Ad-hoc networks for monitoring civil infrastructures: Requirements and Design Principles

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The long-term deterioration of the infrastructure systems, such as highways and bridges, is a serious challenge. Collapse of civil infrastructures occurs more frequently than most people realize. For example, between 1989 and 2000, more than 130 bridges collapsed in the United States. The challenge is that traditional monitoring solutions, which rely on physical inspections, are very expensive to scale up. The research challenge is whether there are other strategies that can be explored. We believe that appropriately designed mobile ad-hoc networks, consisting of sensor nodes and mobile nodes in vehicles, may help provide a solution to actively monitoring the state of the infrastructure. In this paper, we outline some of the characteristics of the network in this application and some of the research challenges from a computer science perspective in managing these networks of sensor nodes.

Wide-area. Short-lived ad-hoc networks

Event-driven, opportunistic data communication

Inter-play between communication layers and vehicle speeds

End-to-end reliable communication

- Data management
- Adaptive, mobile FTP

Security aspects

Other stuff from the NIST proposal:

The roads and bridges are difficult to monitor primary objective of this task is to investigate methods of providing robust and secure multi-directional communication between the distributed wireless sensors installed on the bridges, vehicles instrumented with sensors, and data servers that will store and process the relevant measurements collected from the bridge and vehicle sensors. First, short-range communication between vehicles instrumented with dynamic measurement sensors and instrumented bridges will be developed. As vehicles travel over a bridge, they will be able to communicate to the bridge's wireless monitoring system the weight of the vehicle (as measured at a weigh-station upstream), number of axels, speed and vertical accelerations. This information will be assimilated into the bridge's monitoring system for input-output analysis embedded into the wireless monitoring system's embedded data processing framework.

Second, the extremely high nodal densities necessary for reliable damage detection requires significant amounts of data from infrastructure elements to be transmitted to the locally deployed or central data servers (*e.g.* servers owned by the infrastructure owner). In some cases, this problem can be addressed by a powered gateway node on the bridge that aggregates data from the various low-powered sensors and then periodically transmits it over a wired or wide-area (*e.g.* CDMA, Edge, or 3G) network. But, in other cases, a bridge may be at a remote location; providing network connectivity for such bridges requires the laying of expensive network cables, a task economically unfeasible. To provide a solution that can be cheaply deployed anywhere, even in the absence of networking infrastructure near the bridges, we envisage a mobile data collection and distribution method as an alternative communication channel (Fig X). In this scheme, data will be collected from the sensors on a bridge by a specially instrumented data vehicle, as it drives over the bridge and stored on medium such as USB flash drives. The data will then be uploaded from the storage medium to the central servers either directly from the vehicle, when the vehicle has good connectivity, or from a satellite monitoring office with network connectivity.

The basic idea of mobile data collection is already widely used in other settings. Many homes in the United States now have water and electricity meters that are monitored over a short-range wireless network by the utility company from outside the home. In the case of utilities, a very small amount of data per home, the meter reading, needs to be captured, visual confirmation of a successful capture is possible, and the data is usually collected at slow driving speeds. The required innovation and the research challenge in the case of bridges is being able to extend this idea to reliably handle much larger volumes of sensor data that is likely to be buffered in the sensor network. Furthermore, ideally, we would like the data collection vehicle to be able to drive over the bridge at normal speeds so as to avoid disturbing traffic. Prioritizing, aggregating, and compressing sensor data may also be important in case all the data cannot be delivered to the vehicle at the desired driving speed. The driver also needs to know that the data is being successfully collected or if corrective driving action is required.

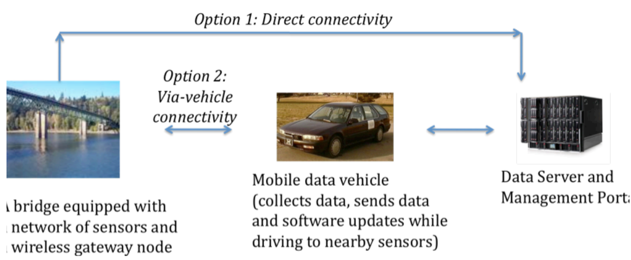

Figure X. Connectivity between sensor networks and servers

Designing a solution to this problem requires cooperation between computer scientists, wireless communication researchers, and transportation engineers, expertise that is strongly represented in this research team. Our plan is to first conduct test simulations in a controlled environment with common local-area wireless protocols (*e.g.* Zigbee) to see how their throughput and reliability is impacted when one of the nodes is mobile at varying speeds. The research approach will focus on the mechanisms to prioritize and compress data, reliability, and security. This will be accompanied by investigation of methods to tune the network and design protocols.

