An Adaptive Peer-to-Peer Collision Warning System

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Abstract— Cooperative vehicle collision warning system is made possible by recent progress in advanced positioning systems and wireless communication technology. In this paper we report our work in developing a cooperative intersection collision warning system that is not limited by the requirement of line-of-sight. 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. The very same system is also capable of collision warning for other scenarios such as frontal and rear-end. Further, the tunable parameters in the algorithm make it possible for the system to adapt to the preference and capability of each individual driver.

I. INTRODUCTION

Each year in the United States, motor vehicle crashes account for about 40,000 deaths, more than three million injuries, and over \$130 billion in financial losses. 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 [1], [2], [3], [4], [5], [6], [7]. Preliminary results have shown that the introduction of collision warning systems could dramatically reduce crash fatalities, injuries and property damage [1]. 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% [8], and Eaton reported that the actual truck fleet accident frequency was reduced by 73% after the fleets being equipped with the VORAD Forward and Side Collision warning systems by Eaton [8].

Despite the fact that intersection collisions account for almost 30% of all crashes, intersection collision avoidance systems received less attention than the forward collision avoidance systems [2], [3], [6]. It is because the intersection collision problem is more complicated than rear-end crash and the limitations 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 systems that require 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 using ad hoc mobile 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 hazards. 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 using 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.

Next we first present the intersection collision warning algorithm we use. Then we briefly discuss the system hardware architecture in section 3. In section 4, we discuss the software architecture in the system. This is followed by discussions and conclusions in sections 5 and 6, respectively.

II. ALGORITHM

Our first design phase is top-down and specification driven. Given the goal of effective collision warning, we specify the top level requirements with human factor concerns, then we derive a top level control algorithm from the requirements. After that, we factor in vehicle kinetics, network latency, and human response time, derived a parameterized control algorithm for the system to work correctly.

A. 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 [9], causing future warnings to be ignored; or distract the driver [10], [11], [12]. Undesired warnings may also make the driver turn off

Fig. 1.   Top-Level Specification for Intersection Collision Warning Sys-
tem(ICWS)

the system completely. With these concerns, we derived a top-
level specification for an intersection collision warning system
(ICWS), as shown in Figure(1).

B. Top Level CWS Algorithm

Given the system specification (Figure 1), an intersection col-
lision warning algorithm is derived, as shown in Figure 2.

ICWS Algorithm

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
6.   **else if** TTC is less than TTA
7.   delegate task to Mitigation unit
8.   **else** goto (1)
9. **else** goto (1)
10. Wait until pass the intersection, goto (1)

Fig. 2. Intersection Collision Warning Algorithm

B.1 Route Contention

Figure 3 shows a general intersection scenario. Two vehicles
at (x_1, y_1), (x_2, y_2), are moving at speeds v_1, v_2, and directions
θ_1, θ_2 respectively. A route contention is identified by the possi-
bility of collision given the current states of the subject vehicle
and the principal other vehicle. Note that when multiple vehi-
cles are threatening the subject vehicle, each of them is handled
separately as a principle other vehicle. From here on, we only
discuss the problem in the context of two vehicles.

In our algorithm, we first compute the expected path intersec-
tion (x_+, y_+) by using both vehicles' headings and locations.

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

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

After the intersection is computed, the expected time-to-
intersection (TTX) for each vehicle is compared. The expected
TTXs of both vehicles are computed by the following formula

$$TTX_1 = \frac{|\vec{r}_+ - \vec{r}_1|}{|\vec{v}_1|} \text{sign}((\vec{r}_+ - \vec{r}_1) \cdot \vec{v}_1) \quad (3)$$
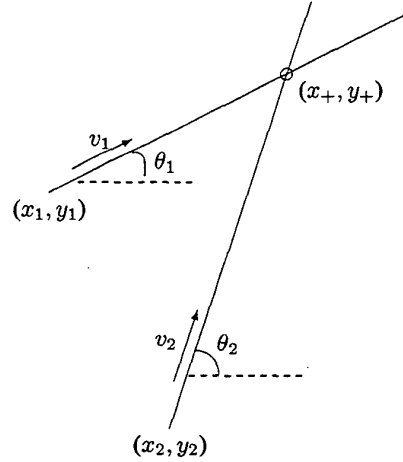

