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EXPERIENCES IN TELEOPERATION OF LAND VEHICLES[1]

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ABSTRACT

Teleoperation of land vehicles allows the removal of the operator from the vehicle to a remote location. This can greatly increase operator safety and comfort in applications such as security patrol or military combat. The cost includes system complexity and reduced system performance. All feedback on vehicle performance and on environmental conditions must pass through sensors, a communications channel, and displays. In particular, this requires vision to be transmitted by closed-circuit television with a consequent degradation of information content. Vehicular teleoperation, as a result, places severe demands on the operator.

Teleoperated land vehicles have been built and tested by many organizations, including Sandia National Laboratories (SNL). The SNL fleet presently includes eight vehicles of varying capability. These vehicles have been operated using different types of controls, displays, and visual systems. Experimentation studying the effects of vision-system characteristics on off-road, remote driving has been performed for conditions of fixed camera versus steering-coupled camera and of color versus black and white video display. Additionally, much experience has been gained through system demonstrations and hardware development trials. This paper discusses the preliminary experimental findings and the results of the accumulated operational experience.

INTRODUCTION

Remote control of land vehicles can be accomplished through provision of auxiliary sensory channels on-board the vehicle (inside-out control) or through observation of the vehicle in the world (outside-in control). Outside-in control is effective only over short visual ranges for vision with no obscuration by smoke, fog, or obstacles. Inside-out control (referred to as teleoperation in the remainder of this paper) is generally applicable for activities such as security patrols or military combat in which any humans present will be at risk. The cost of such operation is increased complexity in the vehicle and control system, since all knowledge of the environment and the conditions of the vehicle have to be sensed, communicated to a control station, and displayed to the human operator. A further consequence of removng the operator from the vehicle is reduced capability for action, since the information content of the operator feedback is degraded by the intermediary channels.

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Vehicles, control stations, and teleoperated systems have been built, tested, and demonstrated by a number of organizations. There is little definitive information, however, on the human factors involved in land vehicle teleoperation (ref. 1). Most information has taken the form of a description of vehicle design or proposed application, with only a few papers reporting actual experimental results. Most of the knowledge base is represented by personal experiences and unreported anecdotal evidence. This paper attempts to expand the data base through a presentation of some of the preliminary results of experimentation in teleoperation at Sandia National Laboratories and through discussion of the observations of Sandia personnel gathered over several years of teleoperation experience.

TELEOPERATION SYSTEMS

Sandia National Laboratories has been actively studying teleoperation for several years. The major effort has entailed the development of a fleet of wheeled vehicles ranging in size from small, interior test beds to large, road and off-road commercial and military vehicles (ref. 2). These vehicles (shown in fig. 1) are being used to conduct feasibility studies on the application of teleoperated vehicles to the physical security and military needs of the U.S. Government. In all of these vehicles, actuators operate the vehicle throttle, brakes, and steering. Control may be derived from manual input at a remote driving station or through some level of automatic control from a digital computer. On-board processing may include simple vehicle control functions or may allow for unmanned, autonomous operation. Communication links are provided for digital communication between control computers, television transmission for vehicle vision, and voice for local control.

Control stations have been developed to support remote operation of the Sandia vehicle fleet. Capabilities range from single television monitor stations with vehicle feedback limited to an audio channel (shown in fig. 2), through large, multiscreen, panoramic displays with computer-generated graphics representations of vehicle speed, pitch, roll, and heading (fig. 3). Vehicle camera mountings have included a single fixed camera, multiple fixed cameras, and cameras slaved to the vehicle steering gear. To date, Sandia has not experimented with stereo vision or with head-slaved displays, although members of the staff have operated such equipment at other locations.

Under the sponsorship of the U.S. Army Missile Command, through the Teleoperated Mobile Antiarmor Platform (TMAP) Project, Sandia has embarked on a major set of experiments to verify some of the observations regarding the "best" driving display (ref. 3). In particular, the experimentation addresses the problems of detection and identification of obstacles in the path of the vehicle. Specific questions include the effect of color versus black and white, the utility of increasing the horizontal field of view through panning a camera in response to steering wheel movements (steering-slaved control), and the errors in operator interpretation of size and distance information as presented by the television system.

