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ABSTRACT

A low cost system has been developed to measure a vehicle's lateral position relative to the lane markings on a roadway. The system is capable of tracking white or orange lines, solid or dashed edge lines, while operating in daylight or at night. The tracking system is comprised of two "off-the-shelf" black and white charge coupled device (CCD) video cameras along with commonly available electronic components. The lane tracking system is capable of outputting real time data at 30Hz through an analog output. Using the data from this sensor system it is possible to detect lane changes, determine the magnitude and duration of lane exceedances, and other metrics commonly used by researchers in the transportation community. This paper will discuss the design and performance of the system, processing of the raw lane tracker data, and the benefits and limitations of the technology.

INTRODUCTION

Lateral position of a vehicle relative to the roadway's lane boundaries has been an important measure for many of the National Highway Traffic Safety Administration's (NHTSA) crash avoidance research programs. Drowsy driver research (Weirwille, 1996), run-off-road research (Pomerleau, 1995), lane change merge research (Chovan, et al, 1994), and automated highway systems research (Hatipoglu, et al, 1997) are several examples of programs in which lateral position measurement or lane tracking has been an important measure. This metric has been used to address issues related to driver attention as well as the performance of vehicle control and collision avoidance systems.

Historically, lateral position has been measured by calibrating a video image to the roadway using a mapped field of view allowing the data to be reduced manually by an observer. This method is very time consuming and labor intensive when dealing with large amounts of data. Over the last several years, many advances have been made in automatic sensing of vehicle lateral lane position. Generally, there have been two methods of sensing which have become popular. Vision based systems such as the Rapidly Adapting Lateral Position Handler (Pomerleau, 1995), Ohio State University's Demo '97 vehicle (Ozgüner, et al, 1997), and others have become quite popular. Most of these systems use a forward looking video camera. Some are capable of outputting data other than lateral lane position such as radius of curvature and can even continue to provide lane tracking data when there are no painted edge lines present. A major drawback of a vision based system is cost. These systems are estimated to cost greater than $10K per unit (small quantities 1-20).

A second type of technology being used for measuring lateral lane position includes sensors which work with an installed infrastructure. These methods rely on magnetic nails, RADAR striping (Ozgüner, et al, 1997), or other devices installed on the roadway and work in conjunction with sensors on the vehicle. One advantage of these technologies is that, in theory, they offer better performance on roadways obscured by snow or debris. Drawbacks to these technologies are that an investment needs to be made into the infrastructure since they will not work on existing roadways.

Given the importance of this measure and lack of availability of commercial systems, NHTSA's Vehicle Research and Test Center (VRTC) has developed an approach that meets the need for a low cost lane position measurement system to be used in it's research programs. The latest version of the system uses a low cost and small (1.25" x 1.25") black and white video camera as the sensor. The sensors can be mounted in the side view mirrors or on the rear end of a passenger vehicle. The video signal from the camera is fed to the analog and digital processing board developed by engineers at VRTC. The cameras used in the VRTC system are sensitive to near infrared light and thus the road can be illuminated at night with infrared light that is not visible to humans. A complete system, both left and right side trackers, costs approximately $1000 in small quantities (10 systems) which includes parts and labor. It is anticipated that this cost can be greatly reduced if the system is produced in larger quantity.

GENERAL SYSTEM OVERVIEW

The lane tracking system is a simple system which provides accurate lateral lane position measurements. For the system to function properly, the roadway must have visible painted lane edge markings. The system is capable of outputting raw data in real time representing how far the painted edge line is from the center of the vehicle at an update rate of 30 Hz. The system is built from commonly available electronic components which are available off the shelf from a variety of electronics stores. The lane tracker is powered directly from vehicle power, requiring 12VDC unregulated input at 200mA.

DESIGN OF THE SYSTEM

The lane tracking system uses any black and white camera capable of outputting a standard National Television System Committee (NTSC) video signal. The system performs analog signal processing, looking for a section of the video that has the signature of a painted edge line. By using an off the shelf camera the flexibility of mounting the camera is greatly increased and all the circuitry for the iris and scan control that would be associated with using a one dimensional line scan camera are eliminated.

