Development of a Peer-to-Peer Collision Warning System

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ABSTRACT

Traditional vehicle collision warning and avoidance systems do not perform well in the perpendicular path intersection case. One major reason is that the threat detection systems they use require line-of-sight. Recently we have designed and implemented a new low-cost collision warning system that doesn't require line-of-sight for threat detection. The novel elements of the system include the use of a dynamic ad hoc wireless network for peer-to-peer data sharing, a new intersection collision warning algorithm, and a flexible and extensible software architecture and system design. This paper, the first paper report on this work, focusing on the system design elements. Detail of field test results and performance tuning will be reported at a later date.

Keywords

Vehicle Collision Warning System, Ad Hoc Networks, Specification, Algorithm

1 Introduction

There have been major improvements in vehicle safety since the 1960's. The introduction of safety features such as seat belts, air bags, crash zone, lighting and new vehicle structures has dramatically reduced the rate of crashes, injuries and fatalities. The fatality rate per hundred million miles travelled has fallen from 5.5 to 1.7 in the period from mid-1960s to 1994 [17]. However, in spite of these impressive improvements, each year in the United States, motor vehicle crashes still account for a staggering 40,000 deaths, more than three million injuries, and over $130 billion in financial losses. All of these safety features are either static or passive. They act to minimize collision damage or give the driver visual assistance or warning at specific geographic areas.

With recent advance in sensing, computing, and communication technologies, researchers have started to design and develop more advanced systems to further improve automobile safety. New driving assistance systems such as night vision systems and collision warning systems (CWS) have been designed, tested, and deployed [17, 10, 13, 5, 1]. While night vision systems simply provide visual assistance to drivers in dark environment, collision warning and avoidance systems generally exhibit some intelligence. By actively monitoring vehicle surroundings and the driver's state, these systems warn the driver of hazard, allowing drivers to take appropriate actions to avoid an accident or to reduce the severity of the crash. Preliminary results have shown that the introduction of collision warning systems could dramatically reduce crash fatalities, injuries and property damage [17]. Studies carried out by Daimler-Benz and National Highway Traffic Safety Administration (NHTSA) suggest that additional one second warning could reduce the rear-end and intersection accident rate by 50 to 90% [15], and Eaton reported that the actual truck fleet accident frequency was reduced by 73% on fleets being equipped with VORAD Forward and Side Collision warning systems by Eaton [15].

Despite the fact that intersection collision accounts for almost 30% of all crashes, intersection collision avoidance systems received less attention than the forward collision avoidance systems [10, 16]. The reason, besides the fact that the intersection collision problem is more complicated than rear-end crash, is the limitation of the radar technology, the most widely used object sensing method in vehicle collision avoidance systems. Most radar systems require line-of-sight for object detection. Yet in most intersection crash cases, the principle other vehicle (POV) is hidden from the line of sight of the subject vehicle (SV) until the last second before the collision. This renders ineffective most collision warning/avoidance system that requires line-of-sight for threat detection.

Recently we have designed and developed a system capable of intersection collision warning using a new approach. The system is based on vehicle-to-vehicle communication on top of ad hoc networks. Threat detections are achieved by vehicles cooperatively sharing critical information for collision anticipation, i.e., location, velocity, acceleration, etc. By sharing the information between peers, each vehicle is able to predict potential hazard. Although this system doesn't require a support infrastructure, the ultimate value of this kind of peer-to-peer cooperative system depends on the percentage of vehicles on the road using it. The more vehicles use it, the more valuable it is. Research is underway to estimate the critical mass needed for the system to have a substantial value gain. As more and more vehicles are equipped with navigation and communication systems, we envision a near future when this type of system will demonstrate its advantages in public use, complementing the function of other driver assistance systems.

As the first report on our peer-to-peer collision warning system, this paper summarizes some design and implementation results of our work. Section 2 presents the problem definition and a solution overview; section 3 analyzes the problem and presents some detail of a collision warning algorithm for the intersection perpendicular path case; section 4 shows the system hardware and software architecture along with some test results; followed by a discussion and conclusions in sections 5 and 6, respectively.

