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Interim Report

Development of Performance Specifications for Collision Avoidance Systems for Lane Change Crashes

Task 6 - Testbed Systems Design and Associated Facilities

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16. Abstract

This report documents the design of an on-road testbed vehicle. The purposes of this testbed are twofold: 1) Establish a foundation for estimating lane change collision avoidance effectiveness, and 2) Provide information pertinent to setting performance specifications for a lane change collision avoidance system (CAS). This design is expected to be a significant advance over other current methods that require manually viewing information stored on video tape.

The key subsystems that make the testbed unique are its scanning laser and eye tracker. The scanning laser is mounted to the right rear corner of the car and scans a full 360 degrees at 10 hertz. A prototype version of this laser has been tested and shown to be effective in providing range data on cars out to a range in excess of 200 feet. This sensor provides digital measurements of ground reference data in addition to target inputs for a prototype CAS.

The eye tracker is able to track driver gaze direction at an update rate of 60 hertz. Using a lightweight, relatively unobtrusive headband, the eye tracker accommodates full rotation of the head, from left blind spot to right blind spot. The eye tracker is thus able to provide a continuous digital record of gaze direction as the driver executes a lane change maneuver.

Post-processing of the digital data taken in on-road tests reveals what, if any, effect the introduction of a CAS has on the driver's behavior.

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ACRONYMS

ABS	anti-lock braking system
ADC	analog to digital converter
CAS	Collision Avoidance System
CW	continuous wave
DAS	data acquisition system
DSP	digital signal processor
FOR	field of regard
FOV	field of view
ft	feet
LCD	liquid crystal display
m	meter
MFLOPS	millions of floating point operations per second
MIPS	millions of instructions per second
mW	milli-watt
NHTSA	National Highway Traffic Safety Administration
nm	nano-meter
NTSC	National Television Systems Committee
nsec	nanosecond
PC	personal computer
rms	root mean square
SMPTE	Society of Motion Picture and Television Engineers
SVHS	super video home system
TAP	task accomplishment plan
VAC	volts alternating current
VCR	video cassette recorder
VDC	volts direct current
VGA	video graphics adapter
W	watt
μm	micron

SUMMARY

This report represents the documentation of the design of a testbed vehicle that is suitable to investigate on-road driver performance using a prototype lane change assist system. The purposes of the testbed are twofold: 1) Establish a foundation for estimating collision avoidance effectiveness and 2) Provide information pertinent to setting performance specifications for a lane change/merge collision avoidance system (CAS). The testbed will accomplish these goals by monitoring the ground reference conditions, driver behavior and inputs from vehicle sensors and storing this information digitally. This is a significant advance over current methods of manually viewing information stored on video tape. This testbed development work was conducted from March 1996 through May 1997.

The key subsystems that make the testbed unique are the scanning laser and the eye tracker. The scanning laser will be mounted on the right rear corner of the car and will scan a full 360°. A prototype version of this laser has been tested and shown to be effective, providing range data on cars out to a range in excess of 200 feet. The scanning laser will be able to generate trajectories of passing cars, and categorize them according to their length and width. Besides providing ground truth information, the scanning laser will also serve as a stand-in CAS. Information from the laser plus other vehicle sensor inputs will be processed by a digital signal processor (DSP) and will decide if a warning shall be presented to the driver. The DSP in the data acquisition system will control the display system by activating one or more solid state relays. The display system will be built into a Government-furnished 1993 Chevrolet Caprice.

The second subsystem that makes the testbed unique is the eye tracker. This device will be able to track the driver's gaze direction at an update rate of 60 Hz. Using a lightweight, relatively unobtrusive headband, the eye tracker accommodates full rotation of the head, from the left blind spot to the right blind spot. The eye tracker will be able to provide a continuous record of gaze direction as the driver executes a lane change or merge maneuver. In addition, we will be able to determine what, if any, effect the introduction of a CAS has on the driver's gaze patterns as he executes a given maneuver.

The system will be built at TRW's Space Park facilities located in Redondo Beach, California, and will undergo considerable testing in controlled areas on the premises. Final shakedown will be performed on a test track operated by the San Bernadino Sheriff's department. The testbed will be extensively road tested by TRW engineers to assess performance before being made available to test subjects.

Since all of the data will be stored in digital form, any lane change maneuver can be examined to determine that particular driver's choice of gap spacings (fore and aft), relative speeds, duration time and gaze direction before, during and after the maneuver. Post processing software can easily compile statistics for each driver and gather this data over many drivers, providing an empirical data base for modeling.

1.0 Introduction and Requirements

This document contains the design details of the testbed vehicle. The design reflects prototype testing that was done at TRW of the primary subsystem, namely the scanning laser. Having tested a laser with excellent long range capability and acceptable accuracy, the inclusion of a 360° scanner allows us to extend our viewing space to the front of the vehicle, in the adjacent lane. This affords us the ability to improve our capability for establishing the final performance specifications.

1.1 Requirements

The overall objectives of the testbed as laid out in the Task Accomplishment Plan (TAP) are: 1.Establish the foundation for realistically estimating collision avoidance effectiveness and 2.Provide information pertinent to setting performance specifications for a lane change/merge Collision Avoidance System (CAS). The approach taken has been to construct a fully automated testbed capable of recording ground truth, subject vehicle inputs and driver response. The output of this testbed is expected to be data on how people merge and make lane changes and how that is modified with the introduction of a CAS. The parameters to be measured include vehicle gaps (fore and aft), relative speeds, maneuver duration, vehicle inputs (e.g. speed, turn signal use, brake use, etc.) and time dependent driver gaze direction.

Since we expect to use the testbed both as a CAS and as a ground truth recorder, there are requirements associated with both functions. These requirements can and do overlap, but they will be enumerated separately. In both cases, these requirements are primarily levied against the scanning laser subsystem.

The requirements for use as a CAS are derived from the Task 4 Preliminary Performance Specifications for Lane Change. These specifications address the proximity/lane change and fast approach functional goals. The basic preliminary specifications (which will be revised) are: 1) coverage of the adjacent lane to ± 80 feet fore and aft of the testbed, 2) measurement accuracy of 2 feet, 3) measurement latency $\leq$ .5 sec, 4) a velocity resolution of 5 feet/sec, and 5) display a warning to the driver.

The requirements as a testbed deal primarily with the ability of the testbed to quantify select parameters and store the data. These requirements fall into four main categories: 1) provide video confirmation of ground truth 2) monitor the driver eye gaze direction to within designated zones 3) provide for a data acquisition and control system and 4) monitor vehicle inputs. With respect to the data acquisition system, it must control the sensors, store data for a two hour run, process position and velocity data of vehicles in the adjacent lane and determine whether to issue a warning to the driver. Vehicle inputs in this case are considered to be the speed, steering angle, brake usage and turn signal usage. Other requirements are as follows:

1. Design electrical system to provide appropriate voltages and currents to installed components.
2. Locate operator control area in rear seat
3. Testbed vehicle must be a passenger car
4. Comply with NHTSA Order 700-1, concerning the protection of the rights of human subjects.

A schematic of the testbed is shown in Figure 1-1. It illustrates the main subsystems such as the scanning laser, video cameras and eye tracker. The laser is located at the passenger side rear corner of the car. It is so located to examine lane changes and merges to the right side. In principle, this should be equivalent to those on the left side. It will monitor an area that is 270° in azimuth, out to a range of at least 100 feet. The video cameras monitor the area to the right of the car (fore and aft) and to the rear.

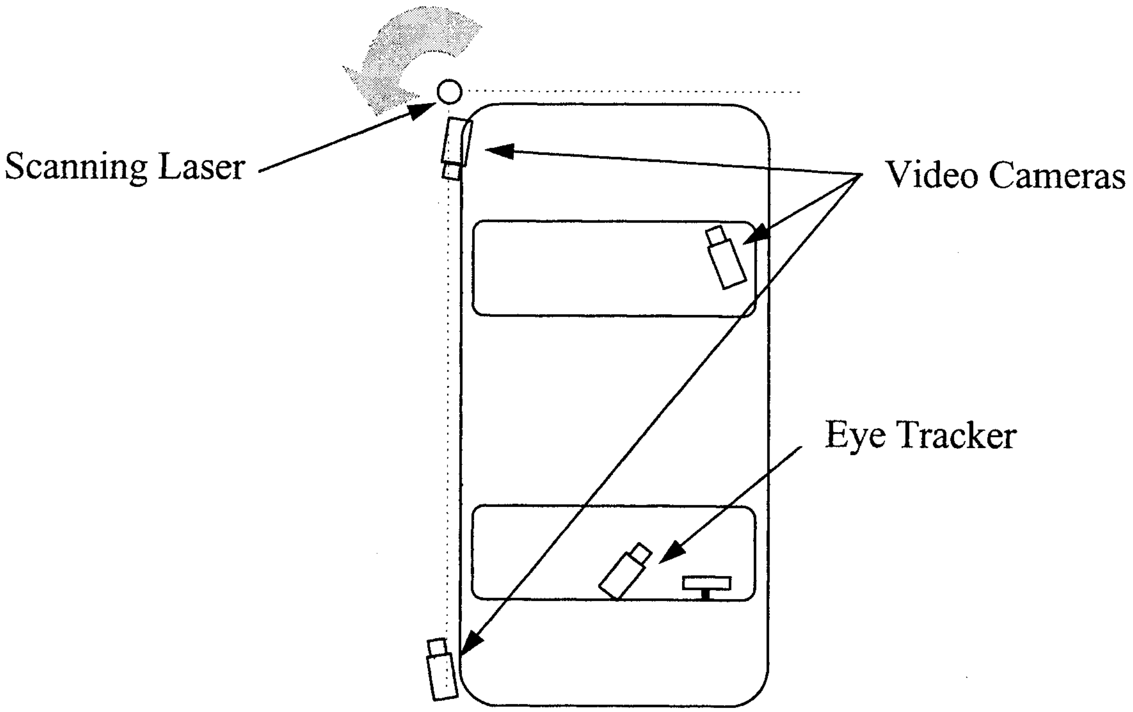
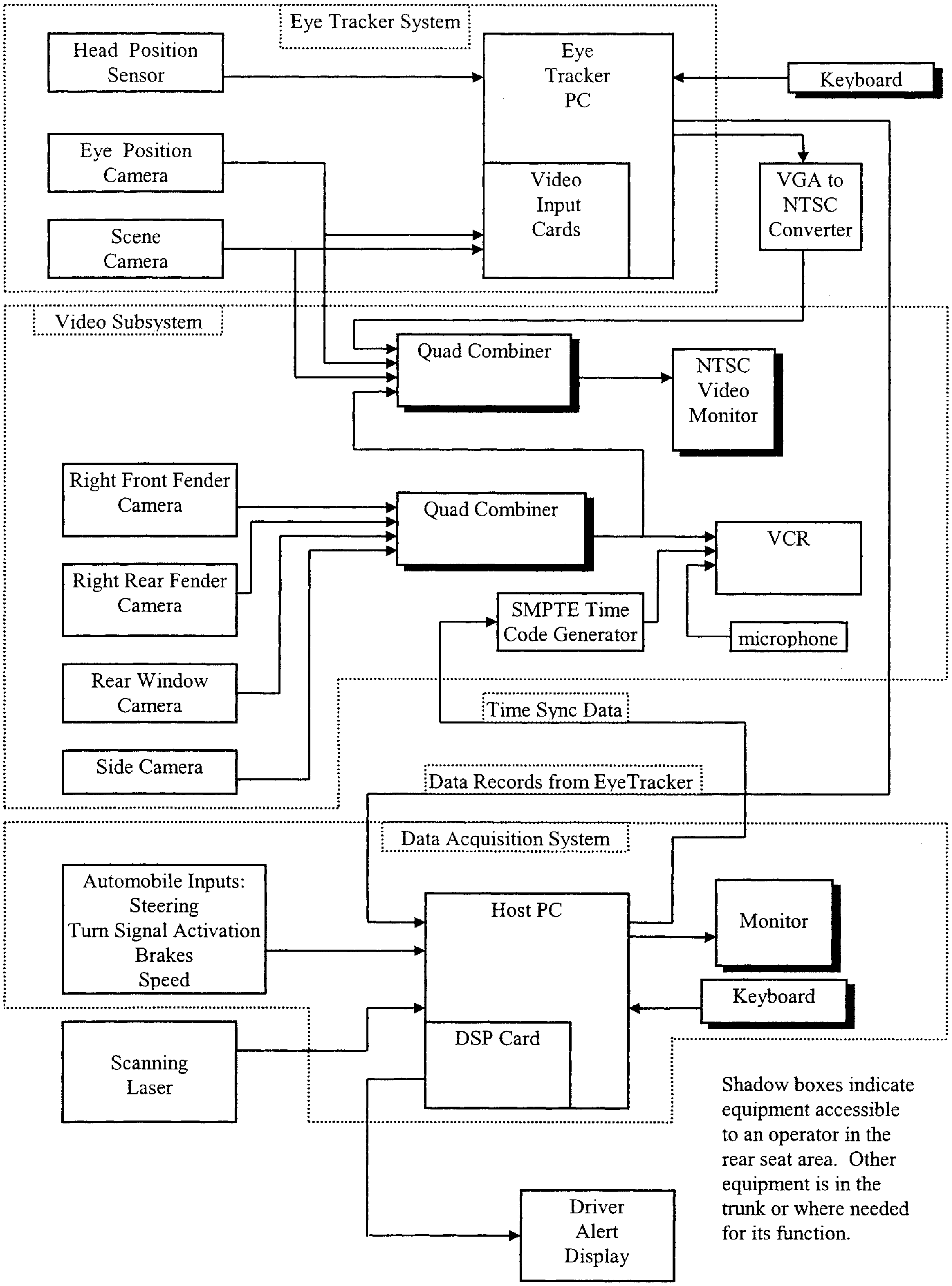


