Fixed, Color Video.
- Scan side to side periodically.
- Motor sound (and gearing sound). Clunking sound if rocks are hit (to give indication of vehicle clearance).
- Sound, vision to the sides.
- Sound of truck.
- More detail.
- Make a chair that pitches and yaws with the vehicle; "seat of the pants" perception of vehicle attitude would be best for remote driver.

Simulation - Steering Slaved, Color Video.
- I think that two cameras would be nice, one for wide angle (detection) and then one narrow angle, slaved for identification.
- More vision (pan and zoom).

- Better color definition.
- I find it hard to make recommendations as I'm not positive as to what aspects of the experiment made the viewing difficult. I think that a camera that was less "jittery" would have helped.
- Sound would help to detect rough spots.
- Sound of accelerating engine. If color is used, use less light exposure.

Remote Driving - Fixed, Black and White Video.
- Another camera with a longer lens for identifying objects, moved with a joystick.
- More feeling in steering. Return-to-center tendencies, even "kickback" from vehicle itself (this would help identify bump-steer type action).
- Sound: Hear the engine. Have a tone fluctuation as the wheel turns with a null at zero.
  Motion: Sense the attitude of the vehicle. I didn't use the gauges.
  Vision: Wider angle color camera.
- Sound.
- A wider field of view. Quality of lens or video clarity would help.
- I don't know how you can help the motion sickness. Add motion?
- The experiment seemed well organized.

Remote Driving - Fixed, Color Video.
- Tactile feedback on pedals and steering. May be useful to have force measurement at wheels translated to steering feedback force.
- More vision.
- Remove steering delay. Mark/indicate a zero steering reference on wheel. Add sound.
- Perhaps sound to judge acceleration - deceleration.
- Sound should help.
- Brake pedal resistance would be helpful as would engine noise for an additional indication of speed.

Remote Driving - Steering Slaved, Color Video.
- Sound could help maybe?
- Little more side vision helpful when turning or correcting vehicle.
- Sound (engine, tire noise, wind).
- Sound and more vision and a fixed camera.
- Extra cameras to increase the field of view. Zoom control on camera to zoom in on objects while stopped.

What can we do to improve our experiment?

Simulation - Fixed, Black and White Video.
- Button for identify was hard to deal with, verbal identify would be better with tester pressing "Identify" button.
- Offer practice runs.
- OK by me.
- Sharpen up the black and white tape, poor contrast.

Simulation - Fixed, Color Video.
- Have one practice run before beginning testing.
- Vary the terrain setting more.
- Use actual vehicle to drive.
- Give a little practice before each new type of test.
- Have tester physically show which screens to watch and buttons to push.
- Get rid of the Detect/Identify buttons and let driver vocalize only. Add more driver input (maybe the tape speed could be varied in response to an "accelerator").

Simulation - Steering Slaved, Color Video.
- Perhaps present the things to identify in a list, rather than embedded in a paragraph. Lists are easier to remember.
- Show obstacles in the beginning tape which are immediately obvious to get used to the controls.
- Make it clear that the white pylons define the area of interest. Instruct subject on proper response when object is never identified.
- ?
- Put up signs to where the site of these tests are located.

Remote Driving - Fixed, Black and White Video.
- Well thought out. The experiment itself seems to be very comprehensive as it is.
- Perhaps use a color slaved camera for half of the driving test. Remove some of the backlash in the controls. Separate the gas and brake pedals further.
- Slow down the steering.
- Possibly more familiarity with the response of the equipment.

Remote Driving - Fixed, Color Video.
- Keep equipment working. Free dinner to participants?
- Improve and tighten servo lag (make steering tighter).
- Show some distances calibrated in vehicle lengths before starting sequence asking for estimation of distances and clearance.
- Can't think of a thing.

Remote Driving - Steering Slaved, Color Video.

- The experiment is OK, but system has too much lag.
- Steering dampened or not so quick; causes over-steering when distracted. Picture quality improve for identification. Less lag time for steering or camera "swing" coupled with steering speed.
- Add a wider angle lens. Add an additional camera slave to move camera independent of steering with automatic return to steering direction. Add roll, pitch, yaw to operator seat to correspond to vehicle.
- More fresh air.
- Serve motion sickness pills.

<u>Other comments?</u>

Simulation - Fixed, Black and White Video.

- Black and white shadows often appeared to be objects.
- Posts near road allowed judgment based on road width.
- I found the cameras to be too bright, causing loss of detail to wash-out.
- Very interesting. Would like opportunity to try real vehicle and also night time operation.

Simulation - Fixed, Color Video.

- In spite of what instructions said (first test), I judged whether obstacles threatened road, (not entire area between cones). In distance judging, I would do better in feet or yards, not vehicle lengths.

Simulation - Steering Slaved, Color Video.

- Need a comparison distance to make distance judgment. Tell them how far away and if they could or couldn't make it through on the first scene.
- I didn't identify many of the ruts or humps, I guess based on my judgment that the vehicle could pass over them. I
- The only thing I felt could be improved is the contrast (sharpness) of the video/tv.
- The gauges didn't do much for the driver in the test.
- I need a car wash.

Remote Driving - Fixed, Black and White Video.

- Steering and throttle not very realistic. Steering is too sensitive and throttle does not have any "feel".
- Operator familiarity/training would enhance remote piloting. The more you do it, the easier it gets (or seems).
- Make the number of turns to wheel lock similar to a car's.

- Would be interesting to read the results of experiment at completion, i.e., depth perception part of experiment.
- Wrist and back gets tired. Also I felt tense trying to guide the Jeep. That would probably decrease as I got used to it.

Remote Driving - Fixed, Color Video.
- Steering ratios should be closer between units. Brake pedal should be separated. Firm-back chair needed. Microphone clip too short.
- I have had some experience with video field systems and find the lighting conditions (amount and angle) to vary one's ability to identify objects drastically. would some sort of lighting on the vehicle help?
- Test was interesting. I'm glad I was asked to be a part of it.

Remote Driving - Steering Slaved, Color Video.
- Get a vehicle that operates with fewer mechanical breakdowns. Add a training segment to alert operator to time lag for vehicle to respond to braking, turning, and changing from accelerate to brake.