2 Problem Definition and Solution Overview

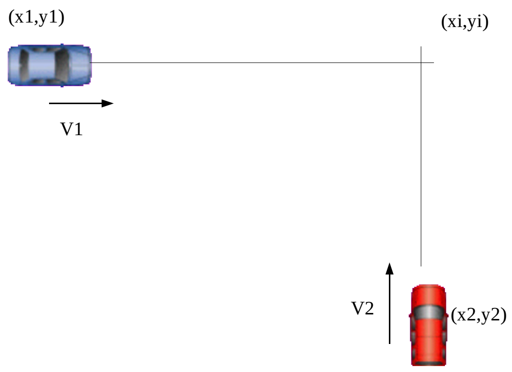

Figure 1: Intersection Perpendicular Path

Our goal is to develop a system capable of intersection collision warning with a special focus on the perpendicular-path scenario shown in Figure(1). This scenario accounts for a significant 44% of the intersection crash cases and the NHTSA intersection collision warning system doesn't work well on this [4, 10]. One major reason that current collision warning systems do not perform well in this case is the line-of-sight limitation of the radar. Instead of using a radar threat detection system, as most of the current collision avoidance systems do, we developed a beacon-based system for threat assessment. The idea is that by sharing kinetic and control information with its peers, each vehicle is able to predict when other vehicles are going to cut its path, thus it is able to compute the possibility of collision on its course and present to the driver an appropriate warning, when needed.

The beacon-based collision warning system is not a new concept. Various forms of beacon-based method have been in use for more than a decade in aircrafts traffic alert and collision avoidance, and have been proven very effective [8, 7, 18] Yet, they are not applicable to vehicular traffic control. The reason is partly because the systems are expensive and they are designed to handle air traffic, which is sparse. Ground vehicle traffic is much denser, vehicles are much closer in space, and vehicle behavior exhibits greater variance. These characteristics of vehicle traffic make that the available effective time for an avoidance decision and manipulation much less than that employed in air traffic. With all these factors under consideration, we aim to design a low cost beacon-based collision warning system that fits vehicle usage pattern.

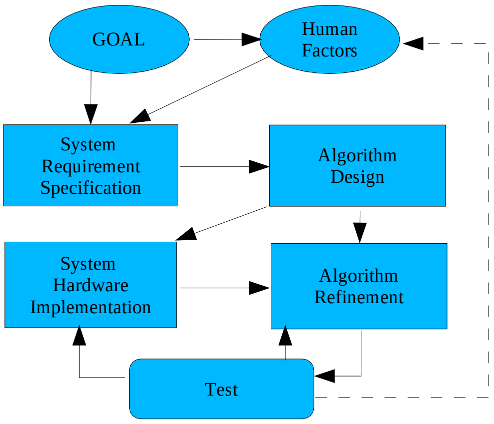

Figure 2: System Design Process

Our system design and development process is top-down and iterative, as illustrated in Figure (2). Starting with our goal, we consider all relevent human factors and generate a top level specification of the collision warning system. Then we develop a collision warning algorithm according to the specification. Next, we select the necessary hardware to implement the algorithm. After that, we test the hardware components individually and refine the algorithm by taking into account the physical characteristics of the hardware system, e.g. communication delay and measurement accuracy. Then we integrate the system, implement the algorithm and carry out field tests. We also expect that extensive field tests will eventually give us better insights regarding to hardware selection, human factors and the design of the collision warning algorithm.

Our work thus involves the following key elements:

- Consider the human factors for the collision warning system.
- Determine the requirements of the ad hoc network system.
- Determine what information needs to be shared for effective warning.
- Design, evaluate and refine the control algorithms for the collision warning system.

Each of these elements is discussed in detail in the following sections.

ICWS Specification

(1). At most one warning is given at one intersection.

(2). No warning if there is no route contention.

(3). No warning if the driver has already taken appropriate action.

(4). No warning if the time-to-collision(TTC) is much greater than time-to-avoidance(TTA).

Figure 3: Top-Level Specification for Intersection Collision Warning System(ICWS)

3 Algorithm and Analysis

Our first design phase is top-down and specification driven. Given the goal, we specify the top level requirements for the collision warning system with human factor concern, then we designed a top level control algorithm from the requirements. After that, we refine our control algorithm into finer and finer detail, factor in physical characterics, and generate a list of specific requirements for the system to work correctly.