Figure 1-1: Testbed Schematic

A block diagram of the testbed system is shown in Figure 1-2. The main subsystems such as the eye tracker, laser scanner, video and data acquisition are outlined in dashed lines: Those items that are deemed essential to the operation of the total system are shown shaded and will be located in the operator area in the rear seat of the vehicle. As many of the components as possible will be located in the trunk, so as to minimize any obtrusiveness in the passenger compartment that might distract the driver. There will of course be some components that need to be located on the outside of the car, such as the scanner and some of the video cameras.



Shadow boxes indicate equipment accessible to an operator in the rear seat area. Other equipment is in the trunk or where needed for its function.

Figure 1-2: Block Diagram of Testbed System

2. Laser Subsystem

The laser subsystem is intended to serve two functions. The first is to serve as a stand-in CAS and the second is to generate a record of the trajectories followed by vehicles in the surrounding area of the testbed.

2.1 Requirements

The requirements that follow are derived from the top-level requirements levied against the testbed. The laser subsystem shall be required to register vehicles in the right-side adjacent lane (fore and aft) and in the same lane to the rear of the testbed. The range shall be from 3 feet to 100 feet, with an accuracy of .5 ft. This requirement at the maximum range is derived from the output of Task 4 of this program, which found that by simulation one reached the point of diminishing returns in terms of collision avoidance if one's sensor had an extent of 80 feet behind the subject vehicle. We have extended this requirement to 100 feet to account for the length of the testbed vehicle. It should be noted that this is a minimum requirement, which will be revised. The laser that was chosen exceeds this by a considerable margin. For those times where vehicles approach even closer than 3 feet, it should be noted that even motorcycles are not point targets and that their finite extent will always have some portion of the vehicle at a distance greater than 3 feet from the laser. Finally an accuracy to within .5 ft will allow reasonably accurate profiling of the surrounding vehicles.

The scan rate shall be such that the vehicle moves a distance less than the instrument's accuracy value in one scan, at any range. Since this is most critical at close distances, assume that the vehicle subtends an angle of 30° at close range. This is equivalent to a car in the adjacent lane (6 ft. lateral distance), approximately 13 feet behind the scanning laser. This then translates to the following simple formula:

$$\text{Scan Rate} > V_{\text{relative}}/\text{Accuracy} * 30°/360°$$

For a relative velocity of 30 mph (44 feet/sec, below which 94% of lane change/merge accidents occur) the value of the scan rate is ~ 8 Hz.

The sample rate shall be such as to ensure that a sample is taken at intervals of no more than 1°. This ensures that a car at 100 feet will produce at least 3 or 4 returns across the front bumper. A motorcycle will, of course, generate less returns, but a high scan rate will increase the probability of detection. This requirement, along with the minimum scan rate of 8 Hz, yields a sample rate of 2.9 kHz.

The final requirement is that the laser shall be eye-safe. The necessity for this should be obvious when used in an uncontrolled environment.

2.2 Design Approach

The approach taken toward the selection of a scanning laser has been necessarily empirical. The set of all vehicles present targets of varying aspect, color, and finish so that merely setting a specification for detectable fraction of incident power returned may result in it being too loose on the one hand or unattainable on the other. Therefore we tested three lasers against cars to determine which would meet our requirements.

The first laser tested was the Accurange 4000 from Acuity Research, Inc. This was an amplitude modulated CW laser. It was found that when used against cars, the laser was unreliable beyond approximately 20 ft. Because of its CW nature, it works best on high reflectance targets. Also, because of its CW nature, it required modification of the optics to be made eye-safe, even when scanned.

We did an extensive series of tests on lasers from Schwartz Electro-Optics and Riegl. From Schwartz we tested the Autosense II and from Riegl the 3100HS. These were not the exact lasers we would get, but were highly representative of the performance we could expect. The Autosense II was designed to image traffic from an overhead position. It is a scanning laser with a 30° field of view, sampling at every 1°. The maximum reportable distance in this configuration is 52 ft. Figure 2-1 shows the results of the scan taken approximately every 2 seconds while the car is being driven toward the laser, but in the adjacent lane (Y is the rearward distance, X is the lateral distance).

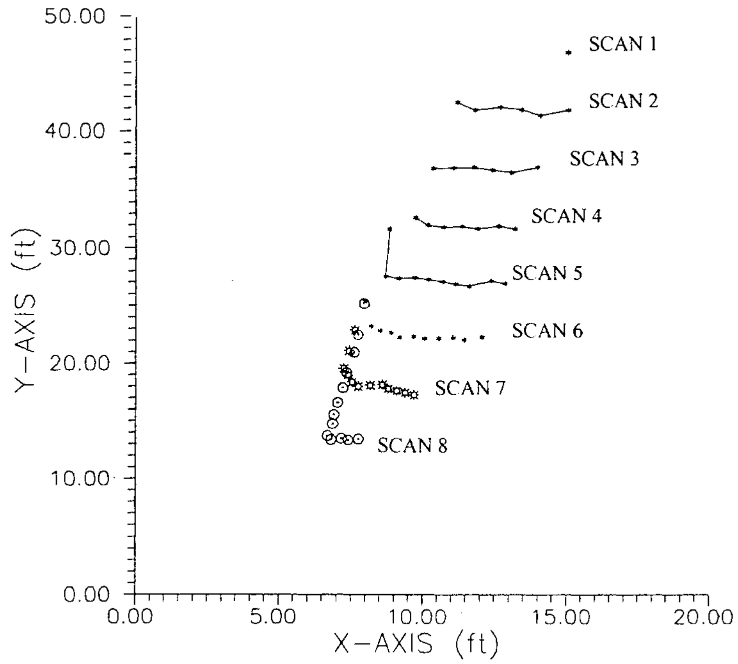
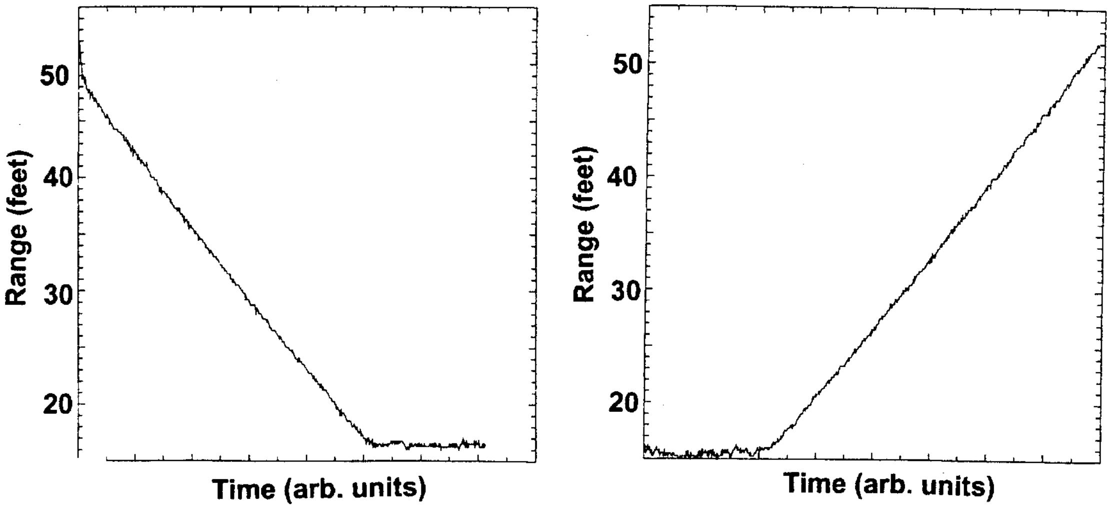


Figure 2-1: Successive Profiles of Approaching Car as Taken by Autosense Laser

The data starts out with only one return from the first scan. After that one sees a fair number of returns from the front bumper, and less so from the side of the car. There are two reasons for this. First, the side of the car presents a rather small solid angle to the laser at large distances, so that a laser such as this, which measures every 1°, may not intersect the side of the car. The second is that for specular reflection at near grazing incidence, the intensity of the returned signal will be very small, and often below the threshold of detection. However, the bumper itself is quite well defined and one could easily project the aspect of the car with respect to the laser, which is necessary in defining the trajectory of the vehicle. The length of the car can easily be measured when it comes closer to the testbed.

