The Next Generation Transportation Infrastructure Performance Inspection: A CPS approach

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I. INTRODUCTION

With more than four million miles of roads demanding a broad range of inspection, the present U.S. transportation infrastructure is facing a monumental challenge in the scheduling (e.g. in prioritization of expenditures within budgetary constraints), as well as in implementation of maintenance and repairs. Current inspection methodologies often encounter issues such as intrusive data gathering (e.g. stopping traffic), manual efforts and subsequently infrequent data collection and limited coverage. A non-intrusive, automated, efficient, cost-effective and adaptive solution for rapid data collection and comprehensive roadway assessment is crucial for understanding the dynamics of tomorrow's civil infrastructure systems.

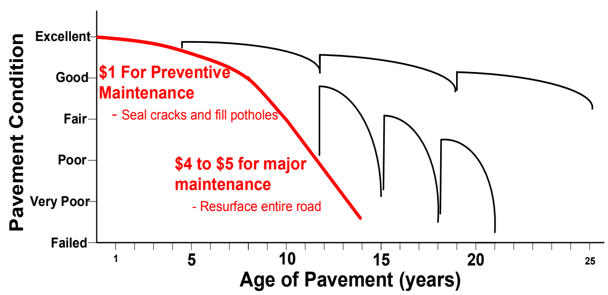

Figure 1 Preventive Maintenance Opportunities

Figure 1 conceptually illustrates dynamics of roads (life cycle modeling) and benefits of early deterioration identification and responsive repairs. If certain distresses are repaired before they reach critical levels, at least 5 times less monetary cost is needed in comparison to non-treatment. More severely, the damage impact exponentially amplifies for the large-scale civil infrastructure. Identifying "trouble spots" as soon as they appear will result in saving huge amounts of money, time, and effort, and extend its overall lifespan. Therefore, frequent infrastructure performance monitoring is essential. With current technology, it is impossible to obtain the life cycle with time-varying behavior of the civil infrastructure due to the challenges in continuous monitoring, and missing automatic performance analysis of diverse big data.

II. A CPS APPROACH

Cyber-Physical Systems (CPS) integrate digital computations with physical processes to observe, react, and actuate the physical entities often involving heterogeneous components, hybrid systems and design automation methodologies. In particular, applying CPS approaches to infrastructure monitoring is promising to address the societal need outlined above through interdisciplinary teams (from computer scientists to civil engineers) to invent solutions in which **CPS meets big data**.

Broadly, infrastructure inspection methodologies can be constructed as a grand control loop that includes construction, usage and deterioration, maintenance. Due to the long latencies this control loop has been overlooked despite its criticality. Figure 2 shows a conceptual solution, which requires a diversity of sensing applications that are embodied in roaming acquisition systems (mobile). Huge amounts of data is collected by these mobile sensory systems feeding into the big data challenge of multilayer multimodal fusion and performance analysis. The resulting vital asset performance metrics are input to multitier decision-support systems, which in turn produce actionable information. Depending on the time constants, the actionable information can control the actuators in the system: mobile sensors and maintenance operations. At the innermost circle, the control loop will guide mobile sensing to improve collection efficiency. This aims to increase the coverage given the same number of mobile sensors; increase resolution based on observation requirements, as well as decreased the storage and processing needs with on-demand sensing.

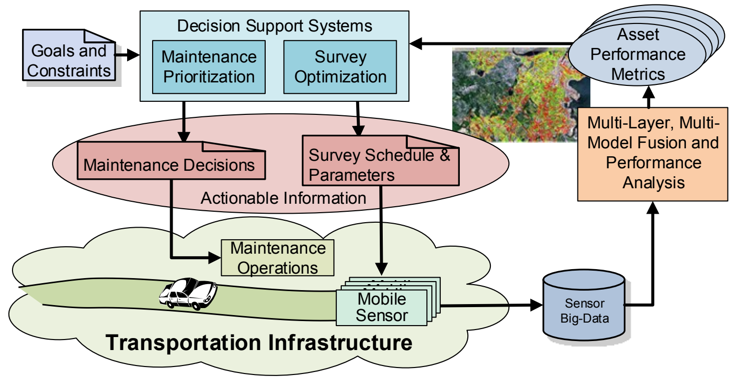

Figure 2 The Grand CPS Control Loop

The asset performance metrics can become part of the survey optimization, such as to avoid overutilization of weak infrastructure by applying wear leveling for infrastructure. It opens up new research for capacity planning that is aware of maintenance cost. In the outermost loop, the goal is to guide maintenance and construction decisions. With fine-grained and continuous infrastructure monitoring, and more detailed modeling of infrastructure deterioration becomes possible that guides understanding of impact factors and time constants leading to deterioration. These in turn, drive a cost-benefit-analysis for early, affordable maintenance instead of late, costly repair. Overall, this CPS control loop initiates a step toward establishing a personalized healthcare for civil infrastructure.

III. RESEARCH CHALLENGES AND OPPORTUNITIES

Embedding a heterogeneous sensor and computing on roaming agents poses secure and reliable communication challenges. Sensing tasks need to be distributed and solved in collaboration with versatile components (both sensors and computing platforms) requiring tight coordination. Communication and coordination challenges are shared with the ones in autonomously navigating vehicles. Especially tight timing synchronization is required to enable sensor fusion in a distributed fast-moving roaming sensor system. Real-time constraints in embedded processing become important considering processing close to the sensor and reducing the overall stored and transmitted data.

In addition, the success of the grand CPS approach hinges also on big data challenges. Here, the intrinsic challenges include the management of large data streams, having efficient data storage and compression, allowing identification and classification, managing data fusion from heterogeneous sensors in versatile collection systems, as well as their geospatial visualization. Next level challenges include the anomaly analysis to extract the asset performance metrics. Specifically intersecting with CPS, the definition of these metrics can benefit from the knowledge of CPS researchers to properly capture time variance of system. This offers a unified solution and ideal research platform for rapid, intelligent and comprehensive evaluation of tomorrow’s transportation infrastructure performance using heterogeneous and hybrid systems.