A major part of the “processing” circuitry is an LM1881 video synchronization (sync) separator integrated circuit (IC). This IC accepts an NTSC video signal input and provides vertical and composite (combined vertical and horizontal) sync output pulses. These pulses allow using relatively simple circuitry to “process” the video signal, by providing information concerning the time location of the horizontal and vertical sync pulses. The vertical sync pulse from the LM1881 is used to find the middle of the video image.

At the start of each frame, an 8.3 ms delay is triggered by a one shot timer. After this delay, a scan line timer is started $9\mu s$ after the next horizontal sync pulse. The $9\mu s$ timer allows the “back porch” of the NTSC signal to be ignored so that only the scan line intensity information is analyzed. Figure 1a displays the raw scan line intensity information which would be analyzed by the system. Figure 1a also shows an offset in the video signal. This is very common due to non-uniform background intensities, such as shadows, surface variations and glare. The raw video signal is high pass filtered to remove low frequency intensity changes. With only edges remaining, the scan line is analyzed for a step increase in intensity followed by a step decrease in intensity (i.e. edge detection, see Figure 1b.). The tracker will only trigger if the video has a step increase in intensity and then a subsequent step decrease in intensity within a certain window of time. Therefore this requires that for a painted edge line to be found it needs to be a certain width. This allows the system to work better if there is a shadow cast by the vehicle on a sunny day.

For the system to track a roadway line, two conditions must be met. First the step increase and decrease must exceed a threshold set during construction of the system. Second, the time between the step increase and step decrease must fall within a set period.

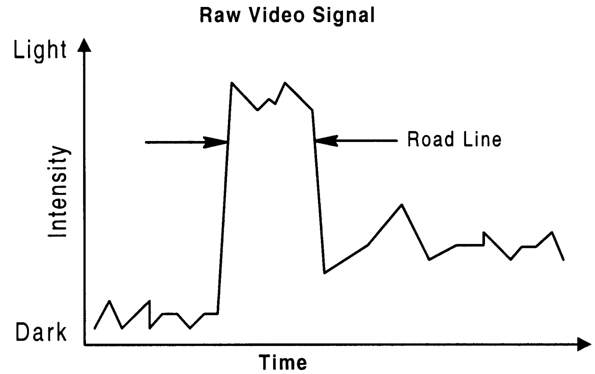

Figure 1a. Raw video signal intensity from one video scan line.

The thresholds are programmable and are optimized to provide reliable line detection while minimizing the tracking of false targets. The upper and lower thresholds are shown in Figure 1b. During construction a test pattern is placed into the field of view of the tracker sensor which provides a contrast ratio of approximately 1.3:1. The contrast ratio is determined by measuring the luminance of the simulated line divided by the luminance of the background image. The thresholds are adjusted so that the system triggers just when the signal exceeds the background intensity level by 1.3.

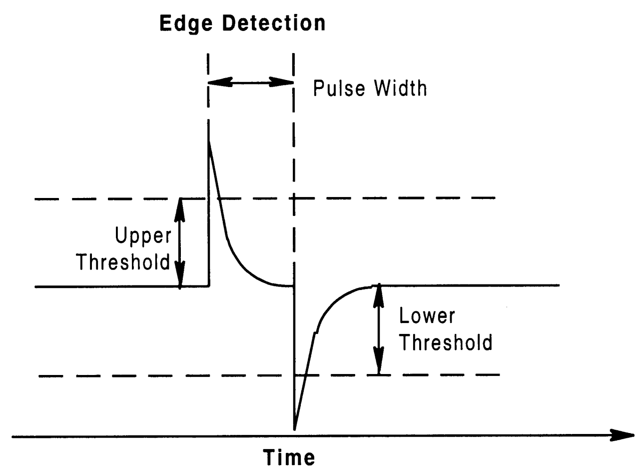

Figure 1b. Edge detection after the raw video signal is high pass filtered.

The time between the step increase and step decrease is used to filter out false triggers that the system may track by solely relying on the thresholds for triggering. By setting a minimum and maximum time width for the pulse, a basic line width detection scheme is implemented. The pulse width must be greater than 1 s and less than 4.5 s wide. This approximately correlates to a minimum line width of 5 cm and a maximum width of 20 cm which compensates for geometrical distortions in the 2D image.