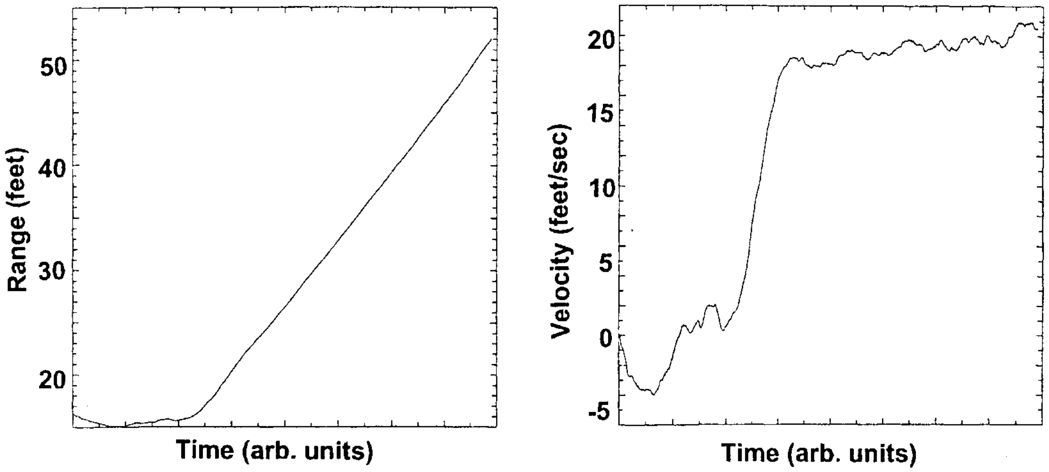
As an example of the kind of pre-processing one can do for collision warning, Figure 2-2 shows the time history of range as measured by the scanning laser for an approaching and receding car. The range was obtained by simply plotting the closest return from the vehicle for each scan. One can see that it is a rather smooth function of time. Figure 2-3 shows the results of some simple filtering of the range and range rate which would constitute the key inputs to any warning algorithm. The slight oscillation in velocity at the early times comes from the error in subtracting values for range which are close together, as the car is not moving at this time. The rms values of the velocity (range rate) are still within the allotted accuracy budget of 5 ft/sec.



Vehicle Approaching

Vehicle Leaving

Figure 2-2: Minimum detected range per sweep from Autosense laser



Range Calculation **Velocity Calculation**

Figure 2-3: Filtered range and range rate data derived from Autosense laser

Given that the Autosense II system did not display distances greater than 52 ft, it was necessary to extrapolate the intensity of returns to distances greater than 52 ft. Because a car is a complex scatterer, very sensitive to incident angle, one cannot assume a $1/R^2$ dependence on scattered signal power that simple theory predicts. Again empirical data was used to estimate the ability of the laser to detect targets at greater than 52 ft. Shown in Figure 2-4 is the average of returns from the bumper while the car is approaching and receding. In one case it is problematical as to whether there will be a measurable return at 100 ft, but for the approaching case it is clear that the trend indicates that there will be no measurable signal at 100 ft.

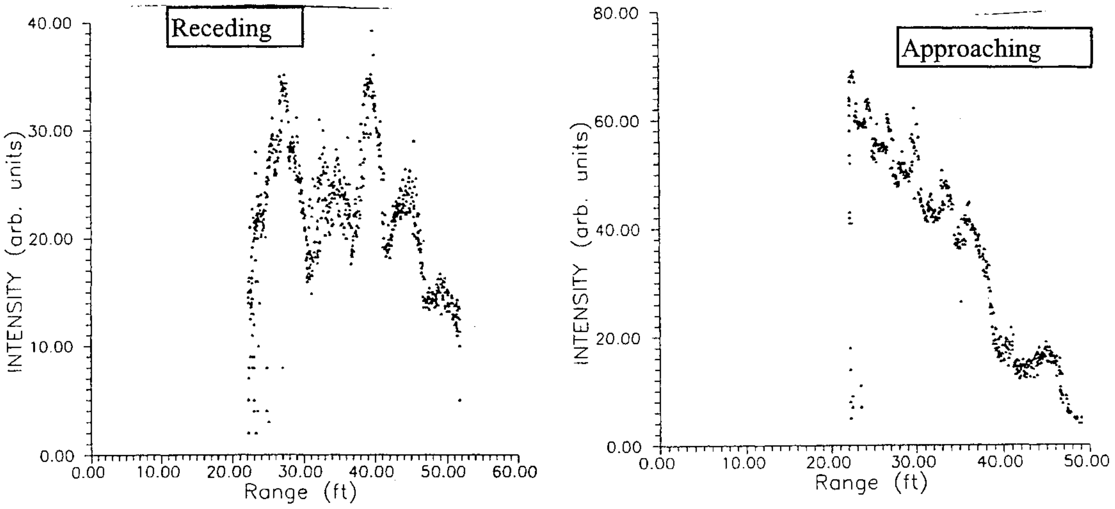


Figure 2-4: Averaged return intensity from rear and front bumpers from Autosense laser

The Riegl laser that we had the opportunity to test was not mechanically scanned. The experiment we conducted is illustrated schematically in Figure 2-5. A car was stationed at some distance away from the laser, as if it were in the adjacent lane. The laser, at approximately bumper height, was then scanned across the car by hand, in the direction indicated by the arrow. The car was then successively moved further away from the laser. The resulting profiles are shown in Figure 2-6. The ordinate represents both the range in feet and the return amplitude in arbitrary units scaled between 0 and 255. The abscissa is in units of time but can equivalently be thought of as scan angle. The important thing to note about these profiles is that good solid returns were obtained beyond 200 feet. It is primarily this comfort margin which gives us confidence in choosing the Riegl laser for the testbed. At the closer ranges one can see the range values change more rapidly before they flatten, as the laser scans the side of the car. This is less pronounced at distances greater than 100 feet. An interesting curiosity of these curves is the presence of two double peaks in the return intensity at three of the four distances. It is believed that these are the signatures of the headlights, which because of their parabolic construction would give a particularly strong return.

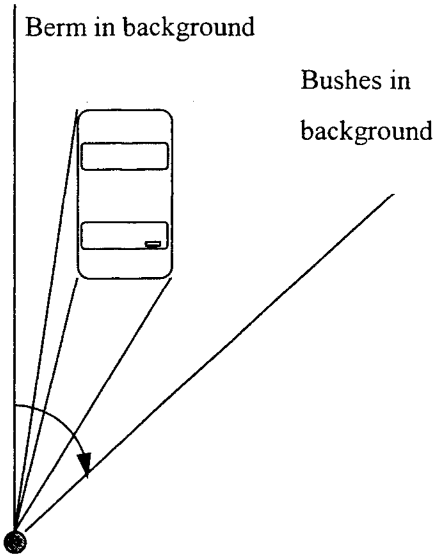


Figure 2-5: Test Diagram for Riegl Laser

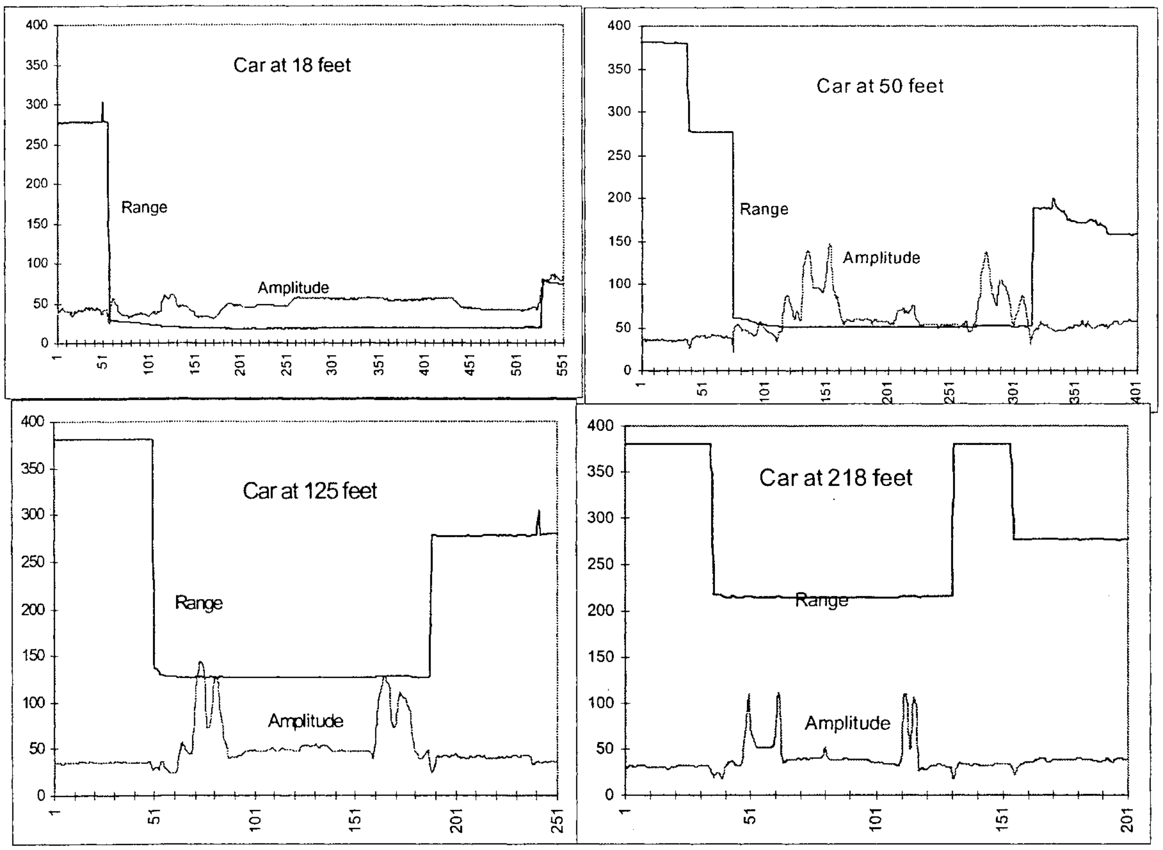


Figure 2-6: Manual scans by Riegl laser

2.3 Implementation and Capabilities

The laser selected is the SLR 4000, which is a Riegl laser mated with a 360° scanner. The standard specifications for this scanner are listed in Table 2-1. The values pertaining to range can be customized somewhat, as explained below.

Parameter	Specification
Range	2-100m
Accuracy	4 cm typical, 10 worst case
Sample Rate	12 kHz
Horizontal FOV, scan rate	360°, ≤ 40Hz
Vertical FOV, scan rate	± 15°, 6 Hz
Wavelength	900 nm
Peak Power	approximately 3.7W
Pulse format/width	single pulse/20 nsec
Eye Safety	Class 3B, eyesafe when scanned

Table 2-1: SLR 4000 Specifications

The block diagram for the SLR 4000 is shown in Figure 2-7 and two photographs of the system, built for another customer, is shown in Figure 2-8. A key feature of this system is the fact that the laser is mated to the scanning optics through the use of optical fiber.