Fig. 3. Two-Vehicle Route Contention

$$TTX_2 = \frac{|\vec{r}_+ - \vec{r}_2|}{|\vec{v}_2|} \text{sign}((\vec{r}_+ - \vec{r}_2) \cdot \vec{v}_2) \quad (4)$$

where $\vec{v}_1$, $\vec{v}_2$ are the velocities of the subject vehicle and the
principle other vehicle respectively, $\vec{r}_n$ is the vector representa-
tion 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 is a route contention. Once there is a route contention,
the TTX is the same as time-to-collision(TTC).

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

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

$$|TTX_1 - TTX_2| < \alpha \quad (6)$$

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

B.2 Time-To-Avoidance (TTA)

Once a contention is discovered, the algorithm needs to de-
cide 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, 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 all of the uncertainties 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 the 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 constant deceleration:

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

where μ is the estimated tire-road friction coefficient, g is the acceleration of gravity, v is the current speed, 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 because, 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]. Further, note that different road conditions will change tire-road frictions.

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

$$TTC - TTA < \gamma \qquad (8)$$

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 possible driver experience. The same is true for the parameters α and β. Human factor studies will be performed to optimize α and β whereby these algorithms will be coupled to an advance driver warning system and a stationary driving simulator.

In summary, our collision warning algorithm makes use of its own state information and that of surrounding vehicles', to make a decision on when to issue a warning. Next we present the system architecture we used to implement the algorithm.

III. HARDWARE ARCHITECTURE

As described in the previous section, the algorithm requires knowledge of the vehicle location, velocity, and other vehicle state information, such as brake pressure. In order to get this information, we attach a Global Positioning System (GPS) receiver to each vehicle. This gives us location and velocity information. Other vehicle state information are taken from the vehicle bus. The vehicle bus data includes brake state, brake pressure, steering wheel angle, throttle angle, RPM, differential wheel speed, headlight and airbag information. Each vehicle is also equipped with a wireless system that supports ad hoc communication and enables the direct sharing of information between peers. As part of the Intelligent Transportation System's wireless strategy the vehicles have been equipped with Dedicated Short Range Communication (DSRC) hardware, as well as with the more traditional 802.11a,b and Bluetooth (802.15b) standards. Further, an audio user interface is used to issue warnings as well as to receive commands from the driver. The em-

bedded audio system is conversational in nature and uses a natural language system. Figure 4 shows the hardware architecture of our system.

IV. 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 future. To facilitate this, we used an agent-based software architecture in our collision warning system. This architecture is designed to ensure reliability, flexibility and extensibility of the system, and to reduce the cost of our long term software and system development. The agent system uses a tuple space based model for interaction.

As shown in Figure 5, the first layer of the architecture is the layer of sensory agents, the second is a layer of 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 breaks down, the audio warning interface will continue to work, and vice versa.