Human Factor Considerations and System Specification

Human factors play an important part in the collision warning system design. As the purpose of the warning is to alert the driver when he/she is unaware of, or not responding to a potential collision, a collision warning system should be aware of not only the external collision potential, but also what the driver has and has not done regarding the collision possibility. If the driver has already taken an appropriate action right before a warning is issued, the warning shall be discarded to reduce the “annoying” factor of a collision warning system. A good warning system should minimize the driver’s attention load instead of creating an extra burden for the driver. A system that gives excessive warning may either desensitize the driver [11], causing future warnings to be ignored; or distract the driver [6, 14, 12]. Undesired warnings may also make the driver turn off the system completely. With these concerns, we derived a top-level specification for an intersection collision warning system (ICWS), as shown in Figure(3). This specification will be refined later in our system design.

Top Level CWS Algorithm

Given the system specification (Figure(3)), an intersection collision warning algorithm is derived, as shown in Figure (4).

There are two critical metrics used in this algorithm, Time-to-Collision (TTC) and Time-to-Avoidance(TTA), to determine if to issue a warning. The detail of the implementation of the algorithm for intersection warning is presented in the next few sections.

ICWS Algorithm

```
LOOP1:
  LOOP2:
    1. Listen for relevant data
    2. On data arrival, compute route contention
    3. if there is a contention on my path
    4.   if TTC is close to TTA and driver is not braking
    5.        issue WARNING, goto(10)
    6.   else if TTC is less than TTA
    7.        delegate task to Mitigation unit, goto (10)
    8.   end if
    9. end if
  END LOOP2
  10. Wait until pass the intersection.
END LOOP2
```

Figure 4: Intersection Collision Warning Algorithm

Route Contention

A route contention is identified by the possibility of a collision given the current states of the subject vehicle and the principal other vehicle [1]. In our algorithm, we first compute the expected path intersection (x_i, y_i) by using both vehicles’ headings and locations.

$$x_i = \frac{(y_2 - y_1) - (x_2 \tan\theta_2 - x_1 \tan\theta_1)}{\tan\theta_1 - \tan\theta_2} \quad (1)$$

$$y_i = \frac{(x_2 - x_1) - (y_2 \cot\theta_2 - y_1 \cot\theta_1)}{\cot\theta_1 - \cot\theta_2} \quad (2)$$

where (x_1, y_1) and θ_1 are the location and heading of the subject vehicle, (x_2, y_2) and θ_2 are the location and heading of the principle other vehicle. After the intersection is computed, the expected time-to-intersection (TTX) of both vehicle are compared. The expected TTXs of both vehicles are computed by the following formula

$$TTX_1 = \frac{|\vec{r_i} - \vec{r_1}|}{|\vec{v_1}|}\mathbf{sign}((\vec{r_i} - \vec{r_1}).\vec{v_1}) \quad (3)$$

$$TTX_2 = \frac{|\vec{r_i} - \vec{r_2}|}{|\vec{v_2}|}\mathbf{sign}((\vec{r_i} - \vec{r_2}).\vec{v_2}) \quad (4)$$

where $\vec{v_1}, \vec{v_2}$ are the velocities of the SV and POV respectively, $\vec{r_n}$ is the vector representation of coordinate (x_n, y_n), and **sign**() is a sign function. Note the sign function is used to identify if a vehicle passed through the intersection. Once a vehicle cleared the intersection, its TTX becomes negative. If the two vehicles are expected to get to their path intersection point at the same time, i.e., $TTX_1 = TTX_2$, then there

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[1] when multiple vehicles are threatening the subject vehicle, each of them is handled separately as the principle other vehicle. Henceforth, we only discuss the problem in the context of two vehicles.

is a route contention. Once there is a route contention, the TTX is the same as time-to-collision(TTC).

$$TTC_i = \begin{cases} TTX_i & \text{if there is a route contention} \\ \text{Undefined} & \text{otherwise} \end{cases} \tag{5}$$

Considering that vehicles have certain size and are not really an abstract point, the following contention criterion is used instead of the simple equivalence condition:

$$|TTX_1 - TTX_2| < \alpha \tag{6}$$

where α is a contention parameter. The larger α is, the more conservative the algorithm is. In general, vehicles' sizes, velocities, and their uncertainties are the major factors in determining the value of α. Further detail is available in the discussion section.

Time-To-Avoidance (TTA)
Once a contention is discovered, the algorithm needs to decide whether to issue a warning. There are two reasons to hold back even if there is route contention. One is because the driver has already taken appropriate action and, e.g., the brake was applied already. The other is because there is still plenty of time for the vehicle to reach the intersection, i.e., it is too early to issue the warning immediately. With of all the uncertainty on the road, a warning issued too early is more likely to be a false alarm, which is not desirable.