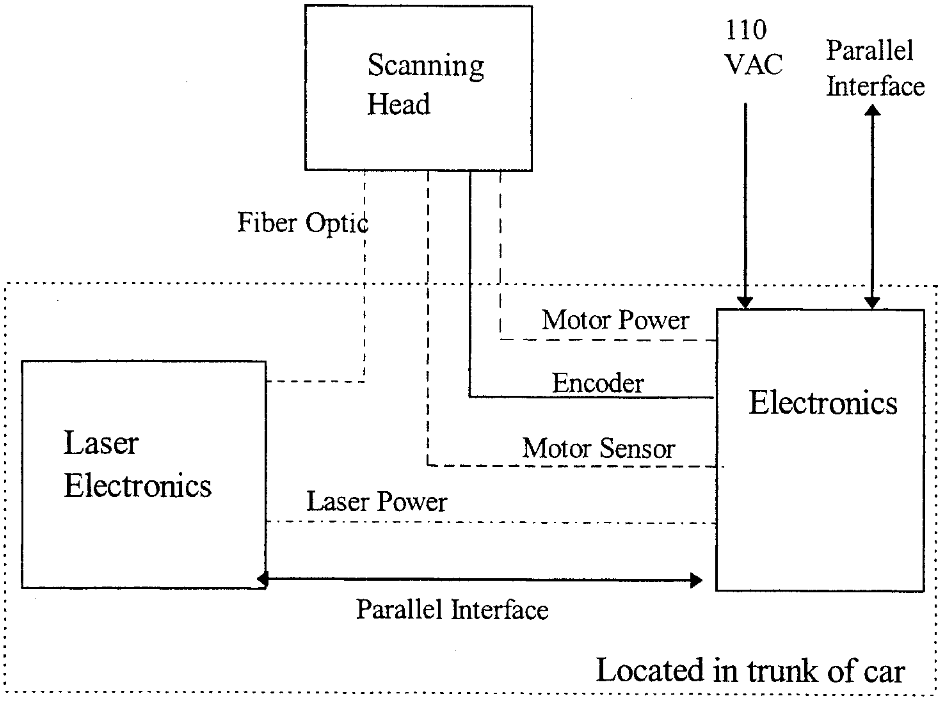


Figure 2-7: SLR Block Diagram

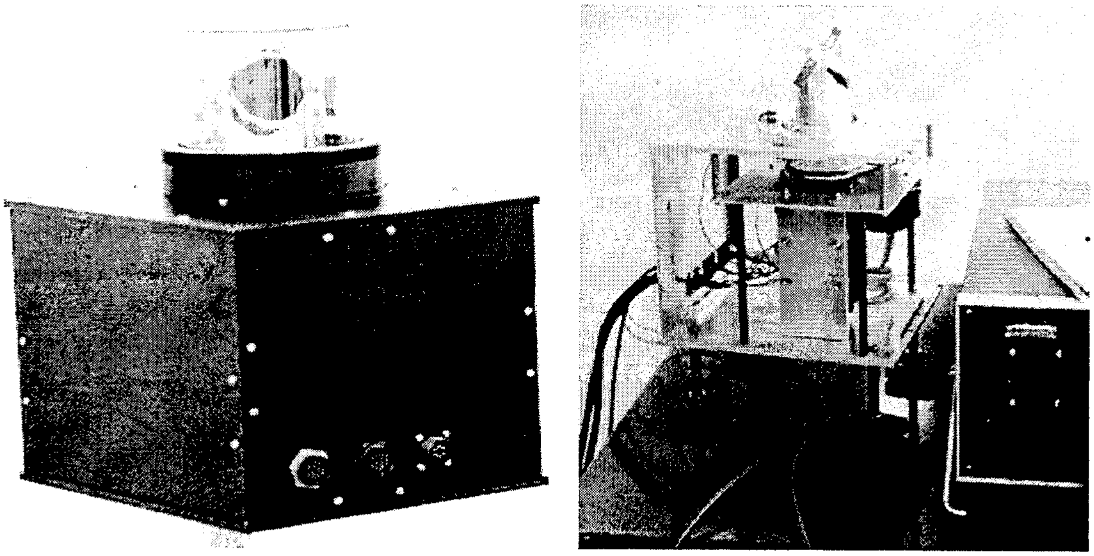


Figure 2-8: SLR 4000 Photographs

This means that we can minimize the hardware that is mounted outside the car to just the scanner and the optics. The photographs show a completely integrated unit, with everything in one package. As can be seen from the open photo there is plenty of empty space inside the enclosure. Our system will be customized by separating the scanning optics from the laser and the electronics, resulting in a package 6 inches in diameter and 8 inches tall that would be mounted outside the car. The electronics and the laser are then installed in the trunk. Two other features of this optical coupling of the laser are: 1) it allows the receive and transmit optics to be located extremely close and 2) it introduces a minimum delay between the transmit and receive signals. Both of these features combine to reduce the minimum range. The primary concern for operating at short ranges is that there paradoxically might not be enough signal return from most natural, diffuse targets. The two features mentioned above act to improve the signal to noise ratio of weak, close-in targets. The first in the sense that the close spacing allows the transmit and receive cones of acceptance to more fully overlap at close distances. The second in that a large minimum delay time means that even for close-in targets, the noise from the electronics generating the laser pulse will be gone by the time the return pulse arrives at the detector. Therefore the return pulse will not be masked, allowing for the detection of faint return pulses from near targets. Because a car is primarily a specular scatterer, and at close ranges would be largely perpendicular to the laser beam, it is apt to return a strong signal which would probably be detectable even without these features.

The necessity for eyesafety in an uncontrolled environment is a legal requirement. The laser itself is classified Class 3B. As defined in the American National Standards Institute (ANSI) publication ANSI Z136.1-1986, Safe Use of Lasers, a class 3B laser operating in the near infrared (.7 to 1.06 μm) means that the laser can have a power level in excess of 1 mW but less than 0.5 W. Such a laser can be made safe by scanning, if the average power level is below that permissible for ocular interception for 20 seconds. Clearly the laser must be interlocked to the scanner, so that the laser does not turn on if the scanner is not functioning.

The final requirement and capabilities chart is shown in Table 2-2. All of the requirements are either met or exceeded. The exception is the minimum range. Conversations with the vendor indicate that there will be no difficulty in adjusting the optics to bring the minimum distance in to 3 ft. We have also arranged with the vendor to bring a scanning version of the Riegl laser to TRW in the mid-July time frame. This laser will be extremely close in design parameters to the laser that we would order. Tests will be performed at that time to determine the exact capability of the laser system.

Parameter	Requirement	Capability
Minimum Range	3 ft	will comply; require vendor to adjust optics from current design
Maximum Range	100 ft	200 ft.
Accuracy	0.5 ft	4 cm typical, 10 cm worst case
Scan rate	> 8 Hz	≤ 40 Hz
Sample rate	> 3 kHz	12 kHz
FOV	>60°	360°
FOR	Adjacent lane, rear facing	Adjacent lane, fore and aft; lane behind testbed
Eye-safety	Eye-safe	Class 3B; eye safe while scanned; laser shall be interlocked to scanner
Environmental	weather resistant	hermetically sealed

Table 2-2: Requirements and Capabilities Chart

2.4 Discussion

The data from the lasers we tested illustrate the fact that the return intensity does not follow the elementary $1/R^2$ dependence that we might expect from theoretical considerations. This being the case, the only assured way in which to determine whether the laser in question will satisfy our requirements is to test it in near realistic situations. This we have done, with the results shown above. The fact that we can demonstrate laser returns at over 200 feet gives us a comfortable margin in meeting our requirements. Moreover, this long range coupled with a 360° scanner allows us to use one laser to view an area of coverage that would correspond to meeting the pertinent specifications for lane change/merge.

3. Video Subsystem

The video subsystem is intended to provide a backup record of the positions of all vehicles in the same lane as the testbed vehicle and in the right adjacent lane. The primary responsibility for measuring position and velocity is assigned to the laser rangefinder described in section 2; the video system provides a backup in case of any laser malfunction and to resolve any ambiguities in the laser data.

3.1 Requirements

The video subsystem shall provide continuous imaging of the lane behind the testbed vehicle and the adjacent lane to the right. The field of view shall be sufficient to provide coverage of these two lanes around gentle curves in the roadway as are found on freeways, but not around sharp curves. The image quality and resolution shall be sufficient to identify vehicle type (automobile, van, truck, motorcycle, etc.) at a range of 300 feet; assuming there are no obstructions or other vehicles between the testbed and the vehicle. The video subsystem is seen as a fair-weather, daylight system. It is not required to perform in inclement weather (thick fog) or at night.

The video image must be time tagged in synchronism with the data acquisition system. The final requirement is that a continuous view must be presented to the operator, located in the rear seat of the testbed.

3.2 Design Approach

The approach to the video subsystem is to deploy an array of video cameras on the testbed vehicle. The location of each camera and its field-of-view are chosen to provide the required coverage and resolution. Four cameras will be used to provide the raw images, and the four images will be combined into a single image for display and recording. The option will be provided to display and record any single camera, or all four at the same time. A monitor will be provided for the operator to verify proper functioning. A video combiner (quad combiner of Figure 1-1) will take the output of all four cameras into one display that can be viewed on the monitor. A conventional SVHS VCR will be provided to record data. It is anticipated that the test drives will be approximately 2 hours in duration; therefore remote control of the VCR will not be required; we simply start the recorder at the beginning of the test drive and allow it to record unattended.

3.3 Implementation and Capabilities

Camera #1 will be mounted inside the car on the rear deck looking back through the rear window (see Figure 3-1). The camera field of view shall be 50° horizontal by 37.5° vertical. The camera has 600 pixels in the horizontal direction and 480 pixels in the vertical direction. This produces an angular resolution of 0.083° x 0.078° and a resolution cell of 0.43 x 0.41 foot at 300 ft range.

Camera #2 will be mounted at the right front fender and looking rearward (see Figure 3-1). The camera field of view shall be 20° horizontal by 15° vertical. The camera has 600 pixels in the horizontal direction and 480 pixels in the vertical direction. This produces an angular resolution of 0.033° x 0.031° and a resolution cell of 0.17 x 0.16 foot at 300 ft range.

Camera #3 will be mounted at the right rear fender and look forward (see Figure 3-1). The field of view shall be 20° horizontal by 15° vertical. The camera has 600 pixels in the horizontal direction and 480 pixels in the vertical direction. This produces an angular resolution of 0.033° x 0.031° and a resolution cell of 0.17 x 0.16 foot at 300 ft range.

Camera #4 will be mounted in the window of the rear passenger-side door, looking out to the right (see Figure 3-1). The purpose of this camera is to monitor for the presence of a vehicle in the portion of the adjacent lane not covered by cameras #2 and #3. This camera is only required to detect vehicles at short range, thus resolution and field of view are not issues. It is expected to be equipped with a wide-angle lens. Even though the actions of the display are under our control, we will mount a fifth camera, viewing the display.

