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ABSTRACT

The future of vehicle safety will benefit greatly from precrash detection – the ability of a motor vehicle to predict the occurrence of an accident before it occurs. There are many different sensor technologies currently available for pre-crash detection. However no single sensor technology has demonstrated enough information gathering capability within the cost constraints of vehicle manufacturers to be used as a stand alone device. A proposed solution consists of combining information from multiple sensors in an intelligent computer algorithm to determine accurate precrash information. In this paper, a list of sensors currently available on motor vehicles and those that show promise for future development is presented. These sensors are then evaluated based on cost, information gathering capability and other factors. Cost sensitivity is lower in large commercial vehicles than sensitivity is lower in large commercial vehicles than in personal vehicles due to their higher initial cost and longer life span making them a good candidate for early adoption of such a system. This work forms the basis for ongoing research in developing an integrated object detection and avoidance precrash sensing system.

INTRODUCTION

Improving occupant safety has been an increasingly important area of study since the mid 1960's. Initially this work was centered on controlling post impact occupant dynamics through the use of structural modifications, seatbelts, and airbags. The next leap forward in occupant safety is precrash sensing. Figure 1 demonstrates some possible safety benefits of precrash sensing.

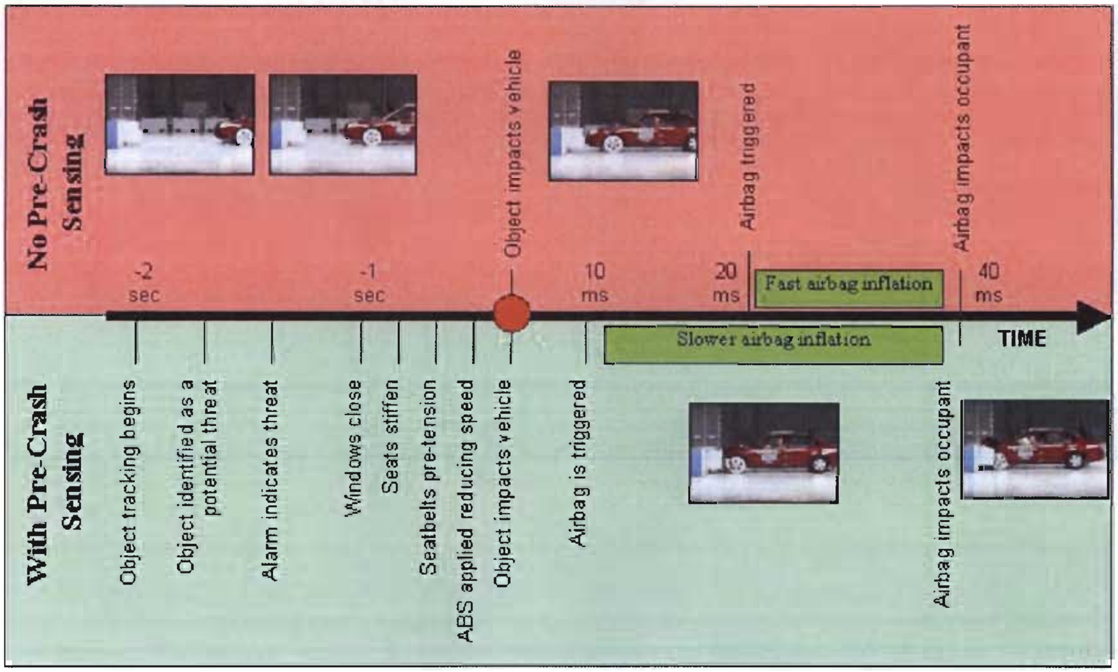


Figure 1 - Timelines for collisions with and without precrash sensing

The idea of using external sensors to improve vehicle safety is similarly not a new one [[1], [2]]. Ultrasonic sensors are commonly used today as parking aids on vehicles with large blind spots and radars are used in adaptive cruise control (ACC) systems to maintain safe following distance when cruise control is active.

This work will identify a possible set of requirements for precrash sensing and survey the current state of the art for a variety of sensor technologies. In comparing the sensor technologies we compare not only the capabilities of the various sensors but also the cost and overhead of including such a sensor on a vehicle. Furthermore a possible group of sensors is presented that is expected to meet these requirements.

Improving occupant safety beyond existing standards requires more information than is currently gathered by automobiles during an impact. Currently when an accident occurs the airbag sensors trigger the airbags within 10ms of the impact. The initial goal of a pre-crash system would be to bias the decision made by the impact sensors allowing for triggering based on expected impact severity. Coupled with seat belt pre-tensioning the number and severity of occupant injuries could be greatly reduced. Figure 1 shows an example impact where the precrash system triggers the airbags early, reducing the pressure required for inflation, and thereby reducing the contact force with the occupant.