V. DISCUSSION

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 is the possible effect of message-passing delays. For instance, once the principle other vehicle (POV) gets its GPS data, it puts a copy to the shared data space for its peers to look up, then the subject vehicle (SV) reacts to the new data, and gets a copy for threat estimation. This process takes time. By the time subject vehicle receives its location and velocity information, the POV could have already moved away from that location and might have changed its velocity. Second, GPS has a sampling frequency of one Hz, thus if the message delivery time is greater than half second, there is a chance of data mismatch. For example, assume when the SV received a copy of GPS data from the POV 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 is 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
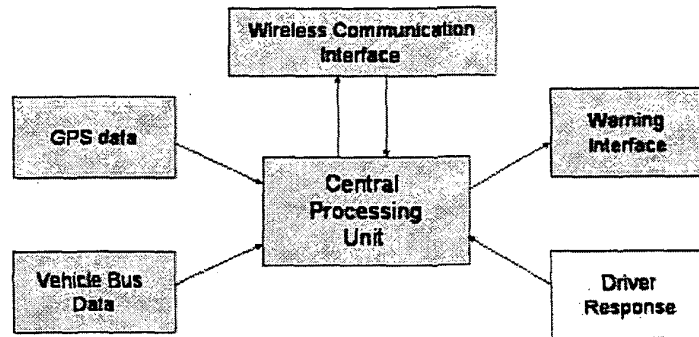
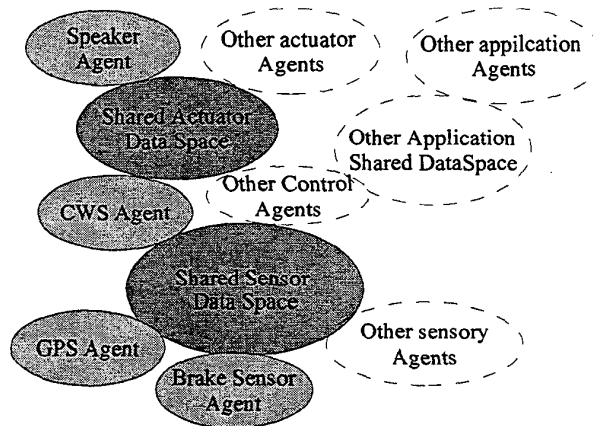Fig. 4. Intersection Warning System(ICWS) System Architecture

Fig. 5. Intersection Warning System(ICWS) Software Architecture

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 extrapolation of vehicle motion:

$$x_1(t) = x_1(t_1) + v_{1x} \cdot (t - t_1) \qquad (9)$$
$$y_1(t) = y_1(t_1) + v_{1y} \cdot (t - t_1) \qquad (10)$$
$$\theta_1(t) = \theta_1(t_1) \qquad (11)$$

$$v_1(t) = v_1(t_1) \qquad (12)$$

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

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 shown 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. Currently our vehicles are equipped with differential GPS receiver with an uncertainty radius of about 1 meter. Further, we also seek to project vehicle location by using speed and heading information obtained from the vehicle bus. This projection is especially useful when GPS information is not available.

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 [1], [9], [13], [14] could be tested using this system.

Note that in the head-on case, $\theta_1 = \theta_2 \pm \pi$, the expected collision point (x_+, y_+) becomes:

$$x_+ = x_1 + \frac{|\vec{v}_1|}{|\vec{v}_1 - \vec{v}_2|} d \cos \theta_1 \qquad (13)$$

$$y_+ = y_1 + \frac{|\vec{v}_1|}{|\vec{v}_1 - \vec{v}_2|} d \sin \theta_1 \qquad (14)$$

where d is the distance between (x_1, y_1) and (x_2, y_2), $\sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2}$. Further, in the rear-ending case, the expected collision point can also be computed by equations (13) and (14) if $|v_1| > |v_2|$. No possibility of collision if $|v_1| \leq |v_2|$. We leave the detail of the analysis to the reader. Corresponding collision warning algorithms regarding these cases will be presented in the future.

VI. CONCLUSION

The pursuit of advanced vehicle collision warning system is one of many efforts by auto makers, national highway traffic safety administration, and U.S. department of transportation (Intelligent Transportation System), etc., to reduce the accident 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. Observing the limitations of present systems, we designed and implemented a new low cost peer-to-peer 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. We presented a parameterized collision warning algorithm, making our system personalizable, i.e., the parameters can be adjusted to the preference, cognitive and reaction capability of each individual. This can be done either through offline measurements or online feedback. 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. From this process we learned the important interplay of the following critical factors in designing a peer-to-peer collision warning system: the

wireless communication range, the network latency, the vehicle speed, the tire-road friction coefficient, the driver response time, and the accuracy of location and speed estimation. Preliminary tests show that our system works well. Further field tests and evaluations are under way, with the expectation of fine tuning the system and improving its performance. Our future work also includes making our system communicate and interact with infrastructure resources, such as the "smart intersection" service by ITS. We believe a wireless safety network (SafetyNet)formed by the integration of vehicle-to-vehicle networks and vehicle-to-infrastructure network will deliver a new generation of automobile safety measures and services.

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