The output signals of cameras 1-4 will be combined into a single RS-170 video signal. In this combined image the scene from each camera will be presented in one quadrant of the screen. In this process the resolution will be degraded by a factor of 2 in both the horizontal and vertical directions. This degradation is acceptable because previous experience with this combiner has shown that the resulting image will still have sufficient resolution to identify vehicles by type. The combined image will be saved on a SVHS VCR. An important advantage of the combiner is that it allows all the video imagery to be saved on a single video tape instead of requiring the use of 4 VCRs. If desired it will be possible to display and record the imagery from any single camera. A second VCR will be needed to record the imagery from the display camera (#5).

3.4 Discussion

In this testbed the video system is considered to be a secondary sensor, providing backup data to confirm the data from the primary sensors. As a secondary system, the requirements are not as stringent as they are for the primary sensor; for example there is no requirement to measure the range to other vehicles or to determine their velocity. There is also no provision to automate the processing of the video data. The video data will most likely be used in the shakedown phase to verify correct operation of the primary sensor, and then later on as a supplement to the data from the primary sensor. It is important to note that the field of view does not abruptly end at the edge of the adjacent lane and is thus adequate for covering any possible merge scenario.

The details of how these cameras are to be mounted on the testbed vehicle have not been addressed, pending the arrival of the vehicle at TRW. Given that VRTC is nearly complete with its modifications, there is no schedule impact. The general plan would be to weld or bolt some fairly simple brackets to the frame or bumpers of the vehicle and mount the external cameras to these brackets. The mounting will be such that the cameras will be easily removable. The internal cameras would similarly be mounted to some convenient rigid structure inside the passenger compartment. Very little range of adjustment will be provided in the mounting of these cameras; once installed the fields of view will not need to be adjusted.

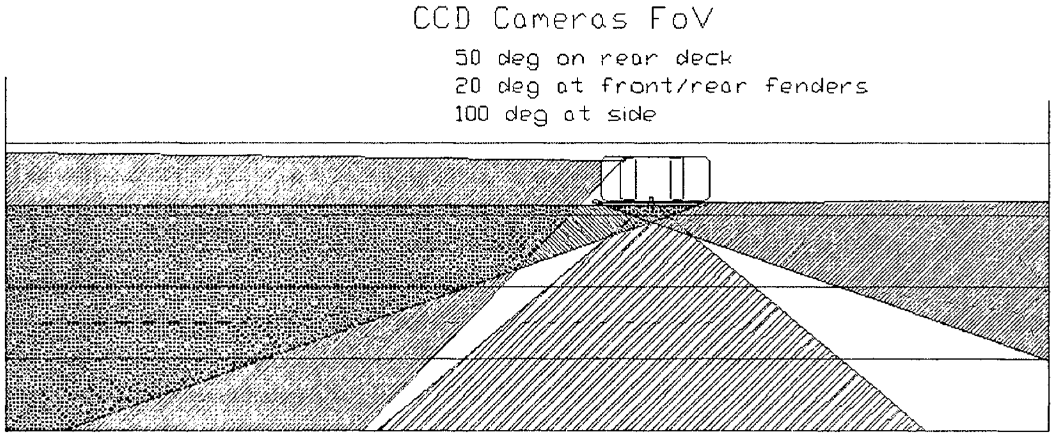


Figure 3-1: Field of View of Ground Truth Cameras

The selected hardware for the video subsystem is shown in Table 3-1.

Item	Description	Manufacturer/Model
Camera	Compact color camera	Hitachi VK-6370
Time code gen.	SMPTE time code generator	Horita TRG-50PC
VCR	SVHS VCR	Panasonic AG-7400
Combiner	Video Combiner	Robot Multivision Processor MV-85
Flat panel display	10.4" x 7.7" screen	Computer Dynamics FPKIT-H927

Table 3-1: Video subsystem hardware

4. Eye-Tracking System

In order to estimate the effectiveness of a collision warning system and to optimize the specifications for maximum effectiveness, one needs to measure its effect on the driver. By constantly monitoring the driver eye gaze, the eye-tracking system will allow one to quantitatively assess the impact of a CAS on the driver's habits.

4.1 Requirements

The requirements on the eye-tracker are listed in Table 4-1.

Parameter	Requirement
Field of View	- 60° to + 170°
Accuracy	1°
Update rate	30 Hz
Environment	Usable information in lighting conditions ranging from bright sun to night, at > 90% of the time.

Table 4-1: Eye-tracker requirements

The above requirements are derived as follows. The field of view originates from the desire to monitor the area between the left side view mirror and the right rear corner of the car, assuming a system designed to study lane changes and merges to the right. The idea is to cover not only the right blind spot, but the entire area on the right hand side of the car. Accuracy is not a major issue here, so that 1° was chosen as a nominal compromise. In fact, it may be sufficient to divide the field of view into zones and simply record the zone number. The update rate was chosen to be the same as the video frame rate; this is not a hard number. Finally the issue of environment is of some concern. The eye-tracker must function in a variety of lighting conditions; from bright sun to night driving. With a 90% response requirement, it was felt that the unit would produce useful data most of the time, and it would be possible to interpolate between known points where the driver was looking during those few times when the unit could not track.

4.2 Design Considerations

The principle behind the eye-tracker is illustrated in Figure 4-1. The eye is illuminated by a low level IR source (1 mW/cm^2 at 850 nm). If the illuminator and the camera are not coaxial, the pupil acts as a sink while the cornea is reflective. As a result, the contrast between the dark pupil and the white cornea is enhanced, allowing the image processing boards to determine the position of the pupil in real time.

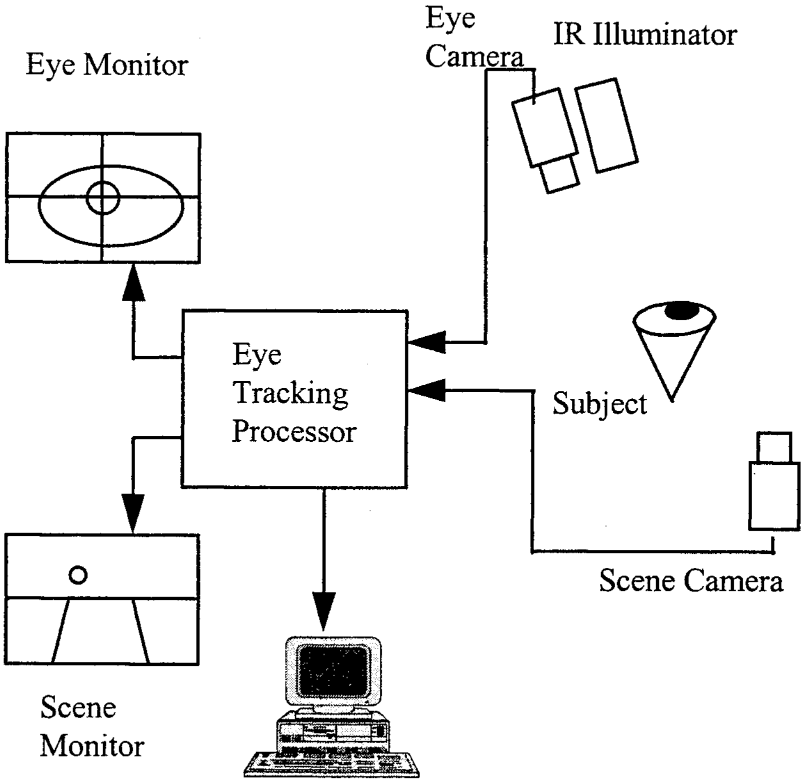


Figure 4-1: Eye-tracker Schematic

Determining the position of the eye is only half the job. The other half is determining the head position. There are two possibilities. The first is termed remote monitoring, wherein the illuminator and camera are mounted away from but pointing at the subject. This method relies on finding the positional difference between the pupil and corneal reflection. This difference is seen to correlate with pure eye rotation. It is a result of the fact that the cornea is spherical in the region of the pupil. This effect is linear over a ± 15° field of view, and is therefore limited to this range in eye gaze direction.

For a less limited field of view, the camera and illuminator are mounted on a headband or visor. A dichroic mirror is set at an angle in front of the subject's eye, as seen in Figure 4-2. The eye position is determined optically, while the head position is monitored by a magnetic sensor mounted on the headband. The sensor measures the local magnitude and direction of a pulsed magnetic field, generated by a fixed coil located near the driver's head. An alternative version of a head tracker would be to locate a tiny video camera on the top of the subject's head looking at a fixed constellation of shapes, attached to the roof of the passenger compartment. The image processing routines would then determine the head orientation. The advantage of this method is the elimination of the clutter due to the coil necessary in generating the magnetic field.

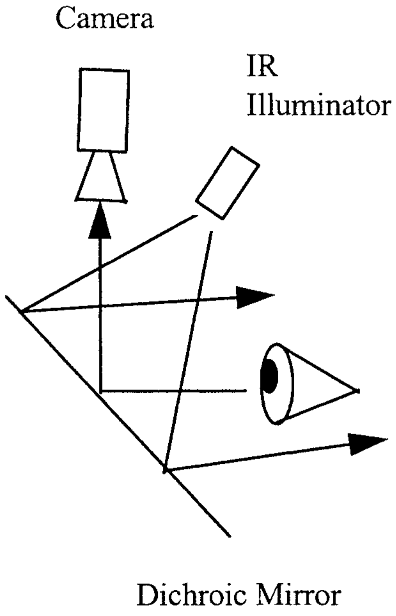


Figure 4-2: Head-mounted optics

The tradeoff here is between having a system that would minimize inconvenience to the driver or one that would produce data over a considerably greater field of view. The decision was to choose the latter over the former. The reasoning is that at this early stage of the research, it would be better to tolerate a slight inconvenience in exchange for a greater range of data. If in the future, after some experimentation, we see that a remote system is acceptable, we could acquire it and plug it in to the existing processing system.

ISCAN, Inc. of Burlington MA was chosen as the vendor. They offered the most flexible system at an affordable price. Most important of all, they were willing to cooperate with us to make whatever modifications would be necessary to make the system perform in a vehicle. As part of their willingness to demonstrate their system, they integrated it into a van and drove it around both during daylight and at night. The resulting video that was sent to TRW showed that in bright sun, the system functioned better than 95% of the time. It was seen that sunlight entering from the windshield was not much of a problem. This is because the dichroic mirror in front of the driver's eye would reflect the IR from the sun away from the video camera. Sunlight entering from the side does cause a problem. This problem however, can be mitigated by installing an IR reflective film on the side windows. Driving at night, even in the face of oncoming headlights was not seen to be a problem.

ISCAN also sent us a prototype head mounted system to test. It was basically a sun visor with the illuminator, camera and mirror mounted on the brim. It was extensively tested over a weekend by one person. Within a few minutes one could easily adapt to wearing the visor such that the mirror in front of the subject's eye was barely noticeable. The intrusiveness could be further diminished by polishing the edges of the mirror and its plexiglass support. Almost all of the other people who tried the visor thought they would have no trouble driving with it. Those who objected felt that the visor itself was either too tight or too loose. It may be necessary to have a selection of visors of varying sizes available for a test subject to choose, and then attach the electronics to the chosen support.