The ability to predict accidents beyond the immediate event horizon has a number of other advantages. In 49% of accidents the brakes are not used at all [8]. By predicting that a collision is imminent a system could activate the brakes prior to the collision reducing the severity of the impact. Furthermore the airbags could be triggered prior to impact further reducing the force of inflation and the risk of deployment related injuries. Other safety technologies made possible with pre-crash detection include an audible alarm, automatic window closing, seat reposition and stiffening, ABS firing and eventually automatic steering to avoid the crash.

It is anticipated the initial implementation of a precrash sensing system will be on less cost-sensitive vehicles such as luxury cars and large commercial vehicles. In particular, commercial vehicles have a higher initial cost, longer life span, and greater liability from accident occurrence. This makes them good candidates for early adoption of such a system.

REQUIREMENTS OF A FRONTAL PRECRASH SYSTEM

To aid in evaluating how sensor technologies fit into the picture of precrash sensing it is important to establish what the system as a whole must be able to do.

SYSTEM ROBUSTNESS

To provide value the system must not produce false positives and must have a low occurrence of false negatives. Furthermore the system should be able to determine when it will not be effective due to road or weather conditions and inform other portions of the vehicle electronics and the driver that the system is not providing a benefit.

RESPONSE TIME

The system must be able to respond to threats in a timely manner. There are two different facets of system response time that, while related, need to be discussed separately. First there is the issue of how long the system takes to begin tracking a threat once it has entered the forward path of the vehicle. This response time will be dependant on the technical limitations of sensor covering the area in which the threat exists. The second type of system response time is related to the time required for the system to tag the object as a likely threat and notify the driver or take protective measures. This is a more difficult issue to address because while it is in part reliant on the technical limitations of system components the major factor is the accuracy of the collision prediction model used.

COVERAGE REGION

Defining the coverage region is a somewhat arbitrary task without specifically defining the vehicle and conducting an exhaustive survey of when driver warnings and other preventative measures are best performed. As a reasonable starting point we shall begin by focusing on objects in the same lane of travel as the vehicle. The distance from the front of the vehicle that should be covered should be far enough to detect objects traveling at high speed, but not so far as to provide information about objects for which predictions are uncertain. To meet these requirements the minimum region of coverage for the system is defined to be an area 3.5m wide and 30m long in front of the vehicle as shown in Figure 2. This is based on travel lane width in the United States and the distance traveled by a vehicle going 60mph in 1 second. In addition side impacts could be considered. The side impact coverage region is not discussed in this work.

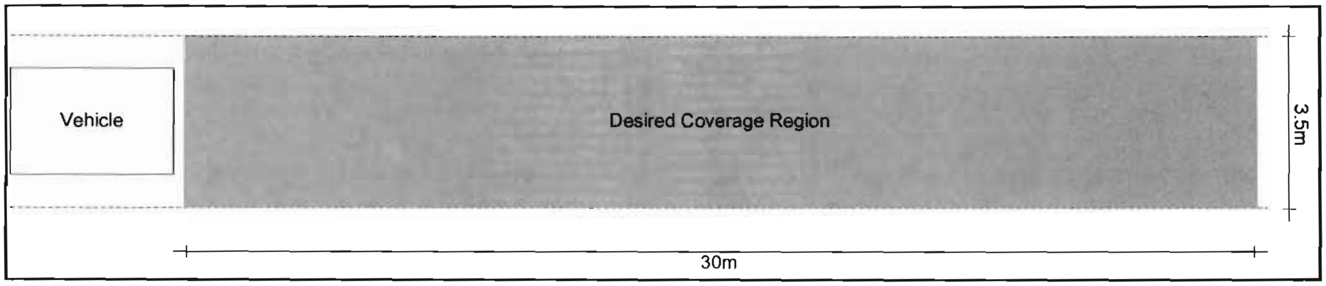


Figure 2 - Coverage Region of Suggested System

OBJECT DETECTION

A precrash sensing system must also be able to differentiate objects that are not threats to the vehicle from those that are. Table 1 gives a list to object types that should be identified and some example objects for each type.

Table 1 - Possible threat objects

Type of object	Example object
Large high mass	Tree, other vehicle, walls
Large low mass	Brush
Medium high mass	Motor cycle, cow
Medium low mass	Pedestrian
Small high mass	Road barrier, utility pole

OTHER CONSTRAINTS

Finally there are several constraints on the system. Most of them are typical for automotive electronics such as temperature, humidity, and vibration. Additionally the sensors must provide information during inclement weather. The incremental cost of such a system is a serious constraint and as a result the chosen sensors should be integrated into other, pre-existing applications such as Active Cruise Control (ACC). Sensors must be placed on vehicles in such a way that the coverage of the sensor is not severely limited due to anticipated occlusion.