One way to judge when to issue a warning is to compare the time-to-collision with time-to-avoidance. In general, time-to-avoidance depends on many factors such as the agility of the vehicle, the response time of the driver, and the time characteristic of the avoidance measure chosen, etc. Rather than trying to take everything into account, in this work, we choose to focus on the physical factors which can be parameterized, such as the response time t_r of a driver. We also choose braking as our expected avoidance measure, and propose the following TTA formula based on the assumption of linear deceleration:

$$TTA = t_r + \frac{\beta v}{f(\mu)g} \tag{7}$$

where $f(\mu)$ is a Berkeley friction scaling function [11], $f(\mu)g$ is the effective deceleration and β is a speed reduction factor. Value of 1 for β indicates that the expected avoidance is a full stop of the subject vehicle. We use β becasue, in most of the cases, a collision can be avoided by reducing the speed by certain amount rather than a full stop of the SV. The range of β is (0,1].

Given the two metricss, TTC and TTA, a warning is issued if

$$TTC - TTA < \gamma \tag{8}$$

where γ is a positive parameter for tuning the timing of effective warning. Larger values for γ lead to more conservative behaviors by the algorithm. As we have mentioned earlier, an algorithm that is too conservative could have negative effects, like annoying and desensitizing the driver. Thus γ needs to be tuned to achieve the best possbile driver experience. The same is true for the parameters α and β.

In summary, our collision warning algorithm requires knowledge of the vehicle's own state, includeing location, velocity and brake status. It also requires information about other vehicles which might cut the path of the subject vehicle. Using all the information, the algorithm estimates collision potential and tries to generate an effective collision warning. Figure (5) shows general data flow for the algorithm.

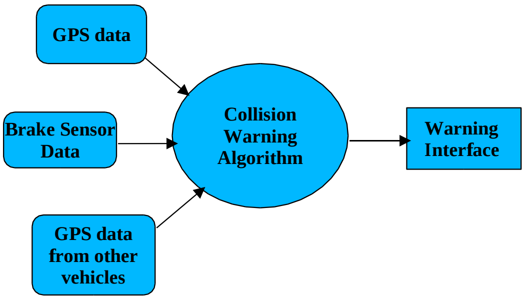

Figure 5: Data flow in ICWS components

Next we show how this collision warning algorithm is implemented on top of a dynamic ad hoc network and how the physical characteristics of the underlying system leads to further refinements of the algorithm. Please note that, even though only the intersection perpendicular path scenario is presented here, the system is compatible with other crash warning scenarios.

4 System Architecture

As described in the previous section, the algorithm requires knowledge of the vehicle location, velocity, and brake information. In order to get this information, we attach a Garmin Global Positioning System (GPS) receiver to each vehicle. This gives us location and velocity information. A brake sensor is used to get the braking state of the vehicle. Each vehicle is also equipped with a wireless system that supports ad hoc communication and enables the direct sharing of information between peers. Next, we present details of the system and discuss some issues we encountered in putting it together.

System hardware components

(1) GPS Receiver and its property test
A Positioning System (PS) is needed to provide constant updates of the vehicle's position and velocity. For the purpose

of navigation it is necessary to locate the vehicle on a map, which requires positional accuracies of about 10 meters with respect to Earth Datum and update rates of 1 second. For the purposes of crash detection and mitigation it is desirable to have positions with respect to other vehicles, or the relative position, known to sub-meter accuracy with update times on the order of 10 Hz.

In this implementation we chose to use a Global Positioning System (GPS) because, being satellite based, the positioning service is available around the world. Further, governments provide the service free of charge so there is no cost to the user beyond the initial investment in the GPS unit. GPS signal is available pretty much everywhere, although the performance of the system may degrade based on the constellation of GPS satellites available at any given time. Satellite signals are very weak (on the order of -160dB) and are fairly high frequency (~ 1.5GHz). As a result, they tend to travel along line of sight, reflect easily and are readily absorbed by natural and artificial structures. Reflected signals and poor reception of satellites are both sources of positioning errors, as is quality of the receiver. A disadvantage of GPS is that it depends on good reception of the satellites scattered across the sky for accurate positioning. For example in tunnels and parking garages GPS may not work at all. In valleys and between mountains positioning may be compromised. This is the case also in ”urban valleys” where a vehicle travels down a street surrounded by tall buildings.