4.3 Requirements and Capabilities

The ISCAN system will meet or exceed all of the requirements listed in section 4.1. The field of view will be a full 360°, and the accuracy is better than 1°. The way in which we plan to use the eye tracker is to divide the field of view into zones. The system will then output which zone the gaze direction intersects. ISCAN has already made the necessary modifications to the software to produce this type of output. Day/night usability was discussed in the previous section and was seen to be more than adequate.

5. Data Acquisition System

The purpose of the data acquisition system (DAS) is to provide an integrated system to collect and store the data from all the sensors described in the other sections of this report. In addition the data acquisition system will record selected parameters concerning vehicle operation, such as speed, turning, braking, etc. Note that there is a second computer required by the eye-tracker system which is described in the appropriate section of this report.

5.1 Requirements

The data acquisition system shall receive data from the eye-tracker subsystem, the laser rangefinder subsystem, and other sensors that provide either voltages or frequencies proportional to parameters to be recorded. Data from the eye-tracker shall be one byte reporting the "zone" at which the driver is looking; this data shall be provided in serial RS-232 format at a rate that does not exceed 60 samples per second. Data from the laser rangefinder shall consist of the look angle, the range to the nearest object detected, and the strength of the return. This data shall be provided over a parallel interface at a rate that does not exceed 12,000 samples per second. Data from the vehicle sensors shall consist of analog voltages or frequencies that are continuously available and sampled by the DAS at a rate consistent with the data rate from the other sensors. Data from all sensors will be combined into a standardized data record, time tagged, and stored. Storage capacity shall be sufficient to accommodate all data from a typical two hour test drive, and a means shall be provided to rapidly and conveniently transfer the data from the vehicle computer to a ground system for processing and archival.

The DAS shall provide output signals to accomplish the following functions: synchronize the SMPTE time code generator to the real time clock in the computer, provide a control function to the laser rangefinder and scanner to set the firing rate of the laser and the scan rate, and provide signals to a display for the driver to serve as a lane-change/merge collision warning.

5.2 Implementation and Capabilities

The data acquisition system will be based upon a PC-class computer with special-purpose I/O cards installed as necessary. The intention is to provide a state-of-the-art computer at the time of delivery. Currently that would be a 200 MHz Pentium Pro computer, but the pace of development in computer systems is sufficiently rapid that we must guard against a premature commitment to a particular technology. For that reason the details of computer selection are best delayed as long as possible.

Interfaces to the SMPTE time code generator and the eye tracker system can be handled by serial RS-232 ports. The time code generator chosen is a Horita TRG-50 model. Typical PC configurations come with 2 serial ports that can be used for these interfaces. The laser rangefinder system will interface to the data acquisition system through a bi-directional parallel port. The parallel port is required to handle the larger data flow from the laser, and a bi-directional port is required to send commands to the laser and receive data back. This interface is the standard printer port on a PC.

Recording the vehicle parameters will require some extra data acquisition cards in the PC. The plan is to monitor the brakes and turn signals by monitoring the voltages applied to the indicator lamps accessible from the trunk interior. Steering angle will be monitored as an analog voltage derived from a potentiometer coupled to the steering column. Vehicle speed will be monitored by tapping a pulse train or waveform available from either the transmission or the ABS system. Voltages will be recorded by a scanning ADC card (Metrabyte DAS-800 or equivalent) and the pulse train to get vehicle speed will be monitored by a counter/timer card (Metrabyte CTM-05 or equivalent).

The DAS computer will also be equipped with a Digital Signal Processor (DSP) card capable of operation at 33 MFLOPS. The plan is to use the same DSP card (Sonitech Spirit-30) used on other projects to take advantage of the experience gained in learning how to program this particular DSP. The data from the laser rangefinder will be processed through DSP to convert range-angle data to rectangular coordinates, identify hits on same target from scan-to-scan, and calculate relative velocity between the testbed vehicle and the target vehicle. Based upon the range, relative velocity, vehicle speed and turn signal status, the DSP will decide whether to activate the driver warning system. The current decision is to use a time to collision algorithm to activate a warning. A visual warning will always be engaged; the auditory warning will be engaged only if the turn signal is activated. It is anticipated that during the course of the program various algorithms will be tested. The primary means of eliminating nuisance alarms would be to determine if the relative speed of a detected object is within some value of the testbed speed, then presumably the object is fixed on the ground and is not a threat, so therefore no alarm would be given. An order of magnitude estimation of the power required of the DSP would be as follows. The number of instructions per second of the laser would be 1000 instructions/degree x 270 degrees/scan x 30 scans/sec ≅ 8 MIPS. Add to this approximately 6 MIPS for data output and communication (from Task 5 Interim Report: Crash Countermeasure Technology Investigation). Taken together this requirement is well below the 33 MFLOPS capability of the chosen DSP. The is not overkill, since it is difficult these days to get a DSP with less power. In this case one can consider a MIP as equivalent to a MFLOP. A block diagram of the DAS is shown in the upper portion of Figure 5-1. The DSP will activate the various display lights by closing the appropriate solid state relay.

The primary purpose of the DAS is to store the data from all the various sensors in a common file structure for later retrieval and analysis. The vast majority of the data comes from the laser rangefinder, so it is logical to structure the data records around the operation of the rangefinder. A data record will consist of the data from one rotation of the scanner along with the current value of all other parameters at the beginning of the rotation. Each record will have a header which will provide a run identifier and a time stamp. An example of one data record is illustrated in the lower portion of Figure 5-1. The net data rate, driven essentially by the laser alone, will be less than 98 Mbytes per hour (3 bytes/sample [range, angle, intensity] x 12,000 samples/sec x 3600 sec/hour x 0.75 duty cycle). We plan to use a 1 Gbyte removable hard drive, so in principle we could record continuously for 10 hours.

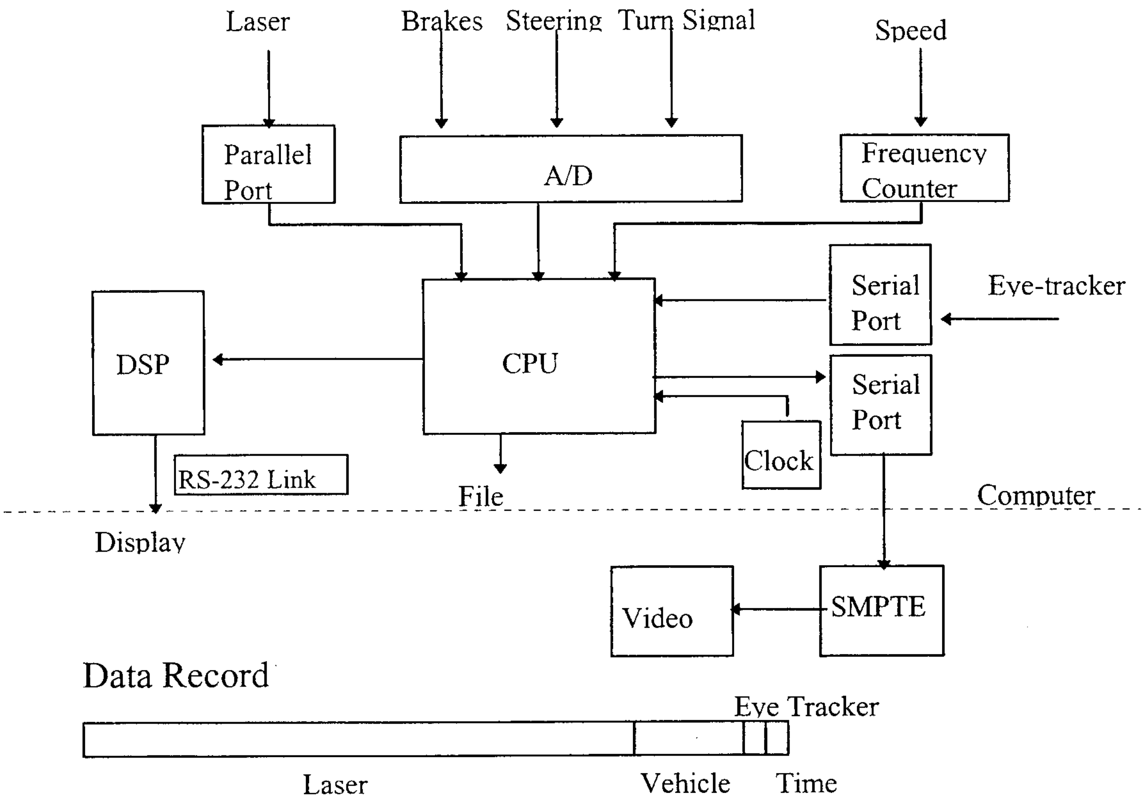


Figure 5-1: DAS and Data Record Schematic

5.2.1 Software

There are two main functions of the software on the testbed. The first is data acquisition and control and the second is running the CAS. The tasks delegated to the data acquisition and control segment have been adequately detailed in the above section. The main product of this segment is a file output that contains all the time tagged laser, vehicle, and eye-tracker data for post-test analysis.

The CAS flow segment is illustrated in Figure 5-2. There are five key processing steps to take the output of the scanning laser and make a decision about what warning, if any, to display to the driver. These separate processing steps will be discussed in order below.

The scanning laser will output a series of ranges for any detected object. This is done for each scan at specified angles. In addition, the amplitude of the scattered return will be recorded. In this way a set of data like that shown in Figure 2.1 will be acquired. Based on the extent of the detected object and the amplitudes of the returns, a decision will be made about the validity of the object's existence. This is the target detection step.