POSSIBLE SENSORS

As a first step toward an integrated precrash sensing system this study will initially focus on sensors that provide telemetric data rather than classification data regarding the object of interest. In identifying possible sensors for this task it is important to understand a variety of issues including the coverage zone that each sensor is capable of providing information for, the type of information provided by each of the sensors, and the cost of the sensor. Table 2 gives a summary of these factors for each of the technologies covered in this survey for typical state of the art sensors of each type followed by a discussion of each.

ULTRASONIC SENSORS

Ultrasonic sensors have the advantage that they are already integrated into the front and rear bumpers of many vehicles for backup and parking assist. The low cost of ultrasonic sensors means they can be placed on the vehicle in such a manner as to cover any region of interest.

Backup and parking aid ultrasonic sensors work by sending out a high frequency pulse and measuring the time until the echo is received.

Individually a typical ultrasonic sensor has an aperture of roughly 45° and has a maximum range of 10m, so in practice three or four sensors are combined to cover either the front or rear bumper of the vehicle. This arrangement is made out of expedience rather than any technical limitation of the sensors themselves. Next generation sensors could use a single transmitter and combine the receivers in a phased array fashion to provide location information in a manner not dissimilar from the way many submarine sonar systems work.

LASER

Laser Imaging Detection and Ranging (LIDAR) sensors work in a manner similar to the ultrasonic sensors. The primary difference is that because of the small beam diffraction of the lasers involved, a fixed laser will not cover more than a small point directly in front of the laser. To overcome this deficiency a mirror or prism can be used to scan the beam over various angles. This means that the update rate of a LIDAR is inversely proportional to the angle of coverage.

LIDAR systems can measure distance with high accuracy. Additionally they can be made to measure object speed based on the Doppler shift of the return signal. Combined with the correct computer algorithm these systems can also provide information regarding target geometry [6].

Table 2 - Comparison Matrix of Current Sensor Technologies

	Ultrasonic	LIDAR	RADAR	Bi-Static	Vision	AIR	PIR
Cost	Low	High	High	Medium	Medium	Low	Low
Computation Overhead	Low	High	Medium	Medium	High	Low	Low
Range	3m	5m to 150m	1m to 150m	5m	Line of sight	2m	20m
Operating Conditions	Clear visibility	Clear visibility to 150m	Normal to heavy rain or snow	Normal to heavy rain or snow	Clear visibility	Normal to slight haze	Clear visibility
Commercially Available	Yes	Yes	Yes	No	Yes	Yes	Yes
Industry Acceptance	High	None	Some	None	None	None	None
Accuracy	±0.05m	±0.3m	±1.0m	±0.1m	NA	NA	NA
Update Frequency	40Hz	400Hz	10Hz	5kHz	<30Hz	NA	NA
Potential for Object Discrimination	Low	Some	Low	Low	High	None	Low
Detection Capabilities	Distance	Distance, speed, geometry	Distance, speed, cross section	Distance and radar cross section	Distance , speed, geometry, object class data	Presence	Presence
Minimum Target Size	Basketball	1" square or larger	Motorcycles and larger	Motorcycles, Pedestrians, and larger	Varies with distance	Pedestrians	Small animals

The point source nature of LIDAR systems means that they generally do not have wide coverage cones. As a result the LIDAR will have blind spots close to the vehicle the LIDAR will have blind spots as shown in Figure 7LIDAR systems rely on the ability of light to travel through whatever medium is between the source and the target. This means the presence of airborne particulates will degrade their capabilities. Military systems have been designed with enough power to overcome all but the most dense clouds of particulate, but such systems can easily damage the human eye and would be inappropriate for use on civilian vehicles.

RADAR

Classically RAdio Detection And Ranging (RADAR) has been the province of aircraft and air traffic control systems. More recently Doppler based systems have been used in traffic speed enforcement and other civilian applications. Currently radars are being used as an aid for cruise control systems to reduce driver interaction. It is these Active Cruise Control (ACC) radars that may be adapted for use in pre-crash sensing.

Radars have the capability to measure both object location and speed. ACC radars are capable of covering most of the region of interest for pre crash sensing. They have trouble detecting objects adjacent to the vehicle, however they are not as limited as LIDAR in the width of the coverage cone.

Radars can operate under nearly all practical driving conditions, although airborne particulates such as rain or snow will reduce the effective range.

BI-STATIC RADAR

Bi-static radars operate in much the same way as conventional (mono-static) radars. The difference is that the receive antenna is displaced from the transmit antenna. This means that the distance returned by such a system is actually the distance from the transmit antenna to the target and back to the receive antenna.