Other kinds of positioning systems are available, including Loran, inertial guidance systems and radar. Each with its limitations - we used a low-cost GPS unit as a starting point. We implemented a Garmin 35 12 channel receiver that updates at 1Hz, is rated to 3-10 meters accuracy (with differential correction) and retails for less than $300. The unit is self-contained in a weatherproof enclosure and is connected via NMEA-0183 (RS-232) to a computer in the vehicle. Figure(6) is a picture of the unit. It has built-in Kalman filters that compensate for selective availability and for statistical errors generated in the antenna and receiver. Dead reckoning serves to compensate for temporary loss of satellite communication.

Figure 6: Garmin 35 GPS receiver

For crash avoidance a faster and more accurate positioning system is needed. The filters in the Garmin 35 add delay to the positioning data when velocity is changing; the overall accuracy is not sufficient; and the update interval of 1Hz is inadequate. More costly GPS units are available that deliver accuracies in the range of 1 meter and provide position and velocity at 10Hz; however, it is also possible that the accuracy of a low cost GPS unit can be improved using other inputs that are available on the vehicle.

An added benefit of GPS is that the absolute time is accurately computed as a byproduct of the positioning calculation. GPS units generally provide a Pulse Per Second (PPS) output that can be used to synchronize network communication. The PPS signal is delivered to the GPS unit of each vehicle, synchronized within 200 nanoseconds. This provides a timing reference point to set up communications windows for particular types of communication. Network performance is improved by reducing network congestion, which allows more timely delivery of messages. This is very important for safety related data communication. One example of using it for synchronization purpose is discussed in Section 5.

(2) Brake sensor
To get the brake information, we tapped into the brake switch system and use an A/D converter to feed data to the on board computer system.

(3) WaveLAN and its enhancement
Peer-to-peer wireless communication is achieved by using Orinoco PCMCIA WaveLAN cards. Our initial analysis shows that we need to improve their wireless range. These commercial IEEE 802.11 wireless cards have an outdoor range of $80 \sim 100$ meters. Normally, vehicle speed is about $15 \sim 25m/s$. This means once the vehicles are in communication range, the max time-to-collision is only about 4 seconds. Yet, the GPS sampling frequency is 1 Hz, and driver reaction time to warning is about 1 second [5, 1], and decelerating a vehicle traveling at 25m/s to full stop needs at lease 3 seconds. This means that a conservative time-to-avoidance is at least 5 seconds. Five seconds(TTA) is needed while only four seconds is currently available means that we need to either to cut down the TTA or increase the TTC. As the deceleration time is imposed by physics, and human response time is not easily reducible by assistance tools, the only way left to reduce TTA is by increasing GPS frequency. It could reduce the TTA by one second at most. We choose to increase max TTC by increasing the wireless range. We used a HyperGain HG2403MU 2.4GHz 3dBi Mini-Mobile antenna and a HyperAmp bi-directional amplifier (HA2401-AG C1000 with automatic gain control 1 Watt, 2.4 GHz) to enhance the wireless range of the Orinoco cards. Figure(7) is a picture of both components.

Arming our vehicles (Lincoln LS and Escape) with the new enhanced wireless system, we did empirical tests and found

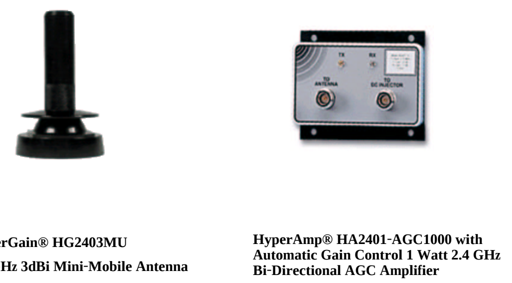

Figure 7: Antenna and Amplifier for Range Enhancement

that the new effective wireless signal range is quite satisfying. Figure (8) is a aerial image of Fairlane mall, one of the sites where we did the range test. In the Fairlane test, we parked the Lincoln LS in one of the parking lots, and drove the Escape around the parking lots and on roads close to the mall. A multicast test application was used to test the quality of wireless link between the two vehicles. Initially, the antennas were placed on the roofs of the vehicles, and the resulting range was greater than 400 meters. Next we placed the antennas in the trunks, and found this placement did not effect the range very much. We also found that while the vehicle parked on the parking lot did not reduce much of the range, the hills and buildings could reduce the range to a significant degree. Buildings in the Fairlane mall and small hills by the Fairlane mall reduce the effective range to $200 \sim 300$ meters. The effective range is defined here on the absence of observable drop of radio packets in our multicast tests. The dotted line in Figure(8) shows a major route driven back and forth by the Escape during the multicast test. The arrows point to the locations where significant loss of packets occurs. Given these test results, the enhanced system met our requirement for effective intersection collision warning, allowing about $4 \sim 7$ seconds for advanced warning.