EXPERIENCE

The experimentation on obstacle detection and vehicle control being performed for the TMAP Project represents the only rigorous data base development in process at Sandia. In this testing, 18 subjects teleoperated a vehicle over a marked off-road course which contained numerous obstacles. An additional 18 subjects participated in a video simulation of the same marked course. Most of the data analysis for this series of tests has been completed (refs. 4 and 5). Additional tests and experimentation are being planned.

The remainder of the experience base at Sandia has been derived from operation of vehicles during hardware and software development and system demonstrations. Operators have ranged from well-trained, highly experienced personnel through people that had not previously driven a remotely controlled vehicle. The primary source of data has been the subjective comments of operators and observers.

The analysis of accidents involving teleoperated vehicles has provided additional information. Table 1 provides a listing. Some of these accidents occurred while the operator was observing the vehicle directly (outside-in operation) and were predominately depth-perception problems involving vehicle clearance or stopping distances. Control reversal caused one accident while operating the vehicle in the outside-in mode. In this accident, the vehicle was heading toward the operator. The operator wanted the vehicle to go toward the left of the operator (operator left). Since the vehicle was approaching the operator, this required the vehicle to turn to the right with respect to its direction of travel. The operator became disoriented and issued a left command. The vehicle responded by veering further to vehicle left (operator right), consequently colliding with a parked car.

TABLE 1.- ACCIDENT HISTORY

VEHICLE	INCIDENT	CAUSE
Outside-In Operation		
Dune Buggy	Hit fence	Underestimated stopping distance
Dune Buggy	Hit tree	Depth perception
Dune Buggy	Hit fence	Underestimated stopping distance
Suzuki	Hit post	Depth perception
Suzuki	Hit car	Control reversal
Inside-Out Operation		
Suzuki	Rollover	Loss of control on hill
Suzuki	Rollover	Loss of control on hill
Suzuki	Rollover	Hit traffic cone
Suzuki	Rollover	Loss of control on hill
Suzuki	Rollover	Loss of control on hill
Suzuki	Rollover	Loss of control while backing
Suzuki	Rollover	Loss of control, hit bump
Suzuki	Rollover	Loss of control on hill
Suzuki	Rollover	Loss of control, hit bump

All of the accidents involving teleoperation (inside-out control) have been rollovers. The particular vehicle involved is a small Suzuki LT50 four-wheel, all-terrain vehicle shown in figure 4. The rear wheels are driven through a single-speed drive with a centrifugal clutch. The vehicle is capable of a 15-mph top speed on flat ground. Control inputs from the operator are through the control station illustrated in figure 2. Figure 5 shows the view provided to the operator. In all but one incident, the vehicle was being operated off-road on a motor-cross track with steep slopes, high banked corners, and high berms at the edges of the track. The only exception was a rollover caused by hitting a traffic cone while operating on a flat asphalt parking lot.

OBSERVATIONS

A number of observations regarding important parameters, operational considerations, and system design features have been derived from Sandia experiences. These are presented below strictly as indicators since, in the absence of hard experimental data, it is not clear that all are generally applicable. Likewise, not all system implementations are represented.

Field of View

It is very difficult to operate a vehicle in restricted space with a narrow field of view. Operations of a Jeep Cherokee on normal roads and parking lots were performed with a single camera, 40° field-of-view system. The operator was not comfortable turning corners. Installation of two additional cameras, to provide a total of 120° field of view resulted in much "easier" operation. Additional tests have been run using a steering-slaved camera, both on the Jeep Cherokee and on the Suzuki all-terrain vehicle. Steering-slaved viewing provided sufficient effective field of view to allow turning tight corners and avoiding obstacles. Provision of a mechanism to allow the operator to force the camera further (an auxiliary pan control) was even more effective.