Mono-static radar obtains angular information by using a narrow-beam antenna pattern, and scanning the beam angle. For bi-static radar, each distance represents an ellipse rather than a circle, with the transmitter and the receiver being foci of the ellipse. As a result, an object traveling on a straight path with constant speed will appear to have acceleration. Figure 3 and Figure 4 show an example of this with simulated objects on an approach

approach path with the front of the vehicle. The closing speed is 40mph, and the transmitter-to-receiver separation distance is 1.8 meters. Speed and acceleration traces are shown for two scenarios. The first is for an impact head-on in the center of the vehicle. The second is for an approach angle 30 degrees from head-on, crossing the center line of the vehicle, and passing the front of the protected vehicle 0.5 meters outside the far antenna, or 1.4 meters from the center line of the vehicle, a near miss in the frontal crash scenario. A bi-static radar system obtains approach angle and impact-point prediction information by processing the bi-static range-ellipse data as the target approaches [9] This processing allows the bi-static radar system to predict impact speed, angle, and offset from the center-point between the two antennas.

The coverage region of bi-static radar depends upon the overlap of the transmitter beam pattern and the receiver beam pattern, which can be tailored to achieve the desired coverage region. The antenna patterns are very wide-beam, which allows the physical size of the antennas to be small, compared to the mono-static radar system. This also allows the system to operate at lower frequencies than the mono-static radar, which makes the bi-static radar system even less susceptible to weather conditions and non-threatening clutter like brush and cardboard boxes than the higher-frequency mono-static radar systems.

A feature of the bi-static implementation is the occurrence of direct-path signal coming straight from the transmitter to the receiver without bouncing off a target. In operation, the interaction between the direct path signal and the reflected target signal provides an estimate of the target's radar cross-section, allowing the system to discriminate between a small target like a pole or motorcycle, and something large like a truck or barrier. This interaction also provides a secondary indicator of closing speed [10].

Current developments have focused upon the side-impact scenario, but the bi-static radar system is readily adaptable to the front, rear, roll-over, blind-spot, and parking aid applications.