If the system is triggered, the value of the scan line timer is outputted to a digital to analog converter (DAC). The value of the scan line timer indicates the location of the edge line within the horizontal field of view of the camera. The analog output from the 8 bit DAC can then be recorded by a data acquisition system or other device. The output value of the DAC is held until a new value is sent from the scan line timer. The analog output is a 0 to 2.5 volt signal.

A status bit was added in the latest version which provides an output that is logic high when the system is triggered, and a logic low if not triggered during the scan line. This output can be recorded along with the analog output signal providing an indication of when the DAC output is not being changed, thus indicating that the tracker is not tracking an edge line.

INSTALLATION

The lane tracking system is installed in one of two ways depending on the requirements for the data being collected. Both methods require the sensor's field of view to be aimed directly towards the ground as seen in Figure 2. The cameras are setup so that the left edge of the image, when viewed on a television monitor, is parallel and near to the vehicle's longitudinal centerline. It has been found that a downward looking approach provides a better contrast ratio under a variety of weather and lighting conditions than a forward looking approach, thus providing a better signal- to- noise ratio for detecting the edge lines.

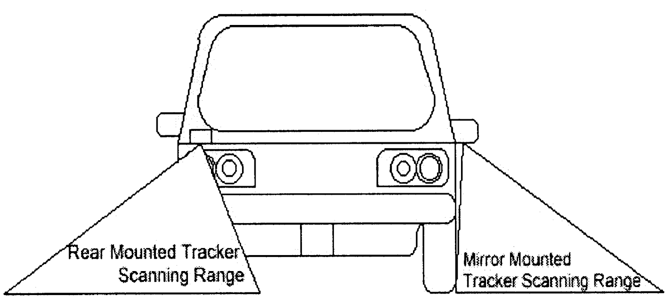

Figure 2. Lane tracker mountings with their associated fields of view.

The first method installs the sensors on the rear of the vehicle. Using this method, the sensors are installed in a short amount of time. The configuration allows for lateral position measurement, lane bust detection, and measures the extent of a lane exceedance. This method of installation has been successfully used for VRTC testing in the areas of drowsy driver research, driver workload research, and car following research. There are several drawbacks to this type of installation. First, the sensor is not easily integrated into the vehicle. Figure 3. displays how the sensors are integrated on the rear of the vehicle. Second, over long term naturalistic data collection periods, the potential exists for the cameras to be "bumped" by the subject entering the vehicles trunk or vandalized in a public parking lot. "Bumping" or vandalizing the cameras would significantly change the systems calibration. Finally, field experience has uncovered problems with glare off of the rear bumper of some vehicles caused by ambient sunlight or following vehicle's head lamps.

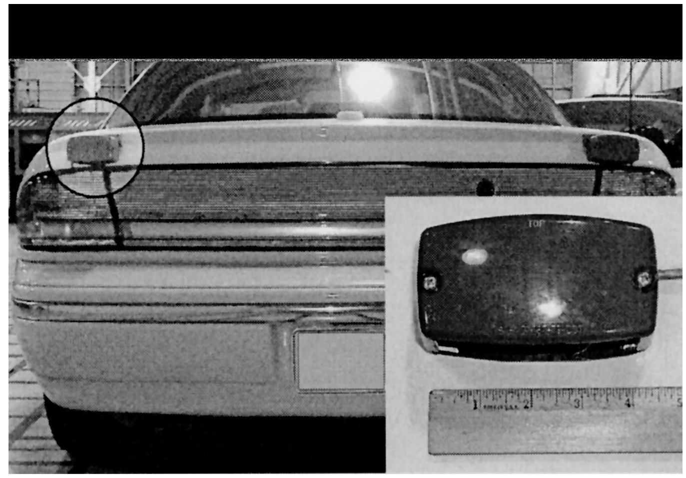

Figure 3. Tracker sensors mounted on the rear of a vehicle.

The second method of installation integrates the sensors into the side-view mirrors of the vehicle. This method is very unobtrusive and robust. System calibration is generally set once with this method since the cameras are not easily disturbed and they are not as sensitive to glare like the rear method. Mirror adjustments made by the driver do not effect the calibration. This configuration allows for lateral position measurement, however lane bust detection and lane exeedance measurements are limited because the edge becomes blocked by the vehicle. Another drawback of this method is that it takes more time to install the sensors. Some side-view mirrors do not have enough room to internally house the small cameras. Figure 4. displays the bottom of a side-view mirror with a tracking camera installed.