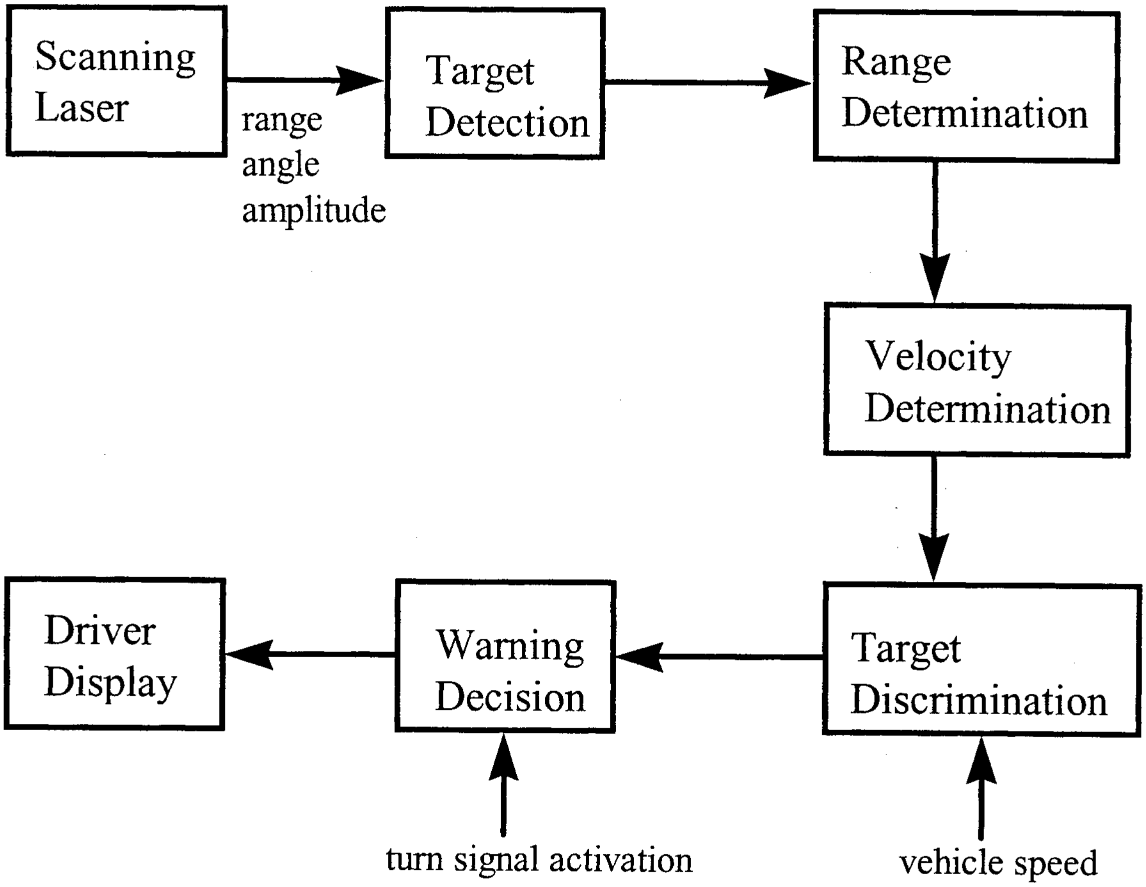


Figure 5-2: CAS flow algorithm

For each scan associated with a detected target, the range and amplitude is recorded at each angular step. A simple algorithm has already been implemented that looks at each contiguous set of ranges over angle and picks the closest value for each scan. That minimum range is assigned as the target range. It is prudent to base any warning on the nearest range of an extended object. In addition, that selection leads to a relatively smooth history of the targets range history. Range data derived in this manner from a scanned laser system is displayed in Figure 2.2.

There are well-established techniques for generating smooth estimates of range and velocity from sequential measurements of a target's range. This is called filtering. Basically, all filters produce future estimates of the target's position and velocity based on the previous trajectory and the present measurement. There are simple approaches that use a fixed ratio of the past trajectory and the present data. One such filter, called an alpha-beta tracker, has been applied to the data shown in Figure 2.2. The resulting range and velocity are displayed in Figure 2.3. One of the most widely implemented algorithms is the Kalman filter approach wherein variable ratios of past and present information are utilized depending on the quality of the measurements. The fixed coefficient filter, the Kalman filter and perhaps other approaches will be tested against the actual scanning laser data and a preferred technique will be chosen.

Given the target's range and velocity, a final decision about issuing a warning can be made. Because a relatively extensive area is being monitored, there are a number of non-threatening targets that may be detected and tracked. By knowing the speed of the instrumented vehicle, a computation can be made to determine if the detected object is fixed or moving. Fixed objects, such as, parked cars, guard rails, road signs, etc. can be discriminated against by comparing their relative velocity to the speed of the testbed.

After that target discrimination step, the final computation involves a decision about the level of warning to issue to the driver, if any. Based on the object's speed and range, a calculation of the time it will take to reach the area where it could potentially interfere with a lane change can be determined. Of course, if the target is close enough to the testbed, it will always pose a threat. Thus a simple binary decision can be implemented based on the deduced range and speed. A rough, preliminary example of the decision space is given in Figure 5-3. Of course, the exact borders of the decision region will be determined during testing and they may be driver-dependent. Also, a different warning algorithm and modality may be applied depending if the turn signal has been activated or not. Note that a negative range has no meaning for a ranging device and hence is marked as non-physical in the figure.

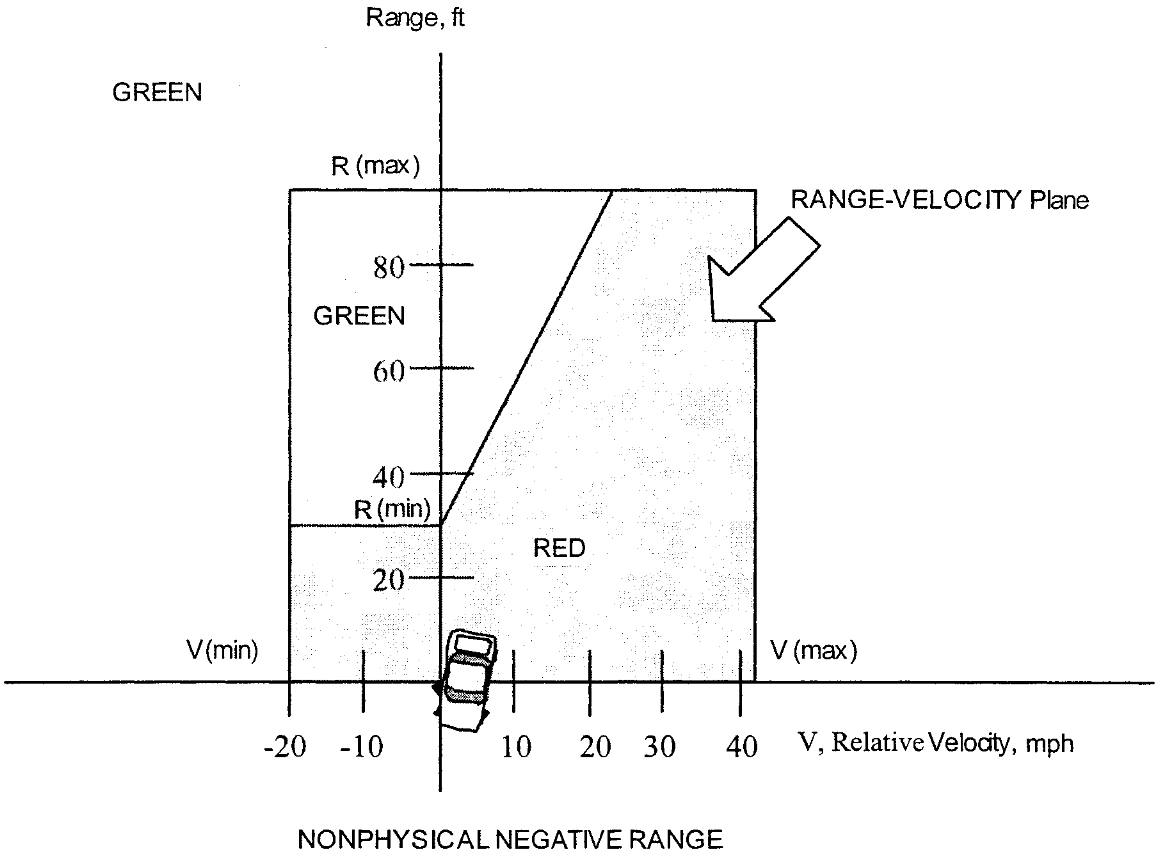


Figure 5-3: Lane Change Decision Regions

The framework for the signal processing required for the activation of the driver interface has been developed and several algorithms have been already implemented. Specifically, the target detection, range determination, and velocity determination functions have been written and tested on the limited data acquired during our laser evaluation tests. The target detection function is provided as part of the scanning laser radar system and its capability is shown in Figure 2-1. Figure 2-2 displays two range profiles extracted from the raw laser data. The simple range determination approach was described in Section 2.2. The ability to determine velocity from the range data is illustrated in Figure 2-3. The results of a filtering of the data is also included in that figure. These figures display the results of the key signal processing steps that are required to turn the raw laser radar data into range and velocity measurements. In order to fully implement the target discrimination and warning decision algorithms, much more data is required along with feedback from drivers. Examples of these algorithms have already been implemented at TRW for different applications, primarily relating to the development of automotive radar. As we acquire hardware during Phase III, we will fully implement this processing chain to test its performance both in the laboratory, in restricted testing, and in real-world tests.

The final software segment is that reserved for post processing. Realistically this segment will undergo continual refinement as researchers ask new questions about drivers' behavior. Because all the data will have been stored, it would be fairly simple to re-run whatever cases are desired. The following information is currently planned to be available. Data analysis will be triggered by the initiation of a turn signal. The window will start approximately two seconds before the start of the signal and extend until it is turned off. This length of time will be adjusted as needed. Information collected will be the forward and rear gaps to any vehicles, driver gaze direction as a function of time and time to complete the maneuver. Also recorded will be a time history of all the vehicle inputs plus the CAS response, if it is engaged at that time.

5.2.2 Control

Issues relating to self testing and fail-safe operation are best handled by the data acquisition system. The requirement for driver override is met trivially by simply switching off the display. Since the CAS is only a warning system there is no other impact on vehicle safety.

The system will be designed to be continually self-testing and hence provide a current indication of its state of health. Since the laser will rotate a full 360 degrees, it will spend some of its time looking at the testbed vehicle. If we monitor the strength of the laser return from the same point on the vehicle approximately every second, we have the first necessary condition for fail-safe operation. The second necessary condition comes from the data acquisition system self monitoring of the expected data inputs. The data must fall within expected ranges, otherwise the operation of the algorithm may be faulty. Passing of these two tests will cause a light to be lit on the display, telling the driver that the system is operating properly.

5.3 Discussion

In general the requirements of the data acquisition system are not very demanding; the data rates and capacity required are well within the current state-of-the-art, and all the sensors for the vehicle parameters are straightforward.

6.0 Mechanical Installation Considerations

This section describes the general approach to installing the required equipment in the testbed vehicle. A few general principles will be followed:

- Install as much equipment as possible in the trunk.
- Allow access to service, maintain, and upgrade all equipment.
- Make minimal changes to the vehicle.

6.1 Equipment installed in the trunk

In general everything not required to be elsewhere will be installed in the trunk. This will include the following equipment:

- battery
- inverter
- PC for the eye tracker system
- PC for the DAS system
- VCR
- VGA to NTSC Video converter
- SMPTE time code generator
- Laser rangefinder power supply and control electronics

All equipment will be rigidly mounted in the trunk; nothing will be left free to move. Equipment such as the computers and the VCR that may be sensitive to vibration will be mounted in a manner such as to minimize transmission of the vibration to the sensitive object. Previous experience has shown that vibration is not a serious problem for such systems mounted in vehicles; therefore elaborate precautions, such as solid state disks, are not called for.

The details of the mounting will be finalized now that the vehicle has been identified, but no problems are foreseen in fitting this much equipment in the trunk of a full-sized car.

6.2 Equipment installed at operator station in the back seat

It is intended to establish an operator's station in the right rear seat of the testbed vehicle. From this station the operator will be able to set up all the parameters for a particular test period, perform any required calibrations, and monitor the proper operation of all systems during the test. To perform these functions the operator will need access to keyboards for both computers, a computer display to monitor the laser rangefinder and the vehicle parameters, a video display to monitor the output of the video cameras, and both of the video combiners to select which camera(s) to display.