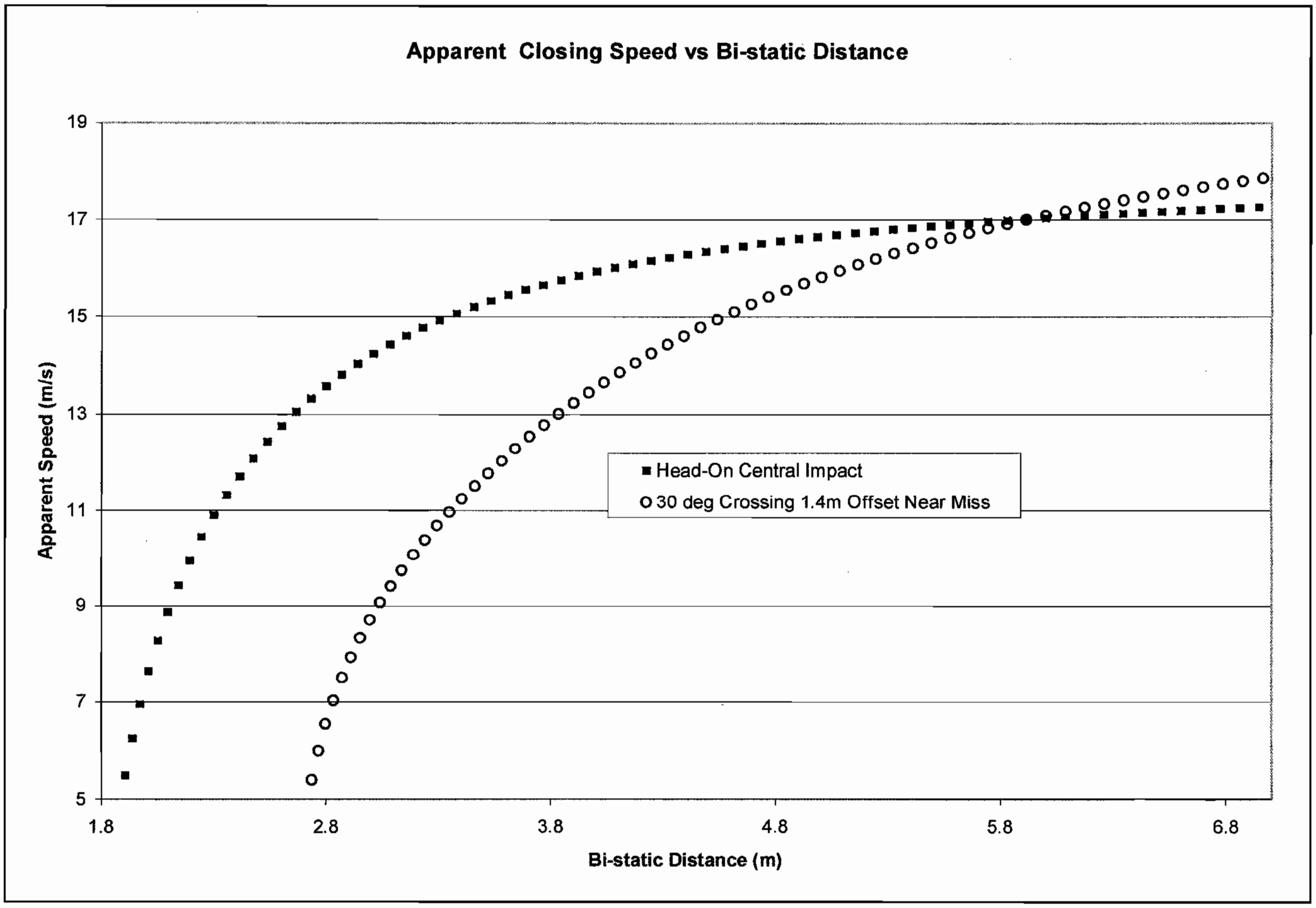


Figure 3 - Measured Speed versus Measured Distance for Two 40mph Approach Scenarios using Bi-Static Radar

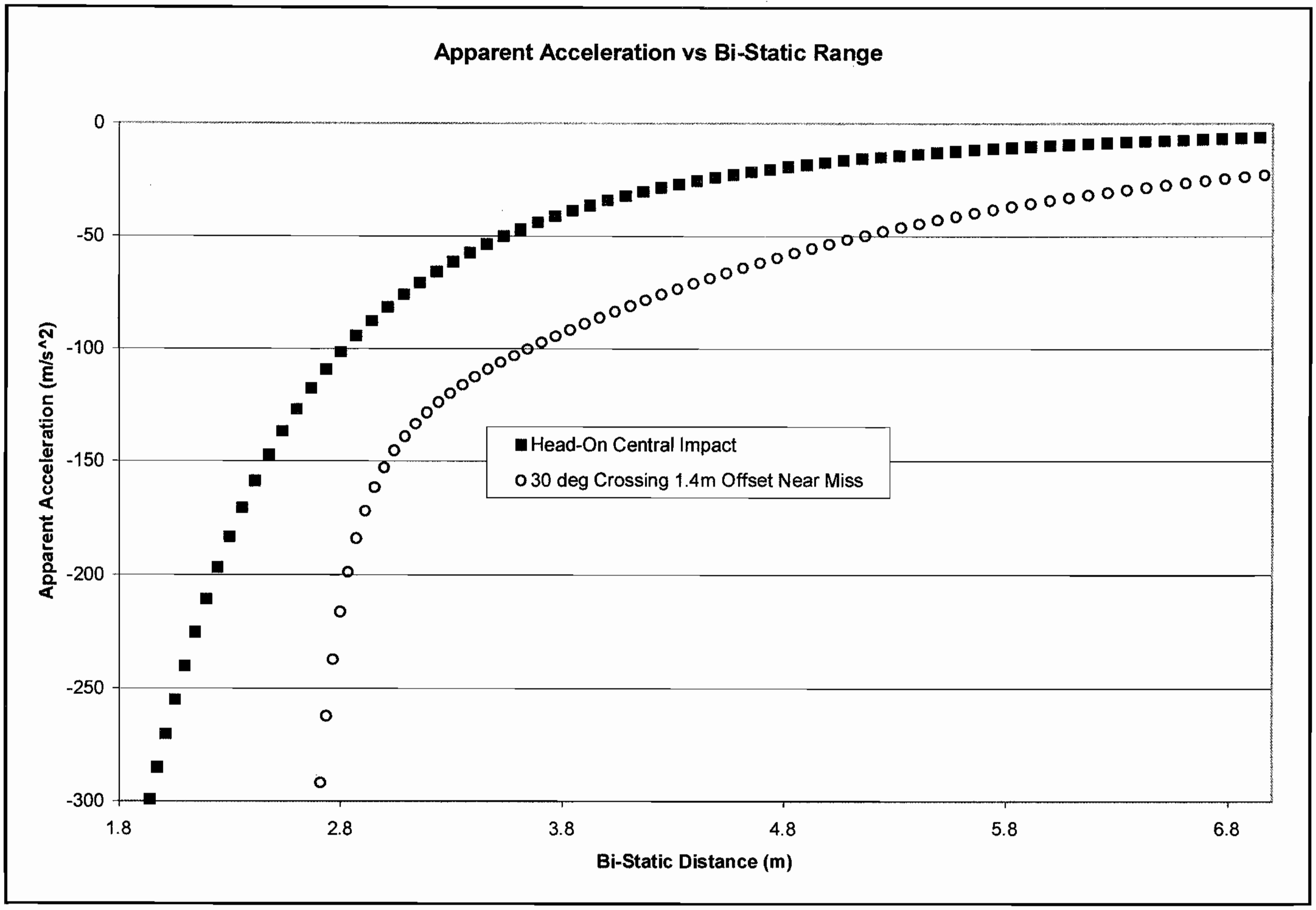


Figure 4 - Measured Acceleration versus Measured Distance for Two 40mph Approach Scenarios using Bi-Static Radar