Figure 4. Side-view mirror with lane tracker camera integrated.

CALIBRATION

Calibration is completed on the system after the CCD cameras have been mounted. Statically, a line is swept from the minimum to the maximum range of the system.

The output voltage at various distances measured from the center line of the vehicle are recorded. This data is then fit with an exponential equation to compensate for the geometry of the tracking system. Although other methods such as interpolation with a calibration lookup up table could be used, the exponential fit provides sufficiently accurate results as can be seen in Figure 5. This calibration should be completed before and after the system is used for testing. It is important that the sensors do not move during testing to maintain accuracy.

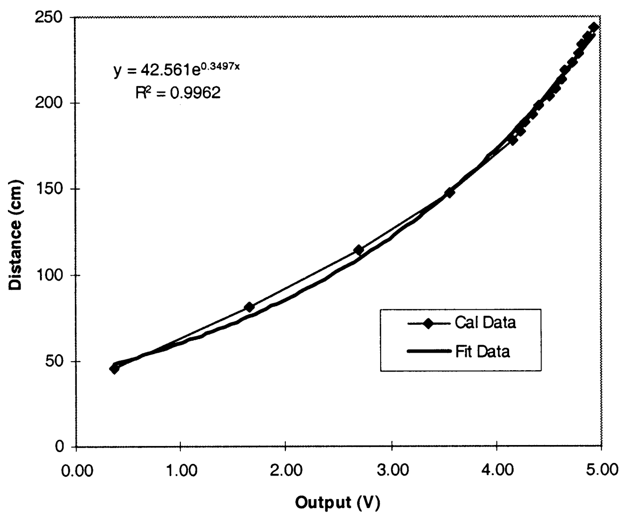

Figure 5. Measured verses fit lane tracker data.

PERFORMANCE

Using the exponential fit data, the system accurately measures the distance to a painted edge line within approximately 6 cm over the systems operating range. The accuracy and full scale operating range will vary based on the installation height and the optics used with the sensors. Table 1 displays the calibration data used for Figure 5. Table 1 also displays the calculated absolute value of the error from applying the exponential fit. For this installation, the maximum operating range for the tracking system was found to be approximately 2.4 m. This distance is typically seen in most installations with about a +/- 0.2 m difference. Accuracy will vary accordingly with full scale operating range. As the operating range becomes larger, the accuracy will degrade. Typical accuracy is within 6 cm with a resolution of approximately 2 cm over an operating range of 2.5 m.

DATA PROCESSING

The analog outputs are processed with several functions to clean up the raw data and derive other measures. Some of the measures that are typically derived from this data include lane width, deviation of the subject vehicle from the center of the roadway, lane exceedance extent/duration, and lane changes.

Raw data is initially processed using a spike removal routine. The routine looks for large spikes of a programmable width which deviate from the average value. Figure 6 displays the raw data against the spike removed data. The noise spikes in the raw data are seen because the tracker is detecting objects which meet the criteria of a valid line before the edge line. However, by looking at the data, the general structure of the system tracking a road edge line can be seen. Figure 6 displays a very noisy segment of the tracking data. In many instances the raw data is cleaner than illustrated. The spike removal function tries to recreate the structure that the human observer can see.

Table 1. Calibration data used in Figure 5.

Volts (V)	Distance from Center Line (cm)	Exp. Fit (cm)	ABS Error (cm)
0.36	45.7	48.3	2.6
1.66	81.3	76.1	5.2
2.70	114.3	109.4	4.9
3.56	147.3	147.8	0.5
4.16	177.8	182.3	4.5
4.24	182.9	187.5	4.6
4.28	188.0	190.1	2.2
4.36	193.0	195.5	2.5
4.42	198.1	199.7	1.5
4.51	203.2	206.0	2.8
4.57	208.3	210.4	2.1
4.63	213.4	214.9	1.5
4.67	218.4	217.9	0.5
4.73	223.5	222.5	1.0
4.80	228.6	228.0	0.6
4.83	233.7	230.4	3.2
4.88	238.8	234.5	4.3
4.94	243.8	239.5	4.4

The spike removed data is then low pass filtered and used to calculate a lane width. The lane width is calculated by summing the left and right tracker values. The lane width value is only updated when both trackers are valid, otherwise the previous value is held. Since gross changes in lane width happen infrequently, this method has proven to work reliably.