Resolution

Camera resolution does not seem to be a factor in the ability to teleoperate a vehicle in the absence of obstacles. Sandia has operated vehicles with malfunctioning communications links resulting in extremely poor resolution. As long as operations take place on well defined areas (such as well marked roads) and there are no obstacles in the path of travel, an operator can successfully maneuver a vehicle from one point to another. High resolution does appear to be important when many sizes and types of obstacles are present and for operation off-road where identification of best path is important.

Color/Black and White

Work with television surveillance systems has indicated that the increased resolution possible with black and white equipment is much more important than any additional information contained in the color signal. This does not necessarily appear true for teleoperation. Color provides additional cues leading to more accurate obstacle recognition and course planning. For example, the difference between dirt and asphalt is important for driving, but cannot be determined from a black and white television picture. Sandia has also found that orange traffic cones (with the color chosen for maximum visibility) tend to disappear on black and white television. These have been used to establish courses during demonstrations and experimentation. Using black and white television, it was found to be necessary to cover the cones with white paper to so that they could be seen.

Vehicle Vibration

Vehicle vibration and bounce has not been observed to significantly degrade the displayed video scene. The small Suzuki has no suspension (springs or damping) other than its large, soft off-road tires. During operations which lead to the vehicle bouncing enough to actually leave the ground, the video remains relatively clear and usable. No operator has ever commented that vibration or bounce in the picture was bothersome.

Distance Estimation

As seen from the accident reports, distance estimation during outside-in driving is a problem. It also creates difficulties when using inside-out control. As reported by Spain (ref. 6) in a related set of experiments, operators using a head-mounted display consistently ran into pylons marking the end of a parking place. The feeling of being further from obstacles and landmarks than the actual position has also been reported by most operators of Sandia vehicles. For all of the systems utilized in these observations, however, the display was smaller than geometric similarity, resulting in a scene minification between 0.4 and 0.7. As discussed by Roscoe (ref. 7), it can be anticipated that size and distance judgment errors can be expected for these conditions. To achieve better results, scene magnification of approximately 25% is required.

Negative Obstacles

Terrain features such as ditches, holes, and drop-offs are extremely difficult to see using television. Negative obstacles such as these have contributed to many of the problems in teleoperating vehicles. In most cases, small ditches cannot be differentiated from variations in ground coloration until the vehicle has hit them. At that point, the horizon on the video scene changes, indicating that the vehicle just hit a ditch. It can be anticipated that stereo vision could help in this problem, but no experimentation has been reported.

Tilt and Roll

The large number of rollovers reported establish vehicle tilt and roll control as a major problem. In the Suzuki driving system, the only feedback is the video signal from the camera and an audio pickup providing engine sound. Vehicle attitude parameters are neither measured nor displayed. The typical accident scenario entails "launching" the vehicle from a ramp or attempting to traverse a side slope which is too steep for the vehicle to maintain stability. Most rollovers have occurred at close to maximum vehicle speed (about 10-15 mph) and have been a result of ground features representative of extremely challenging terrain. These have included hills with up to 45° slopes and highly banked corners on a motor-cross course. As the rollover occurs, the operators express surprise. In debriefing, it appears that the operator had no indication that the vehicle was approaching a dangerous condition.

Overcontrol

A typical characteristic of novice operators is extreme steering overcontrol. The operator applies a small steering input to the vehicle, but no result is immediately seen. The steering input is increased until a response is finally observed. The resulting turn is more than intended so the operator applies a small correction. Again, the response is not seen so more correction is applied, etc. The outcome is vehicle travel oscillating about the desired path. Operators report this to be a very stressful situation. Overcontrol has also contributed to several of the vehicle rollover accidents. The operator applied excessive steering input, sending the vehicle over the edge of a berm. Observing novice drivers learning to control the vehicle, it is apparent that considerable internal control is being exercised as the operator adapts. After some minutes of operation, steering operation is considerably slower and at lower amplitude, resulting in smoother vehicle control. Spain (ref. 6) reports similar findings.

Navigation

An associated problem in vehicle teleoperation is the difficulty of maintaining spatial orientation with respect to major landmarks, map features, or compass directions. It is not uncommon for operators to become lost on the motor-cross course. Even with landmarks and a map of the course, they have not been able to determine how to return to the starting location without assistance.