VISION

When discussing vision systems we are really discussing three different types of systems: visible light, passive infrared vision (PIRV), and active infrared vision (AIRV). Vision - primarily visible light - systems have been presented in the literature, [3] and [1], as means of solving many of the problems related pre-crash sensing. This is in no small part due to the fact that vision systems are what humans use as our primary sensor for vehicle control. In fact vision sensors are the only sensor presented that would be able to cover the entire region of interest effectively while collecting control related information at the same time.

Vision sensors also collect data far beyond the telemetry data collected by most other sensors presented in this survey. Figure 5 shows an example of this. Based on this image we can tell that the road being traveled on is about to make a right turn, it is relatively flat, there are two lanes of travel, and most importantly there no objects in the probable path of travel that present a danger to the vehicle.The biggest drawback of vision systems of any type is not the sensors themselves but rather the computational overhead associated with extracting the information that most human drivers can gather from a scene almost instinctively. Figure 6 shows lane makers detected using the Hough transform, a well understand algorithm for finding lines in images. This process alone is no trivial task [7], and this is just a small piece of the information that could be extracted from the scene. This simple task requires significant computer overhead to provide data at a reasonable rate.

Additionally, vision sensors themselves do not provide any telemetry data about objects in the scene. This data has be to gathered either with a separate sensor or inferred from a second vision sensor using stereovision triangulation.

Unlike the human eye, CMOS or CCD vision sensors do not automatically adjust to scene light and contrast. They must be tied to a system that correctly estimates the amount of light present and adjusts the gain of the sensor appropriately. This must happen rapidly and accurately as light conditions can change dramatically during either sunset or sunrise.

Figure 5 – Typical road scene

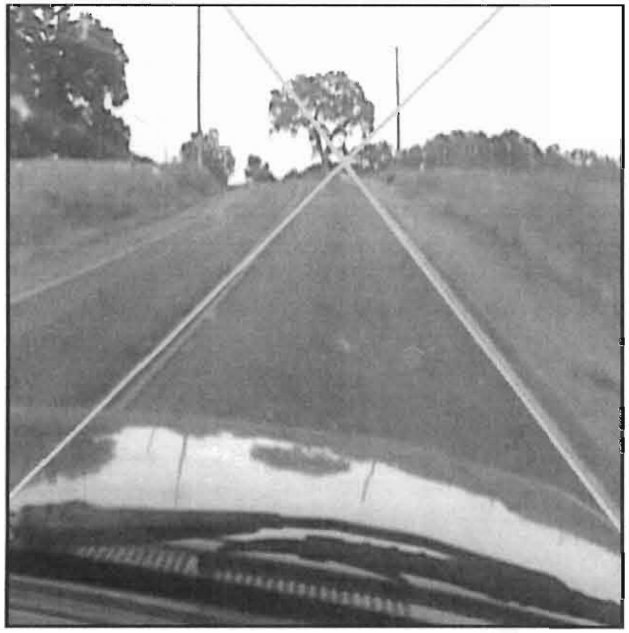


Figure 6 – Road scene with lane markers identified

The final drawback to vision based systems, especially visible light systems, is that their performance degrades rapidly in the presence of airborne particulates such as

sensing since they rely on a known ambient null condition on which to base decisions regarding the presence of objects. For example at sunrise or sunset the sun produces far in excess of enough IR to trip such a system. While this condition can be accounted for in a fixed system it is likely to have problems on a platform that moves.

NON-VISION ACTIVE INFRARED (AIR)

AIR systems are used in many industrial and commercial applications to determine the presence of objects, including people. Direct AIR systems work with an emitter and detector that are placed at separate locations and aimed such that light from the emitter travels to the detector. Such systems detect objects when the detector no longer receives a signal from the emitter. Reflected systems work in much the same way except that they rely on a reflective surface to bounce the light from the emitter to the detector. Such a system relies on the emitter producing enough light to illuminate the target object so that it reflects more IR light than is present in the background.

AIR systems do not use time of flight measurements to collect distance information, but rather relay on the presence or absence of a return signal to determine if an object is present. Some systems exist that use the strength of the return signal to determine distance, however the distance measurements are only valid for objects whose reflectivity characteristics match the calibration object under carefully controlled conditions.