Combining the left and right tracker data with the current lane width information, a channel is created indicating the vehicle's deviation from the center of the roadway lane. In the event that one side of the system stops tracking, the lane deviation can still be calculated using data from the other tracker and the lane width data.

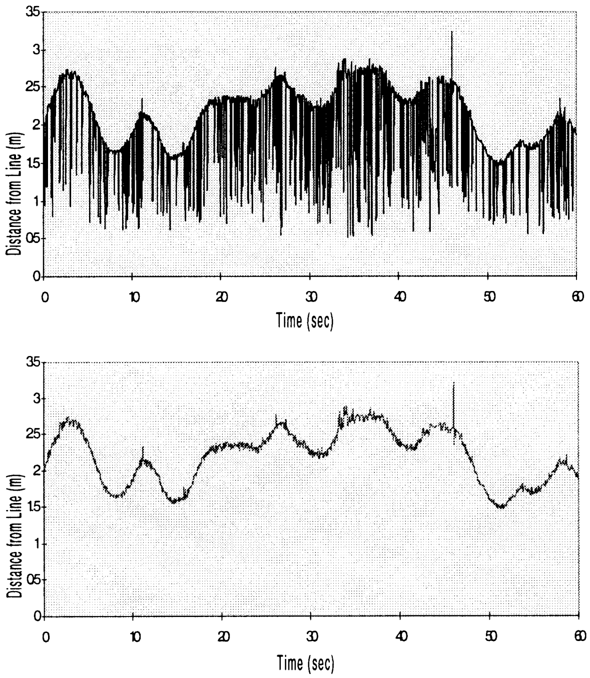

Figure 6. Raw tracker data compared to processed data with spikes removed.

Using the measures described above, various maneuvers can be detected such as lane changes. Lane changes can be detected provided that one of the lane tracker sides is functioning correctly throughout the maneuver. A routine has been implemented in an attempt to detect them automatically. Figure 7a displays a vehicle's distance from the center of a roadway throughout a lane change maneuver over time. To detect a lane change, the vehicle's distance from the center of the roadway is differentiated to obtain a lateral velocity. The lateral velocity is then processed with the spike removal routine so that the resultant data can be integrated to obtain a continuous lateral position as seen in Figure 7b. The lateral position is then analyzed by the routine for changes in direction (ie. lateral velocity approaching zero) as can be seen in Figure 7c. The amplitude of the continuous lateral position is measured between zero crossings of the lateral velocity. If the delta of the amplitude is greater than 1.5 meters, the maneuver is considered to be a lane change.

LIMITATIONS

Although the system performs well on roadways with good quality, painted edge lines, in the real world not all roadways have them. In a recent test program conducted at the VRTC to study the effectiveness of detecting driver drowsiness, validity of the tracker was tested. The test program involved eight subjects. The subjects' personally owned vehicles were instrumented with a VRTC lane tracking system. The participants selected were traveling on long distance trips that they had already planned on making, i.e. college student driving home for semester break. Data was recorded, during daytime and nighttime, throughout the duration of their trip only when they were traveling at speeds above 70 kph. Subjects were not instructed to follow any pre-described route nor were they asked to limit their travel to a particular type of roadway. It is believed that this data set accurately characterizes the realistic performance of the lane tracker system on typical public roadways.

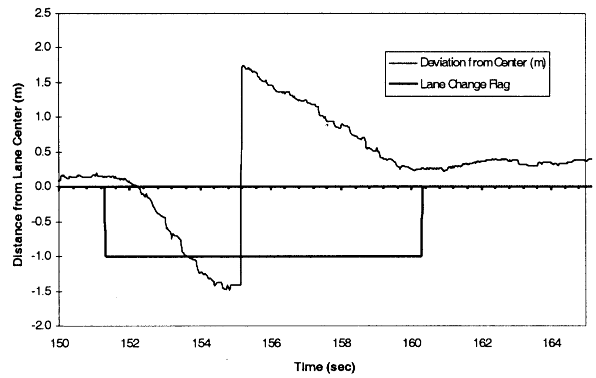

Figure 7a. Vehicle's distance from the center of the roadway through a lane change maneuver.