For the computer display it is intended to use a flat-screen LCD display mounted in the back of the front seat. The details of the mounting will be finalized now that the vehicle has been identified, but what is planned is a fairly simple bracket that either hangs over the back of the seat or clamps to a headrest post. The balance of the equipment will be installed in a mini-rack placed on the seat next to the operator, similar to what is shown in Figure 6-1. The mini-rack will be restrained securely to the seat belt anchors, similar to the way in which a child safety seat is installed. Its height will be restricted so that it does not extend beyond the top of the front seat.

Referring to Figure 1-1, the two quad combiners allow the operator to perform tasks with a minimum of monitors. Before the run, he can monitor all the video outputs of the eye tracking system in order to establish the calibration. After calibration is complete, it is not anticipated that it will be necessary to refer to these cameras during the run, so the operator can then switch to the scene cameras and monitor these continuously.

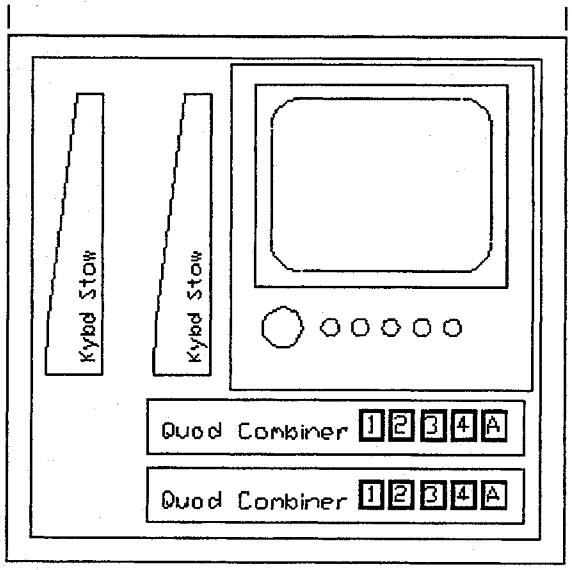


Figure 6-1: Rear Seat Rack

6.3 Equipment installed on the outside of the vehicle

Equipment that is to be mounted on the outside of the car will be removable at the end of the day so that the vehicle can be parked anywhere overnight. The equipment that falls into this category are the scanning laser and the forward and rear directed cameras. As detailed above, the part of the laser that needs to be mounted in this fashion is the rotating mirror and optics. This will be a cylinder of approximately 6 inches diameter, 8 inches in length that will be mounted at bumper height. The unit will be rigidly mounted to a box beam frame that will be welded to the structural members of the car. The forward facing camera can be mounted to this same frame, while the rear facing camera since it is small and lightweight will be attached at a convenient position to be determined when the vehicle arrives at TRW.

7.0 Electrical Power System

7.1 Requirements

The electrical power system shall provide ample power at both 12 VDC and 110 VAC. It should also be capable of isolating the vehicle electrical system from the data acquisition system, so that there will be no possible impact on the safe operation of the vehicle. Complete isolation shall satisfy the fail-safe operation requirement spelled out in the CET, section 4.6.2.

7.2 Implementation and Capabilities

In order to plan the electrical system it is first necessary to determine the power consumption requirements of the items being added to the vehicle. The major power consumers are listed in Table 7-1, with those items that require 12VDC ,so designated.

Item	Quant.	Power/unit (w)	Total Pwr. (W)
Computer	2	100	200
Video MUX (12v)	2	15	30
Flat Panel	2	30	60
cameras (12v)	4	5	20
Laser scanner	1	200	200
VCR	1	30	30
			540

Table 7-1: Power Budget

The power budget indicates that a 500 watt inverter will be barely adequate for the AC needs. Therefore a 1000 watt true sine wave inverter (EXCELTECH SI 1000-012) has been selected. A true sine wave inverter is preferred because it will generate the cleanest sine wave for the AC components.

The block diagram for the electrical system is shown in Figure 7-1. We will use a dual battery isolator to isolate the vehicle from the system battery. The alternator will be sized for at least 120 Amps.

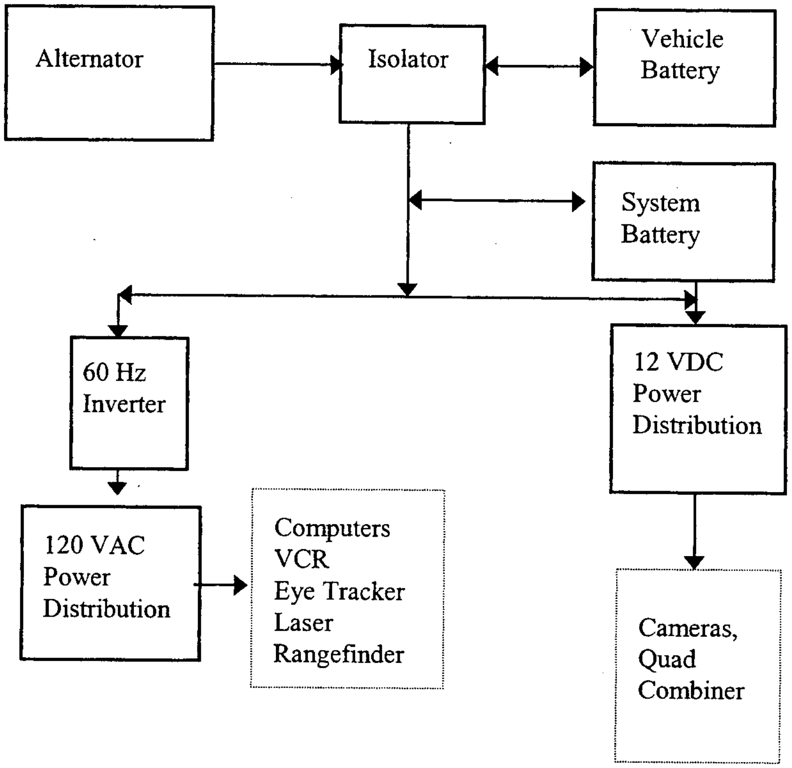


Figure 7-1: Electrical Subsystem Block Diagram

8.0 Associated Test Facilities

Ancillary facilities associated with the testbed are 1) laboratory equipment, 2) office computers 3) assembly and integration areas, and 4) restricted access field test area. TRW maintains an extensive pool of test and measurement equipment that can be used on this project as necessary. There has been extensive upgrading of desktop computing facilities within TRW as of late. Members of the project team all have 200 MHz Pentiums on their desks with which they can process the data gathered from the test drives. Laboratory space for subassembly development has been secured in Building R1 on the TRW campus in Redondo Beach. This space is associated with the department containing the key personnel on this program. A commitment for space in Building 67 to integrate the equipment into the vehicle has also been secured. This building has a large roll-up door, that can accommodate the car and also store it overnight. This building is also equipped with machine shop facilities.

In the area around the TRW facilities there are many parking lots that can be roped off to perform the tests defining the coverage zone and delay times. Specifically, this would be the areas around buildings R1 and R6. Both of these areas have unobstructed sections of at least 400 feet in length. In addition these outdoor areas will be useful in checking calibration of the scanning laser, both during the shakedown phase and the data gathering phase of the coming program. The area in these parking lots is sufficient such that speeds of up to 30 mph can be easily accommodated. These areas will be used extensively to calibrate the laser system and check out the operation of the warning algorithms.

It is the opinion of TRW that all calibration and algorithm checkout can be performed with the testbed vehicle stationary. It is possible to accurately determine the lateral and longitudinal position of a passing car by having it drive over a fixed flexible marker at a known position and determining the exact time of this event using the video system. This would be the most cost effective means of performing this task. Sensitivity to clutter and fixed objects can be determined in exactly the same fashion as in phase I, by means of a series of road tests.

The customer requirement of using a test track to test the algorithm performance introduces a significant level of complexity. Once the testbed is put into motion, a method of determining relative positions of the testbed and the chase vehicle must be used that has an accuracy on the order of the system being used, namely the scanning laser. For this purpose the video system is totally inadequate, especially at long ranges (up to 100 feet). Using Figure 4.4-1 from the Task 3 final report we see that the relative uncertainty in the longitudinal position of the chase vehicle exceeds 100 per cent for distances greater than 65 feet, using a two camera triangulation method. In addition, we are making a concerted effort in this phase of the program to develop a system that is automated so that maximum information can be extracted from the tests.

Accordingly we are proposing the use of a differential GPS system with a local base station to provide the relative positions and velocities of the two vehicles involved. One GPS antenna will be mounted on each of the two cars used in the test. Using an Ashtech Reliance Decimeter System we can achieve an absolute positional accuracy of 10 cm, after the system has maintained satellite lock for greater than 20 minutes. After 45 minutes, the accuracy is reduced to 1 cm. This is quite comparable to the laser accuracy of 4 cm. Data will be taken once per second, with a timing pulse outputted to the data acquisition system for correlation with the scanning laser. The timing jitter of the pulse output is less than 100 nsec. This is well within our requirement of 10 msec, which derives from the restriction of any relative motion be less than one foot at a relative velocity of 30 mph. Data from this system will be postprocessed to display the tracks of the two vehicles, and their positions when the CAS delivers its warning.

TRW has located a test track in Devore, CA about 60 miles from Space Park, operated by the San Bernadino Sheriff's department. The test track, or the entire facility is available to be leased on a daily basis. The track is a 1.5 mile triangle. The straight sections are about 500 feet in length and can easily accommodate speeds of approximately 70 mph. There is one tight turn, with a 35 mph limit, while the other two turns can accommodate 50 mph.

9.0 Conclusions

The broad outlines of the testbed as described in the TAP has been verified by analysis and test. In fact the current design of the testbed has expanded its utility by the broadening of the scanning laser field of view to include the forward direction in the adjacent lane. This allows us to monitor the forward as well as the rear gap spacing that a driver will require when making a lane change. It will also allow for tracking of merging vehicles at greater ranges, for all azimuths. Along with the other features of the automated testbed, the capability for acquiring meaningful data in a timely manner has been greatly enhanced.

Overall performance in adverse weather conditions is reliant on our two key sensor systems; the eye tracker and scanning laser. The eye tracker performance with respect to bright sunlight has already been discussed. It's performance on foggy and rainy days should be equivalent to that during night, which has already been shown to be unperturbed. The scanning laser will be unaffected by bright sunlight. This is primarily due to the fact that the receiver optics include a narrow bandpass filter, centered around the laser wavelength. Its performance however may be affected by fog, rain or snow. This is because laser light will continuously scatter off water droplets in its path to the target vehicle. As presently configured, the laser electronics looks for the first strong return and calls that the target. The vendor has just come out with a new version that is geared for dusty environments such as construction or factory sites. In this case, the laser electronics looks for the last strong return, which would be the intended target (such as a vehicle). The price one pays for this laser is a loss in resolution by better than a factor of two. It was decided that at this early stage without extensive testing experience that accuracy should not be sacrificed.