The primary limit to the range of an AIR system is the power and cost of the emitter. Focusing lenses on both the transmitter and receiver can be used to increase the range of the system as the cost of reducing the aperture.

As a result of their wide use and acceptance of AIR systems might seem to be a perfect fit for precrash sensing. The drawback of these types of sensors is that they only provide presence information. Considering that AIR systems are only slightly less expensive that ultrasonic systems and they only provide presence information rather than presence and distance they do not appear to be cost effective.

SUGGESTED SENSOR COMPONENTS

interest, except that right in front of the vehicle, is covered by two of the three sensors. Given that the cost and capabilities of each of the sensor technologies is constantly changing it is important to bear in mind that in the future there may be different and better combinations.

The radar was chosen because it gathers the most telemetry information under the widest range of environmental conditions at the highest frequency. Radars are one of the most expensive sensors available; however, since they are an integral part of ACC systems that are now becoming popular on commercial and luxury vehicles the incremental cost of adding this to the system is lowered. Figure 9 shows the relationship between the desired coverage region and the region covered by an the region covered by an ACC radar.

The scanning laser or LIDAR is selected to be a complement to the radar. While current systems do not sample as fast as the radar they provide additional information. They provide some indication of object geometry is important and can be used to predict how the vehicle will deform during the impact. Second when used in combination with the radar the system should be able to determine when there is a fault and indicate this to the driver. Thirdly there is the possibility of object discrimination based on the type of signal from each sensor. Figure 7 shows one possible coverage region for a scanning LIDAR, note that a LIDAR could be designed to have an arbitrary aperature.

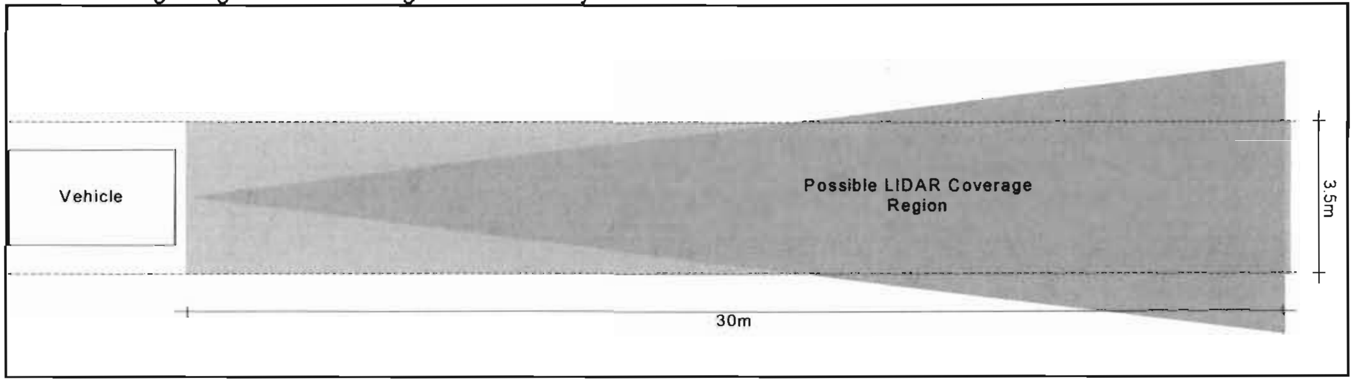


Figure 7 - LIDAR coverage region overlayed on suggested coverage region

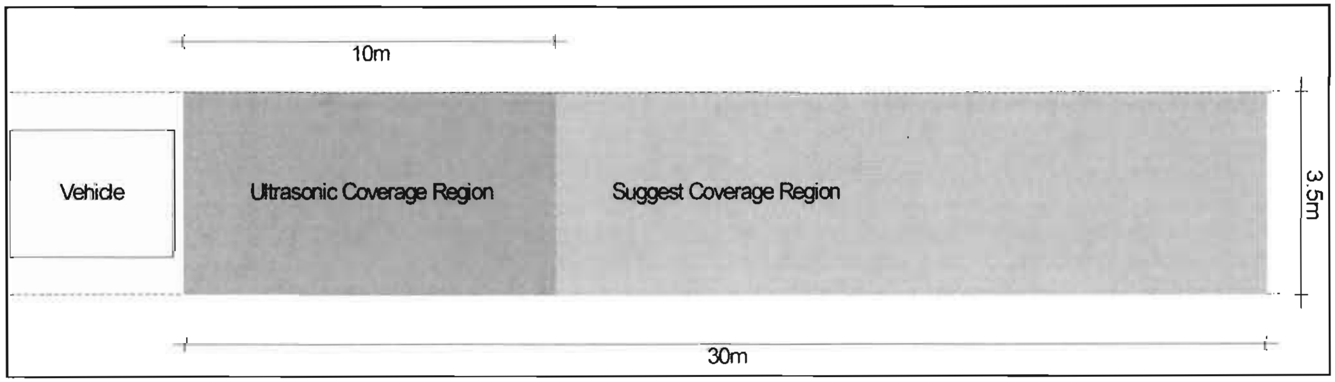
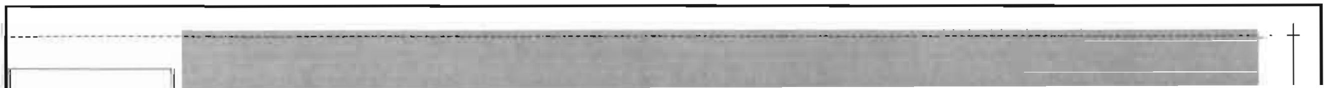