SUMMARY AND CONCLUSIONS

Operational experience has been gathered at Sandia through development, test, and demonstration of a number of vehicles. A large experimental program in vision system requirements for teleoperation is also in process. Through the knowledge gained in these programs, several key areas can be identified as critical to successful control of a teleoperated vehicle. The primary area is the quality of the visual display provided to the operator. It has been shown that vehicles can be controlled in restricted environments with extremely poor conditions of viewing. As viewing improves (both in resolution and field of view), better control can be expected.

Negative obstacles create difficulty in that operators cannot distinguish them from other terrain features which do not affect vehicle travel. The result is hitting ditches, holes, or berms at excessive speed.

The interaction of the vehicle with the environment, as interpreted through the mediating effects of the television display system, can lead to poor control capabilities and hazardous operating conditions. Overcontrol of the vehicle steering, coupled with the operator's inability to accurately perceive vehicle attitude and terrain requirements has led to a number of accidents. This can be partially linked with the absence of kinesthetic feedback to the operator. Experimentation with vehicle simulators has shown a distinct lag in response to environmental inputs, such as wind gusts, when no kinesthetic feedback is present (ref. 8). With the addition of kinesthetic feedback to the operator (simulator platform motion), response time to sudden wind gusts dropped from an average of 0.56 sec to an average of 0.44 sec. Similar results have been reported for the addition of steering wheel torque feedback, thus providing "feel of the road" to the operator (ref. 9). The lack of kinesthetic feedback is similar to operating with a time delay in the control system. Additional lags are introduced by the communications systems and vehicle actuator and control systems.

Given the ability to maneuver a teleoperated vehicle in the real-world environment, the problem of navigation is encountered. Operators tend to get lost, disoriented, and confused when provided with visual input and maps. The effect of addition of vehicle heading, plotting of route traveled, or other aids remains to be investigated.

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Figure 1.– Teleoperated vehicles.

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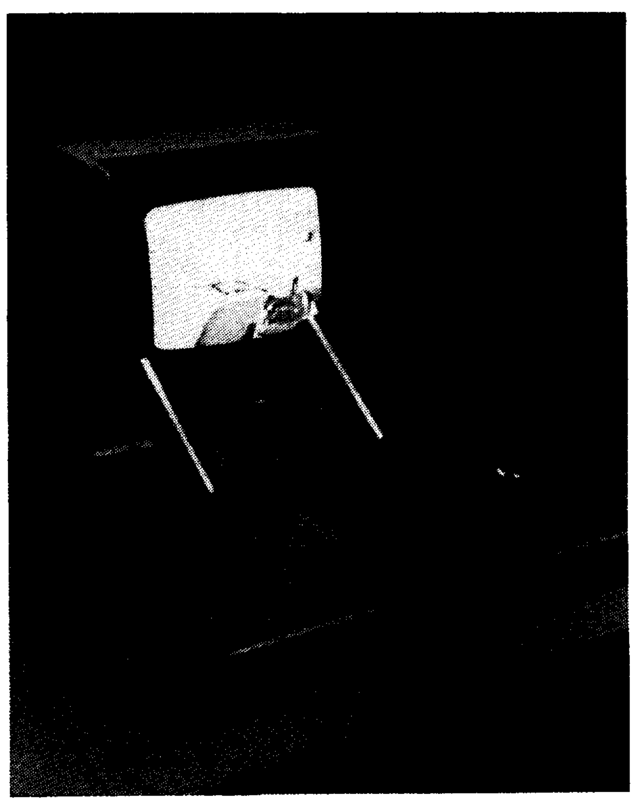

Figure 2.– Single monitor with audio feedback.

