A Lane-Level Cooperative Collision Avoidance System Based on Vehicular Sensor Networks

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ABSTRACT

In this paper, we design and implement a lane-level cooperative collision avoidance (LCCA) system using vehicle-to-vehicle communications. The LCCA system applies vehicular sensor networks to preventing chain vehicle collisions, which allows vehicles with merely onboard sensors to prevent such collisions on the road because of sharp stops. To the best of our knowledge, this is the first CCA system that does not use inaccurate GPS locations and costly roadside infrastructures to avoid chain vehicle collisions. LCCA employs inter-vehicle communications and onboard sensing to form warning groups, where each warning group is a set of vehicles that drive along the same lane and every pair of adjacent cars is within a certain distance. Only single-hop transmissions are needed to join/leave a warning group, thus keeping the group maintenance overhead low. When a sudden braking is taken in a warning group, LCCA can quickly propagate warning messages among group members. This paper demonstrates our current prototype.

Categories and Subject Descriptors: C.2.1 [Network Architecture and Design]: Distributed networks

General Terms: Algorithms, Design, Management

Keywords: Collision Avoidance, IEEE 802.11p, Traffic Safety, V2V Communication, Vehicular Sensor Network

1. INTRODUCTION

Recent advances in vehicular communication technologies and embedding sensing MEMS make *vehicular sensor networks (VSNs)* possible. VSNs combine the advantages of both *vehicular ad hoc networks (VANETs)* and *wireless sensor networks (WSNs)*, which consists of many sensor nodes deployed on roads or vehicles to detect various phenomenons to facilitate vehicular applications. Many VSN applications have been developed, such as environment monitoring, traffic safety, mobile surveillance, and vehicle security.

In this work, we design a *Lane-level Cooperative Collision Avoidance (LCCA)* system to prevent chain collisions among vehicles even there is no global positioning system (GPS) onboard. GPS is a worldwide localization technology adopted by vehicles, which consists of a number of satellites transmitting periodical coded signals. GPS receivers with multiple radio channels can observe multiple GPS satellites at once and obtain a distance measurement from each satellite signal. A GPS receiver can compute its location in three dimensions from four distance measurements. However, the distance measurement contains global and local errors caused by atmospheric and multi-path effects, respectively, with a typical accuracy range of $10 - 50$ meters.

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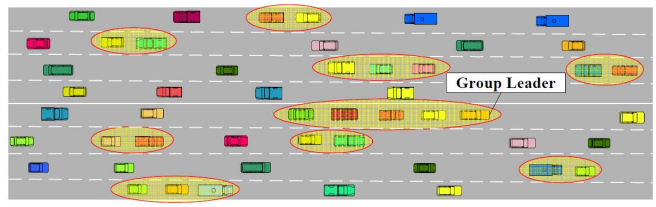

Figure 1: Warning groups formed by LCCA on a highway.

During satellite signals that originate in the atmosphere and travel to the surface of Earth, global errors consisting of satellite clock errors, ephemeris errors, ionospheric delays, and tropospheric delays are generated. In particular, the effect of global errors on receiver measurements varies from one geographical area to another. Local errors depend on the hardware accuracy and surrounding environment of the receiver that are caused by the receiver hardware itself and multipath effects without line of sight.

GPSs are generally assumed to be deployed on vehicles by most safety protocols and applications in VANETs [1, 2, 3, 4, 5]. However, the current geographical locations of vehicles can not be accurately estimated due to GPS errors. In addition, the availability of GPS is uncertain as the vehicles enter areas where GPS signals may not be detected such as inside tunnels, streets between high buildings, etc. On the other hand, in the traditional CCA system, the vehicle encountering an emergency situation will broadcast warning messages to all other vehicles behind it. But a large number of messages are generated and flooded in the VANET. In addition, redundant messages are produced for the same emergency event. Thus, message collisions are occurred very often with the increasing number of vehicles on the road, which lead to a substantially high delay in delivering the warning message.

To eliminate the above GPS error and message collision problems, we design the LCCA system consisting of dynamic grouping and message forwarding schemes with GPS-less protocols. To the best of our knowledge, this is the first CCA system that avoids chain vehicle crashing without using inaccurate GPS locations and merely rely on vehicle-to-vehicle communications to dynamically form warning groups. A warning group is a set of adjacent cars within a certain distance driving along the same lane. Only single-hop transmissions are needed to join/leave a warning group, thus keeping the group maintenance overhead low. When a sudden brake event is detected in a warning group, LCCA can quickly propagate warning messages among its group members. Fig. 1 shows an example of warning groups formed by LCCA on a highway.

2. SYSTEM DESIGN

In the LCCA system, each vehicle is equipped with an image sensor (e.g., video camera) and a distance sensor (e.g., magnetic sensor or laser range finder) in its front end. The image sensor is to recognize the license plate number (i.e., communication ID) of the vehicle in the front, whereas the distance sensor is directional and to detect the distance from one vehicle to another in its front. With this sensor, a vehicle can also estimate the relative velocity of the vehicle in its front. For the absolute velocity, it is obtained through the On Board Diagnostics (OBD [6]) interface. All vehicles have WAVE/DSRC [7] radio interfaces to freely communicate with each other.