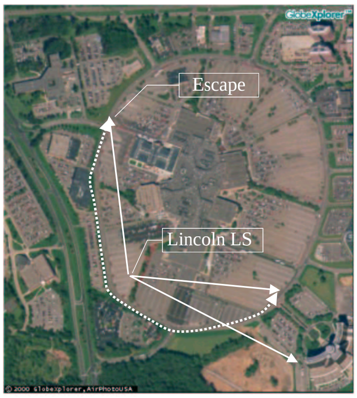

Figure 8: One Test Location: Fairlane Mall, Dearborn, MI

(4) Vehicle driver interface
Audio, visual, and haptic interfaces have been studied for presenting warnings to the driver [17, 5, 13]. For the prototype, we used the existing audio system in the vehicle for audio warnings and the computer monitor for visual warning. Studies [5] have shown that audio signal are among the most effective warning cues and recommended a combination of audio and visual cues. A multimodal driver interface presentation including haptic interface will be in-cooperated in our future study.

(5) Central Processing Unit
The central processing unit is a SONY VAIO laptop PCG-Z505LEK.

(6) System integration
Figure (9) is an architecture diagram for our collision warning system.

System software architecture
As this collision warning system is our first step in an intelligent collision warning, avoidance and mitigation system, we expect more sensors, different algorithms, and different driver interfaces to be deployed and tested in the near future to support continueous improvement and refinement of the system. To facilitate this, we used an agent-based software architecture in our collision warning system, it is designed to ensure reliability, flexibility and extensibility of the system, and to reduce the cost of our long term software and system development. Furthermore, we specifically choose a Java implementation of LIME [9], a tuplespace-based mobile-agent middleware for mobile computing, to speed up our software development.

Figure (10) shows the software architecture of our collision warning system. The first layer is the layer of sensory agents, the second layer contains control agents. The two layers interact through a shared reactive dataspace. The third layer contains presentation agents, they are in charge of presenting the system decisions from the second layer to the driver. This architecture separation of observation (sensory), decision, and presentation makes the software system very flexible and extensible. For instance, when a new haptic warning interface is integrated into the vehicle, one doesn't need to rewrite and recompile most of the code. One can simply code a new Haptic Agent, listening to the shared Actuator Dataspace and make independent presentations of the warning accordingly. In such a way, this software architecture is able to dramatically reduce the cost of software development, and speed up the design and implementation process. Furthermore, the decoupled nature of the interaction among the components makes the system more reliable. For instance, if the new haptic warning interface somehow brakes

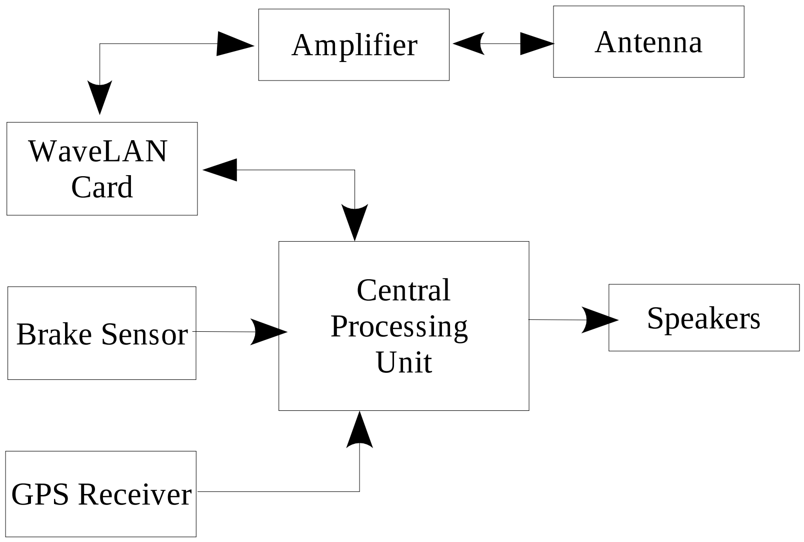

Figure 9: Intersection Warning System(ICWS) System Architecture

down, the audio warning interface will continue work, and vice versa.