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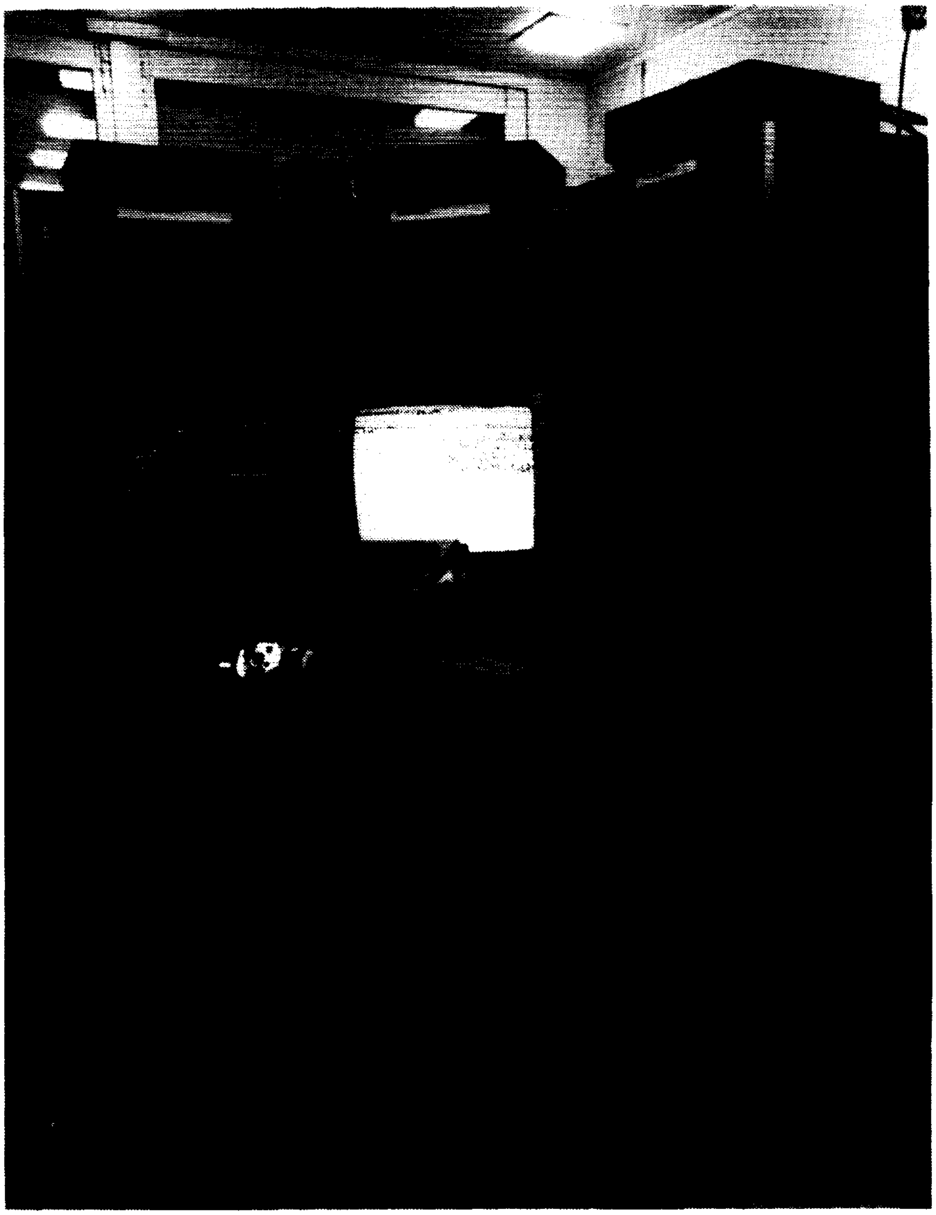

Figure 3.– Panoramic display.

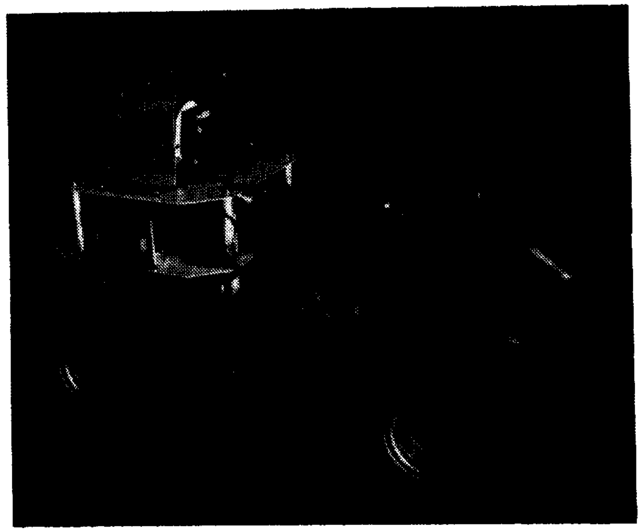

Figure 4.– All-terrain vehicle.

