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Optimal placement of omnidirectional sensors in a transportation network for effective emergency response and crash characterization

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ABSTRACT

Rapid motor vehicle crash detection and characterization is possible through the use of Intelligent Transportation Systems (ITS) and sensors are an integral part of any ITS system. The major focus of this paper is on developing optimal placement of accident detecting omnidirectional sensors to maximize incident detection capabilities and provide ample opportunities for data fusion and crash characterization. Both omnidirectional sensors (placed in suitable infrastructure locations) and mobile sensors are part of our analysis. The surrogates used are acoustic sensors (omnidirectional) and Advanced Automated Crash Notification (AACN) sensors (mobile). This data fusion rich placement is achieved through a hybrid optimization model comprising of an explicit–implicit coverage model followed by an evaluation and local search optimization using simulation. The compound explicit–implicit model delivers good initial solutions and improves the detection and data fusion capabilities compared to the explicit model alone. The results of the studies conducted quantify the use of a data fusion capable environment in crash detection scenarios, and the simulation tool developed helps a decision maker evaluate sensor placement strategy.

1. Introduction

The US Department of Transportation (DOT) is planning for a future wherein, the transportation system will be equipped with automated sensor systems that sense unsafe driving conditions and take action to prevent crashes thereby decreasing fatalities. In those cases in which a crash is not preventable, the systems will automatically detect and characterize incidents through interoperable, wireless networked communications among vehicles, infrastructure and travelers personal communication devices. The Connected Vehicle Program launched by the DOT envisions this future system and aims to achieve the required sensor technology, vehicle and infrastructure connectivity to transform the US transportation system.

Sensors play a crucial role in this future transportation system, monitoring and measuring every change on the road. The next generation of Intelligent Transportation Systems (ITS) sensors will add wireless networking capabilities to the last generation of sensors and new technology to improve current state of the road conditions. ITS have long been helping traffic managers with incident detection and provide a means to monitor traffic.

One area that is expected to benefit from the next generation of ITS is emergency response to motor vehicle crashes. Emergency medical personnel refer to the 60 min following traumatic injury as the "Golden Hour" (Lerner and Moscati,

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2001). The exact impact of providing emergency care during the golden hour on survivability has not been clearly quantified. However, it is generally agreed that shortening the time to definitive care will improve chances of survival for many crash victims (American College of Surgeons, 2004). Many motor vehicle crashes on roads go undetected, delaying the delivery of emergency services and thereby result in higher morbidity and crash-related fatalities. To improve the situation, there is a need to quickly identify motor vehicle crashes and characterize them. ITS systems with incident detection capability fill this need.

The focus of this paper is to study the use of omnidirectional sensors in a future ITS system where every sensor has wireless communication capabilities. This study includes developing a general approach for optimally placing these sensors to maximize detection capabilities and provide higher quality crash assessment. Acoustic sensors are one type of omnidirectional sensor, which we expect to have a functional role in a future transportation system. We use them in this paper as a representative sensor type and as a proxy for all omnidirectional sensors. Some key papers and patents that use acoustic sensors (mobile and stationary) (Harlow and Wang, 2002; White et al., 2011; Lagassey, 2008; and Kuhn et al., 1998). These studies demonstrate clear potential for application of acoustic sensors in transportation systems.

Our primary goal is to study the impact of stationary omnidirectional sensors while exploring the benefits of using mobile sensors data along with existing infrastructure sensors. To this end, we note that there are many advances in sensor technology for automobiles; one of the most prominent is Advanced Automated Crash Notification (AACN). AACN systems combine the information from in-vehicle sensor suite (GPS, accelerometers, rollover sensors, etc.), to detect a crash and transmit (via cell phone communication) a crash report with crash location. In this paper, we use AACN sensors as a secondary sensor system to the omnidirectional acoustic sensors to understand and demonstrate the utility of a data fusion environment.

The distinguishing features/contributions of our paper are as follows:

- The use of data fusion in locating omnidirectional sensors.
- Evaluates the performance of a data fusion capable omnidirectional sensors network using a simulation of a road network.
- Provides insight on the number of omnidirectional sensors needed for a required detection level.
- Considers the use of multiple sensor types and quantifies the use of sensors independently and together.
- Uses simulation as an evaluation and optimization framework.

The organization of the remainder of this paper is as follows: Section 2 presents the literature survey and background on the sensors considered for the study. Section 3 introduces the node and path based formulation and the solution methodology comprising of an implicit and explicit model. Section 4 presents the simulation model used to evaluate the solution methodology, the simulation-based optimization framework and the improvements possible with the proposed solution methodology. In Section 5, we present how omnidirectional and mobile sensors work in a data fusion environment and evaluate the simulation with both sensor types. Finally, in Section 6, we present our concluding remarks.

2. Background on sensor location problem and sensors considered in our study

Advanced transportation sensor systems typically include a variety of sensors, some mobile (i.e. drones, in-vehicle sensors) and some fixed. The fixed sensors can be directional (e.g. cameras, with a fixed line of sight) and non-directional or omnidirectional (e.g. chemical, radiation and some radio frequency antennae). For the analyses reported in this paper, we choose to consider a set of omnidirectional fixed sensors (i.e. acoustic sensors) and a set of mobile sensors (i.e. AACN sensor). We note that at present AACN sensors are part of onboard sensors in a small subset of vehicles whereas acoustic sensors are not widely used in transportation systems. However, the potential effective use of acoustic sensors in transportation systems is discussed in Harlow and Wang (2002), White et al. (2011), Kuhn et al. (1998) and Lagassey (2008). Section 2.1 presents the literature review on sensor location problem and its applications in road transportation systems. Section 2.2 introduces acoustic sensors and explain in detail their functional capabilities and shortcomings. Section 2.3 introduces AACN sensor and the role of AACN as a complementary sensor to the acoustic sensors.

2.1. Sensor location problem

The fixed/infrastructure sensors performance in an incident detection system depends on both the sensors and location/placement of sensors. This necessitates the need of a systematic approach to place the sensors. This placement also needs to consider the data fusion opportunities that arise from multi sensor coverage. There is a large resource of research in this field of sensor placement that we can use to solve the omnidirectional sensor placement.

Sensor location problems typically refer to placement of sensors in a large distributed sensor network. These problems tend to maximize or minimize a certain performance measure depending on the problem. For example (Li and Ouyang, 2011) proposes the use of linear programming model to determine effective sensor placement for vehicle ID inspection stations to determine O–D flow count and travel time estimation. Linear programming model proposed assumes that all the vehicles are equipped with RFID technology and can be used to detect each car passing the detection stations. The model assumes that the detection stations can be erroneous and may even fail to work. The authors propose the use of lagrangian