A vehicle will join a warning group as its following distance with the vehicle in its front is less than the safety distance. On the contrary, a vehicle will leave a warning group as its following distance is more than or equal to the safety distance. When a group vehicle performs an emergency brake (i.e., the deceleration of brake is more than a predefined threshold), it will immediately send a warning message to all other group vehicles behind it. The warning message is assigned the highest priority than other control messages or data packets for its emergency. Group vehicles beyond the transmission range of the braking vehicle will be warned through a multi-hop manner. Thus, drivers can become aware of emergency brake before they actually see the braking light of the vehicle in the front.

Our goal is to design an efficient lane-level CCA system for vehicles to join/leave a warning group. In addition, when any vehicle in a warning group performs an emergency brake, the system needs to immediately broadcast a warning message to all behind group vehicles. The warned vehicles could slow down their speeds in advance to reduce the chances of chain vehicle collisions. In the lack of vehicles' self-locations, we consider the following issues:

1. Vehicle Grouping: How do we construct a warning group that can be joined/left by vehicles in the same lane so that the control overhead is minimized?

2. Member Updating: How do we update a warning group as some members change their lanes or following distances so that the group maintenance overhead is minimized?

3. Group Warning: How do we quickly propagate a warning message to all members behind the braking vehicle through multi-hop forwarding so that the warning message cost is minimized?

4. Forwarder Decision: How do we explicitly specify an optimal forwarding vehicle so that the number of rebroadcasted warning messages is minimized?

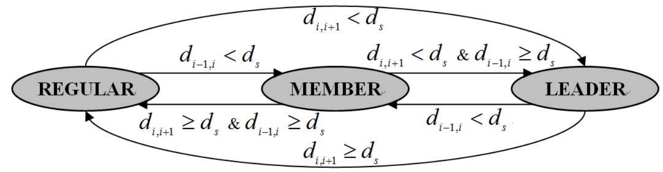

Figure 2: State transition diagram of vehicle i.

3. LANE-LEVEL COOPERATIVE COLLISION AVOIDANCE

Based on our previous work [5], we further design a new GPS-less framework consisting of a distributed grouping mechanism and a receiver-based forwarding scheme. The dynamic grouping of vehicles is employed to notify related vehicles with the emergency event, which keeps control and warning messages in local. To minimize the number of warning message transmissions for emergency brakes in a group, the receiver-based forwarding scheme specifies the optimal group vehicle to rebroadcast the warning message without infrastructure and GPS supports.

For dynamic grouping, after a vehicle i gets on the road, the safety distance d_s supposed to be maintained by i is equal to $s_i \times \eta$ meters, where s_i is the current speed of i and η is the statistical factor for the safety distance between vehicles. For example, $\eta = 0.55$ by using the two-second rule [8]. If $d_{i-1,i} \geq d_s$, it means the distance between i and $i-1$ is enough for i to deal with the emergency brake of $i-1$. There is nothing to do for both onboard units of i and $i-1$. Conversely, if $d_{i-1,i} < d_s$, it means i may not react in time to the emergency brake of $i-1$ such that a crashing is possible to happen.

When $d_{i-1,i} < d_s$, i will send a message M_{join} to $i-1$ for joining $i-1$'s warning group. Then, $i-1$ will reply a message M_{reply} to i for indicating the group leader ID (i.e., ID_{GL}) and $i-1$'s group number (i.e., GN_{i-1}) in the warning group, and add i to its warning list L_{i-1}. If $i-1$ has kept d_s from vehicle $i-2$ in its front, $i-1$ will serve as the GL. ID_{GL} and GN_{i-1} will be passed to i by $i-1$ and $\text{GN}_i = \text{GN}_{i-1} + 1$, where $\text{GN}_{GL} = 1$. On the other hand, when $d_{i-1,i}$ is getting larger than d_s, i will send a message M_{leave} to $i-1$ for leaving $i-1$'s warning group. Then, $i-1$ will remove i from its L_{i-1} since $d_{i-1,i}$ is enough to deal with the emergency brake of $i-1$. Note that M_{join}, M_{reply}, and M_{leave} messages are only transmitted in single hop so that the control overhead to join/leave a warning group is localized and thus minimized.

For example, there is a sequence of vehicles A, B, and C in the same lane. If B detects $d_{A,B} < d_s$, it sends M_{join} to A. A adds B into its L_A and replies M_{reply} to B that indicates $\text{ID}_{GL} = A$ and $\text{GN}_A = 1$. According to M_{reply}, B can calculate its $\text{GN}_B = \text{GN}_A + 1 = 2$. Similarly, if C detects $d_{B,C} < d_s$, it sends M_{join} to B. B adds C into its L_B and replies M_{reply} to C that indicates $\text{ID}_{GL} = A$ and $\text{GN}_B = 2$. According to M_{reply}, C can calculate its $\text{GN}_C = \text{GN}_B + 1 = 3$.