Vehicle-to-vehicle information sharing is transparent in the program as we use a middleware called LIME. It handles all lower level ad hoc communication and sharing of information through the shared data space across peers. The shared dataspaces of the peers dynamically merge when the vehicles get within communication range, and the merged dataspace automatically splits when they move out of range. Further details and papers relating to LIME can be found at http://www.cs.wustl.edu/mobilab.

5 Further Analysis, Refinement and Discussion

So far we have presented general aspects of the our algorithm and system design. Next we look into the detail physical characteristics of the system and their implications for the algorithm.

Latency of GPS and Communication Systems

Our collision warning system works by each participating vehicle sampling its own location and velocity through GPS, and sharing the information with peers within the communication range. So far we have glossed over the asynchronous nature of the solution. Several things need to be looked at in detail. First, it is the possible effect of message passing delays. For instance, once the POV gets its GPS data, it puts a copy to the shared data space for its peers to look up, then the SV reacts to the new data, and gets a copy for threat estimation. This process takes time. By the time SV receives its location and velocity information, the POV could have already moved away from that location, and might have changed its velocity too. Second, GPS has a sampling frequency of one Hz, if the message delivery time is greater than half second, then there is a chance of data mismatch. For example, assume when the SV received a copy of GPS data from the POV [2] that is obtained at time t_2, it uses the data to compute POV's TTX, and compares with its own TTX, computed from its own GPS data obtained at t_1. t_1 may not be equal to t_2. Without taking this into account, the threat detection would be less accurate. In Equations (3,4,1,2), the locations, headings and speeds used should be the projected locations, heading and speeds at the time of computation, rather than those sensed directly from GPSs. In order to do the projection, each GPS message is explicitly time-stamped. This is made easier since the GPSs receivers are also highly accurate clocks. Assume the most recent GPS data is sampled at t_1, the threat detection computation is carried out at t, the projections are computed using the following linear extrapo-

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[2] Please note SV and POV are relative. Each vehicle view itself as SV and other(s) potential POV.

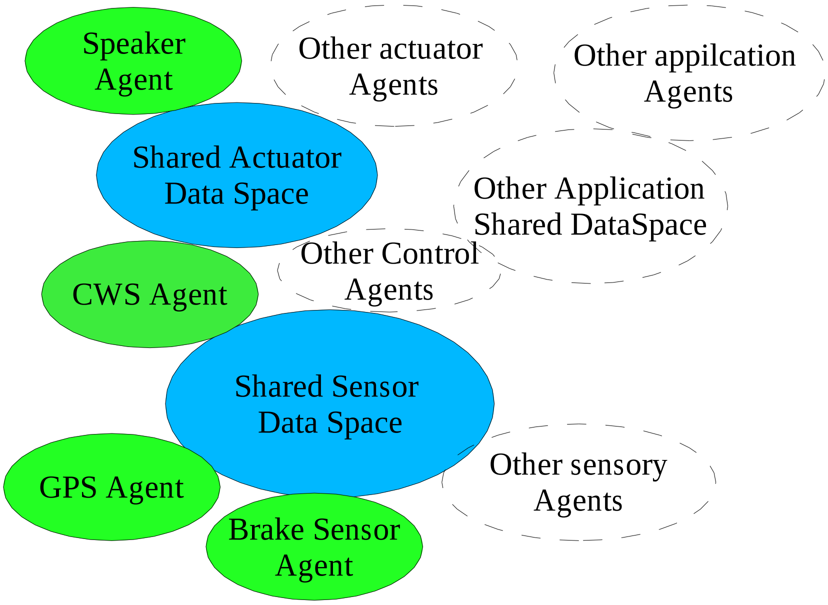

Figure 10: Intersection Warning System(ICWS) Software Architecture

lation of vehicle motion:

$$
\begin{aligned}
x_1(t) &= x_1(t_1) + v_{1x} \cdot (t - t_1) && (9)\\
y_1(t) &= y_1(t_1) + v_{1y} \cdot (t - t_1) && (10)\\
\theta_1(t) &= \theta_1(t_1) && (11)\\
v_1(t) &= v_1(t_1) && (12)
\end{aligned}
$$

Note that by using above equations, we assume there is no acceleration between time t_1 and t, and the angular speed of the vehicle is zero. If acceleration and angular speed information are available, taking them into account would improve further the accuracy of the threat detection.