Figure 8 - Ultrasonic coverage region as compared to system coverage region



Ultrasonic sensor were selected as they are already common on vehicles today, they are inexpensive, and they cover an area directly in front of the vehicle that is not commonly covered by other available sensors. The region that they do cover is possibly the most important as it is where the data has the highest degree of validity and the prediction of an impact is most reliable. Figure 8 shows the portion of the region of interest covered by Ultrasonic sensors.

SYSTEM FUNCTIONALITY

The proposed system would work by first identifying the presence of an object using the RADAR. The object is then tracked using both the RADAR and the LIDAR so long as it is in the region of interest. At this point the system would begin to make predictions regarding the likelyhood that the object will collide with the vehicle and of closing velocity. As the object gets close the ultrasonic sensor tracks it and the system alerts the vehicles active safety systems of the likelihood of an imminent impact, along with information regarding the possible seriousness of the impact.

FUTURE WORK

While all of the above sensors are specified by their manufactures, for most of them there is sparse information regarding their performance relative to precrash sensing. A uniform test procedure needs to be established and the sensors need to be individually tested against a variety of objects under simulated environmental conditions. This is the next step of our research plan.

This paper has addressed the needs of precrash sensing as they relate to vehicles approaching objects in the path of travel. An important extension to this is expanding the coverage region so that a precrash system could potentially predict object approaching from the sides such as at an intersection.

Finally an algorithm must be developed that relates telemetric data of an object to the probability of impact. This involves not only generating significant simulations, but also real world testing to ensure that the simulations are representative.

CONCLUSION

A survey comparing the cost and capabilities of current state of the art sensor technologies has been present for use in intelligent vehicle design. A possible set of requirements for a precrash sensing system has been laid out. A framework for integrating several sensors together to meet these requirements has been presented.

ACKNOWLEDGMENTS

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REFERENCES

[1] Knoll, Peter, Schaefer, Bernd-Josef, Guettler, Hans, Bunse, Michael, & Kallenbach, Rainer, *Predictive Safety Systems – Steps Towards Collision Mitigation*, SAE 2004 World Congress & Exhibition, March 2004, Detroit, MI, USA, Session

[2] Breed, David, Sanders, W. Thomas, & Castelli, Vittorio, *A Complete Frontal Crash Sensor System – 1*, SAE S.A.E. transactions. 102, no. 6, (1993): 900

[3] Hamilton, Lisa, Humm, Lawrence, Daniels, & Yen Huan, *The Role of Vision Sensors in Future Intelligent Vehicles*, S.A.E. transactions. 110, Part 7 (2001): 613-617

[4] Cherry, James, *Applications of Ultrasonic Technology for Obstacle Detection*,

[5] Cartwright, Kert & Jindal, Gopi, *An Ultrasonic Proximity System for Automobile Collision Avoidance*,

[6] Beraldin, J.-A., Rioux, M., Livingstone, F.R., King, L., *Development of a Real-Time Laser Scanning System for Object Recognition, Inspection, and Robot Control*, SPIE Proceedings, Telemanipulator Technology and Space Telerobotics. Boston, Massachusetts, USA. September 7-10, 1993. Vol. 2057, pp. 451-461

[7] Chen, Ling, Chen, Hongjian, Pan, Yi, Chen, Yixin, *A Fast Efficient Parallel Hough Transform Algorithm on LARPBS*, The Journal of Supercomputing 29, no. 2 (2004), pp 185-195

[8] Statistics from the *Gesamtverband der Deutchen Versicherunswirtschaft e.V.* (Association of the German Insurance Indsutry) (2001)

[9] Crosby, Robert Radar detector for pre-impact airbag triggering. Patent 6,025,796. 9 December 1996

[10] Crosby, Robert Radar detector for pre-impact airbag triggering. Patent 6,097,332. 1 August 2000