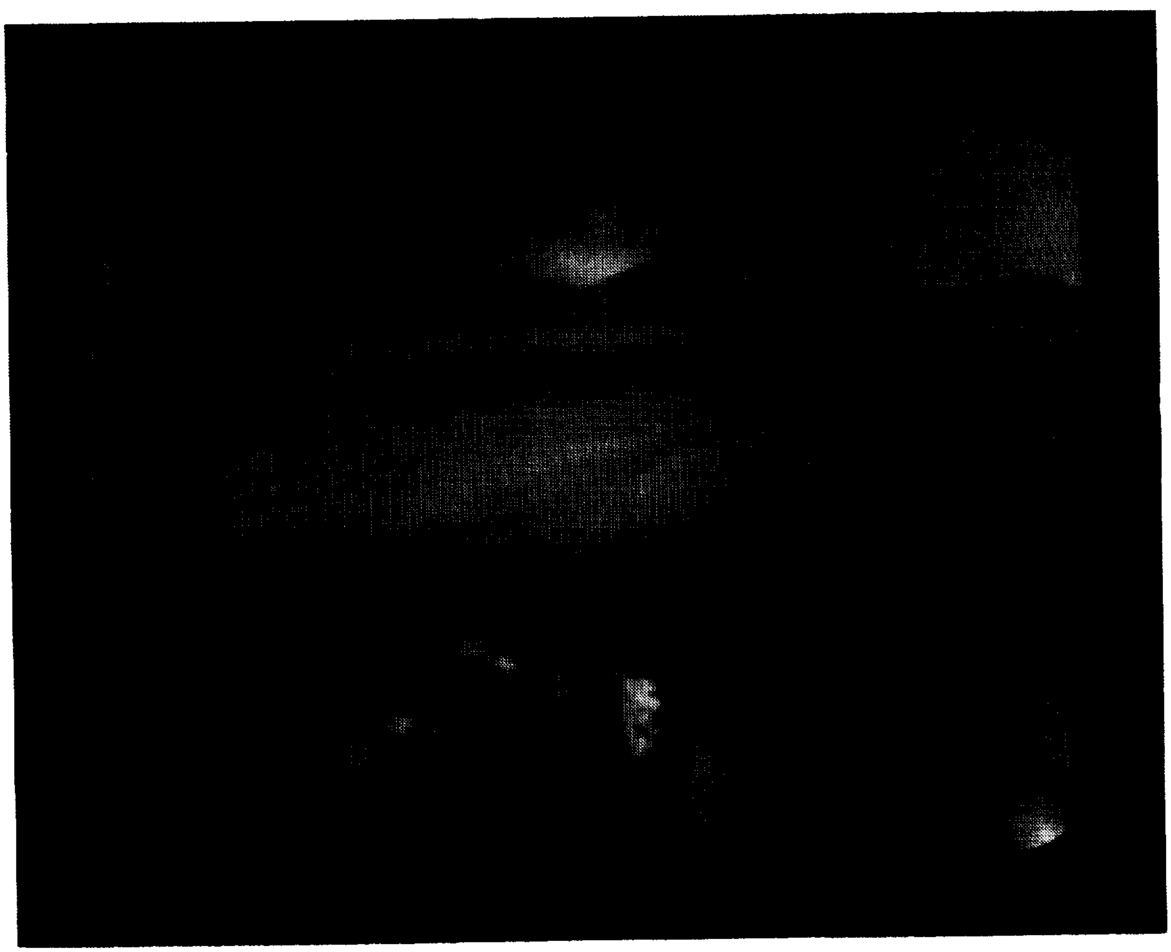

Figure 5.– Operator's view via control station.