The state transition diagram of vehicle i is shown in Fig. 2, where vehicle i is in front of vehicle $i+1$ and behind vehicle $i-1$ in the same lane. There are three possible states for vehicle i:

- *REGULAR*: i keeps in d_s from $i-1$ and so does $i+1$ from i.
- *MEMBER*: i does not keep in d_s from $i-1$.
- *LEADER*: i keeps in d_s from $i-1$, but $i+1$ does not keep in d_s from i.

(a) Android Phone + IWCU (b) OBD II Interface

Figure 3: LCCA hardware components.

Whenever i transits to the LEADER state, it broadcasts a M_{update} message to all behind group member j for updating ID_{GL} to ID_i and GN_j to $\mathrm{GN}_j - \mathrm{GN}_i$. Whenever i is in the LEADER/MEMBER state and performs an emergency brake, it immediately broadcasts a M_{warn} message to all behind group members. A vehicle only accepts a M_{update}/M_{warn} message from the vehicle in front of it in the same warning group. The forwarding of M_{update}/M_{warn} is through a multi-hop manner as some behind group members are out of the transmission range of i. In our framework, the redundancy of M_{update}/M_{warn} will be completely eliminated by the proposed receiver-based forwarding scheme (due to space limitation, the detailed mechanism is omitted). Note that we can also simply use general broadcast forwarding to relay M_{update}/M_{warn} to all behind group members.

4. PROTOTYPE IMPLEMENTATION

We have developed a prototype of LCCA. In our prototype, the radio interface is implemented by ITRI WAVE Communication Unit (IWCU [9]), which has two IEEE 802.11p interfaces and one Ethernet connector. Vehicle grouping and warning operated in LCCA can send UDP packets via standard socket APIs, such as sendto() and recvfrom(), and IWCU can convert UDP packets to WAVE short messages (WSMs [10]).

The image sensor is implemented by the camera of an Android phone recognizing the license plate number of the vehicle in the front to obtain the communication ID. In addition, the camera also recognizes the license plate size to detect the distance from itself to the vehicle in its front. As shown in Fig. 3(a) and Fig. 3(b), the Android phone communicates with an IWCU and an OBD II interface through Wi-Fi and Bluetooth, respectively. The Ethernet connector of the IWCU is connected to a Wi-Fi access point for communications with the Android phone. The 802.11p interfaces are set to WAVE/DSRC mode for communications with neighboring vehicles. The graphical user interface (GUI) in the Android phone shows the messages received from neighboring vehicles and status of vehicles in the warning group.

Fig. 4 shows the indoor demonstration of LCCA. As shown in Fig. 4(a), we use three Android phones on the separate modeled cars to simulate traffic flows on a road segment with four lanes (two lanes per direction). As shown in Fig. 4(b), the GUI shows the license plate tag and warning group status. The Android Augmented Reality (AndAR [11]) Library is adopted to recognize the license plate number and tag size of the vehicle in the front. In our demonstration, the first vehicle (i.e. green car) is joined by the second one (i.e., red car) as the distance between them is smaller than a predefined safety distance, as shown in Fig. 4(c). Then, the third

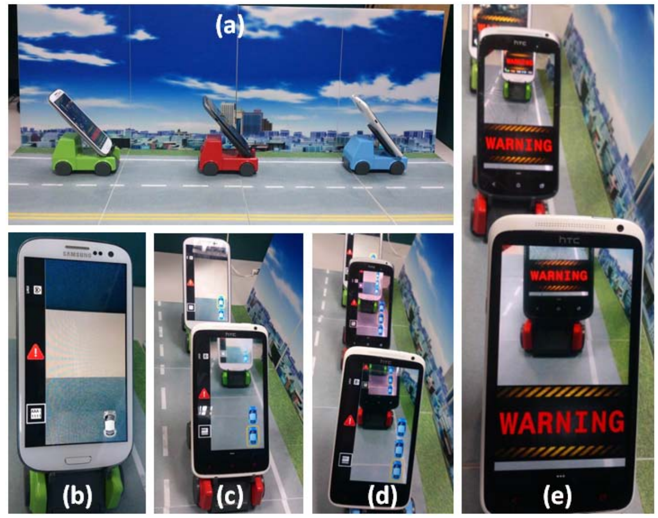

Figure 4: Indoor demonstration of LCCA.

vehicle (i.e., blue car) joins the warning group formed by the first and second ones, as shown in Fig. 4(d). After the warning group is formed, the first one of these three vehicles takes an emergency brake by pushing a button on the GUI to broadcast a warning message. As shown Fig. 4(e), the group vehicles behind the braking car are notified, and the drivers are warned by the alarming sign and high frequency sound while other vehicles ahead or in different lanes discard the warning message.

5. ACKNOWLEDGMENTS

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