Any location and velocity based collision warning solution is further complicated by the fact that the GPS data are not 100% accurate. Our own measurements have show that the GPS has an uncertainty radius of about 5 meters. This uncertainty affects the parameters α and γ in the threat detection and warning decision. GPS data with higher accuracy would result in a less conservative threat predication and more accurate warning.

Popular navigation systems in today's vehicles can be used to improve GPS performance. Navigation systems locate a vehicle on a particular path and GPS velocities are generally more accurate than GPS position (velocity is calculated using Doppler shifts while position is based on range). Since the velocity and path of the vehicle are known it is possible to remove some position error by averaging multiple positions measurements, assuming a good initial position is known. Elevation data can be supplied to the GPS by a navigation system that reduces one degree of freedom for the position calculation and increasing the overall accuracy of the calculation. If GPS systems are augmented by radar the distance between vehicles is known, allowing position data to be averaged between multiple vehicles. It is also possible to transfer satellite range data between vehicles of known relative position to fill in holes in individual vehicle satellite constellations. Optical lane finding can be used to further refine a vehicle's position, and to determine a vehicle's offset in the roadway.

Another approach to improve the relative positioning is the use of interferometric techniques. The Garmin 35 puts out phase data that includes a wave count and the phase of the carrier wave at the sample time for each satellite in view. This defines a set of parallel surfaces separated by one wavelength and perpendicular to the direction of propagation of the signal for each satellite. Each vehicle has its own set of parallel surfaces based on its location in each wave train. If four satellites are in view and are reasonably well separated it is possible to determine the relative position of the two vehicles given the set of parallel surfaces is known for each of the vehicles. The method is dependent on the antenna and its ability to exclude reflected signals and on the quality of the receiver. Garmin 35 units would be expected to be accurate to about 1 meter using this approach.

A more direct way to improve the system is to use a GPS receiver with much higher accuracy and sampling frequency. There are more expensive GPS systems which can provide centimeter level location accuracy. We are considering using them for future research if higher accuracy is needed for system fine-tuning.

This collision warning system is applicable to most of the crash scenarios, although only the intersection perpendicular crash scenario is discussed in detail in this paper. Many forward collision warning criteria developed by other researchers [17, 11, 3, 2] could be tested using this system.

Extra Observation

One unexpected phenomena we observed during some of the initial field tests is some sporadic dropping of packets when one of the vehicle was driving by the trees, even if the two vehicles are well within normal wireless range. The reason, we suspect, is the diffraction of the radio waves. 802.11 uses 2.4Ghz carrier frequency, the corresponding wavelength is about 10 centimeters. When a wave of this length passes around a pole of similar diameter, there will be significant diffraction effect, causing relatively big wave amplitude changes in the space closer by. It doesn't really affect the function of our system because packet dropping due to this reason are rare events. Yet, further study along these lines would give deeper insight into what would be a better radio frequency for wireless communication between vehicles, given the common environment for vehicle traffic. More field tests of the system are underway.

6 Conclusion

Vehicle crashes incur huge financial losses each year. Making vehicles safer has been one of the most important goals for auto makers. The pursue of advanced vehicle collision warning system is one of many efforts by auto makers and national highway traffic safety administration to reduce the crash rate. Most of the existing collision warning and avoidance systems are designed for forward and side collision warning. Very recently, NHTSA did a detailed study of intersection collision scenarios, and developed a prototype for intersection collision warning. Yet, the function of their system is limited by the use of radar as the only threat detection tool, as most of other collision warning systems do. Yang *et.al.* [16] at Japan Automotive Research Institute has reported about an intersection collision warning system using DGPS. Their solution is centralized, relying on base-stations and the use of modems for communication. Observing the limitations of present systems, we designed and implemented a new low cost beacon-based collision warning system. This new system doesn't have the limitation of requiring line-of-sight to operate properly, thus it can handle the hidden vehicle problem, which has been troubling other systems. Our system design also features a flexible and extensible software architecture, making it a test-bed for easier modification and augmentation of the system when better sensing technologies are available and newer algorithms are devised. We finished the first design and implementation phase, examined key factors examined and test the solutions we proposed. Preliminary tests show that the system works well. Further field tests and evaluations are under way, with the expectation of fine tuning the system and improving its performance. Results will be presented in subsequent papers.

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