Table T3-1. Vehicle-infrastructure integration approaches

Approach	Strength	Weaknesses
Video-based Vehicle Identification [Fraser 2006; Koutsia *et al.* 2008; Douret & Benosman 2004; Setchell and Dagless 2001]	▪ Few high-resolution cameras characterize traffic loading ▪ Easy to measure vehicle location and speed	▪ Sophisticated image recognition methods required ▪ Can not account for vehicle dynamics ▪ Expensive and unproven technology
Passive Interaction (*e.g.* RFID based access control)	▪ Convenient in situations where a small amount of data is to be transmitted in one direction (e.g. vehicle to reader) ▪ Relatively cheap implementation costs for large scale deployment	▪ Narrow bandwidth and limited range of communication ▪ Inability to communicate data bi-directionally and at high speeds
Bi-Directional VI Interaction [*this proposal*]	▪ VI integration is based on well-validated vehicle models ▪ Secure and speed-adaptive information management support for sensor networks	▪ Need to facilitate VI data exchange at normal driving speeds is a source of risk ▪ High vehicular traffic on bridge may affect performance

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As noted earlier, the proposed sensor network scheme requires two-way communication between the sensors and the data servers. For example, software running on the sensors will need to be updated for patches, etc. If a sensor fails, other sensors may need to be instructed to exclude it. The research team plans to design a management portal at the central server to specify and distribute such updates. These updates will either be sent directly to the sensors (if they have network connectivity) or sent indirectly via the data vehicle. While this problem has similarities to the patch management problem for software (*e.g.* Microsoft Windows update), there are significant differences; bandwidth is at a significant premium and updates may need to be applied to either all cooperating sensors in a network or to none. Mechanisms will also be needed so that central servers know whether updates were applied successfully. Finally, updates need to be tamper-resistant without expensive security protocols.

Success Metrics and Decision-Points: The research in this thrust will primarily be conducted at the University of Michigan (UM) College of Engineering (CoE) and the UM Transportation Research Institute (UMTRI) by investigators Drs. Karamihas, Gordon, Robinson, and Prakash. As shown in Fig. X, the decision point strategy for each task focuses on achieving the intended objective, while managing the amount of risk inherent in each contemplated approach. For each step in a task that is considered high or moderate risk, appropriate metrics for success and decision points have been identified. In addition, each high and medium risk approach is backed up with a relatively lower risk alternative that will maintain the integrity of the overall sensing, monitoring, and management framework.

Uniqueness of the Approach: Typically, managers of highway infrastructure elements measure the loads

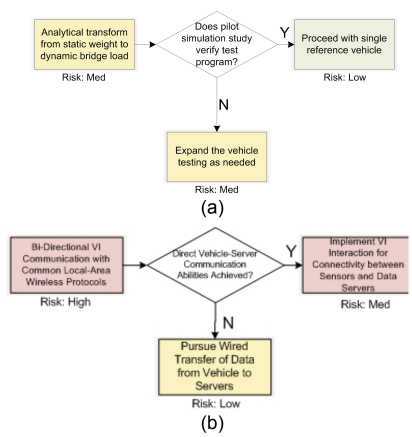

Figure X. Decision point strategies fc
Thrust 3: (a) fleet characterizatior
(b) vehicle-infrastructure communications

imposed by heavy trucks using a single "weigh-in-motion" scale installed in the road. This provides a biased characterization of the traffic fleet because of the dynamic load variations that occur as the vehicle vibrates in response to road and bridge surface roughness (Cebon, 1991; Karamihas, 2004b). Accurate characterization of the loads imposed on a bridge structure requires a robust, accurately validated system of estimating the dynamic component of bridge loading by trucks. In this proposal, a set of reference trucks with wireless sensors are used that log their location as well as the dynamic interaction with the structure. This approach offers complete input-output measurement data for drastic improvement in the accuracy and resolution of damage detection algorithms. Quantification of traffic loading on our roads and bridges has been an area of active research in recent years. To track traffic loads, high resolution cameras that record the location and speed of vehicles have been proposed (Fraser 2006; Koutsia et al. 2008; Douret and Benosman 2004; Setchell and Dagless 2001). However, these approaches offer no information on the dynamics of the vehicle nor its interaction with the underlying road or bridge. Hence, the usefulness of the vehicle data provided (location and speed) is of limited value to damage detection in infrastructure. The second unique advancement proposed in this thrust is the designing mechanisms for adaptive and secure communication of information between installed sensor networks on bridges and mobile data collection vehicles. The unique advances proposed in this thrust are highlighted in Table T3-1.

Potential to Address Needs of the Societal Challenge: A new generation of vehicle-infrastructure and human-infrastructure communication capabilities to support the proposed sensing framework is the primary outcome of the proposed tasks. Successful outcomes in these tasks will put into place unprecedented capabilities to access and analyze the rich information produced by installed sensor networks on bridges, and make informed decisions pertaining to a bridge's safety, integrity, and serviceability in real-time, both in the field and at off-site locations.

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Comment: I think most of this para dwells too much on one aspect: sensors in trucks. It should have a broader focus. You are not going to get all trucks to carry these sensors. I tried to revise it so that it is clear that we are not looking to instrument all trucks on the highways. Please take a look.