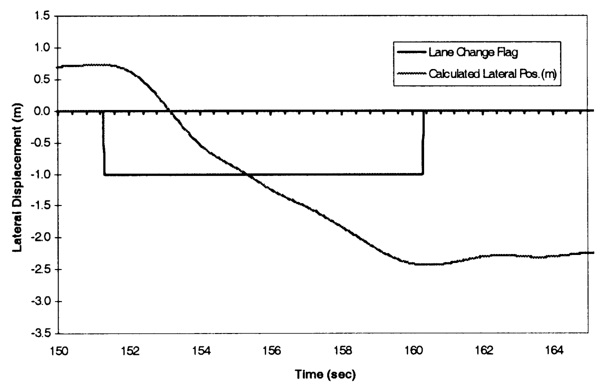

Figure 7b. Calculated lateral position through a lane change maneuver.

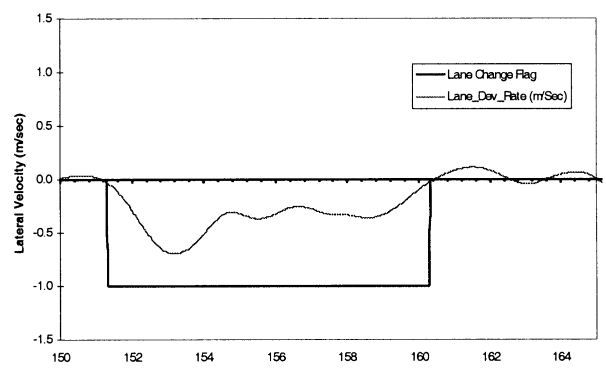

Figure 7c. Vehicles calculated lateral velocity throughout a lane change maneuver.

A channel representing the validity of the tracker data is generated as part of the post-hoc processing. The validity flag indicated that throughout the 89 hours of data collected, the system provided valid lane position approximately 62% of the time as can be seen in Table

2. An observer confirmed the accuracy of the validity flag by manually reviewing time history traces of the raw tracker data. No significant discrepancies were found by the manual observer.

Table 2. Performance of the lane tracking system operating in the open road environment.

Subject	Amount of data (Hours)	Tracker Valid (%)	Amount of Valid Tracker Data (Hours)
1	8.2	71%	5.8
2	12.1	70%	8.5
3	14.3	70%	10.0
4	13.8	37%	5.1
5	2.8	78%	2.2
6	14.5	63%	9.1
7	13.8	47%	6.5
8	9.8	87%	8.5
Overall	89.3	62% ($\bar{x}$)	55.7

Table 2 also breaks out the performance of the lane tracker on a subject by subject basis. It should be noted that the worst performance of the lane tracker system was 37%. This low performance was attributed to a hardware problem and not the roadways traveled. The sensors were mounted on the rear of this subject's vehicle. Reviewing recorded video from this subject, a noticeable glare caused from sunlight reflecting off of the vehicle's bumper was observed. The glare caused a flare in the optics of the CCD sensor, creating a vertical stripe through the video image. This resulted in the system falsely tracking the flare instead the painted edge line.

The condition was replicated in the lab using a bright light source. It was observed that this condition could happen on any vehicle with a protruding bumper. Vehicles with glossy/waxed plastic and/or chrome bumpers seem to be affected the most. A shield has been fabricated and installed into the sensor to remedy the flare problem.

CONCLUSIONS

A system has been developed which measures vehicle lateral position in reference to the painted edge lines of a roadway. The system can be installed on almost any vehicle and can resolve lateral position within 6 cm over a range of approximately 2.5 m. The lane tracking system is capable of operating under a variety of light and weather conditions.

The system was found to report 62% valid data while operating under real world conditions. Although the tracker does have performance limitations, significant benefits are attainable when using the system. Improvements in efficiency of data analysis are realized through the elimination of the need for intensive manual data extraction and reduction. As a result, the time and cost of data analysis are greatly reduced.

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