Transportation Infrastructure Performance Monitoring and Life-Cycle Management

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Societal Need

The past years have brought an increase in research for smart civil infrastructure. This includes Smart Home (or building automation system (BAS)) and Smart Grid for optimizing utility networks. However, transportation infrastructure has seen less of attention despite the tremendous challenges ahead. According to the 2013 ASCE report card [1] America's infrastructure scores only a D+. There are more than four million miles of roads (grade D) in the U.S. requiring a broad range of maintenance activities. The nation faces a monumental problem of infrastructure management in the scheduling (e.g. in prioritization of expenditures within budgetary constraints), as well as in implementation of maintenance and repairs. Maintenance, repairs and new constructions are crucial to ensure roadway safety, prevent catastrophic failures, and promote economic growth.

To address these challenges new research is needed that starts the age of personalized health care for transportation infrastructure and smartly caters to the **slower control loop** cycles (of construction, deterioration and maintenance). **Smart transportation infrastructure** (new, retrofitted, or dynamically inspected) is needed that continuously monitors it's status without human intervention, that recognizes and alerts potential problems before they can lead to failures damaging lives and/or property [2].

To understand the time constants, Figure 1 conceptually illustrates deterioration of roads over time and the opportunities of early repairs. If certain distresses are repaired before they reach critical levels, at least 5 times less money is spent in comparison to not doing anything. 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 lifetime. 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**.

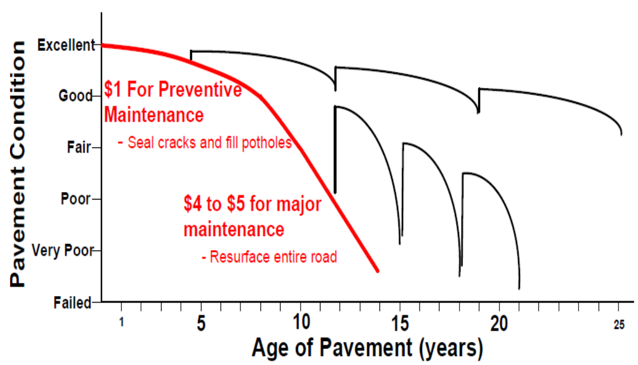

Figure 1 Preventive Maintenance Opportunities

The benefits of **smart transportation infrastructure** are tremendous and far reaching. Cost savings through well scheduled and targeted maintenance are significant (early maintenance is 5x cheaper than late repair). Significant interest by government and regional authorities exist, which ask for prioritizing based on up-to-date network-wide pavement condition information [3] (Map21). This will pave the path to improved average road conditions in the medium to long term. Data describing the deterioration process would allow for material durability and repair methodology comparisons. Such data can also be analyzed for the impact of traffic and environmental factors on the transportation infrastructure providing new insights to improve the systems sustainability.

Transportation Infrastructure Lifecycle Management

Addressing the societal need outlined above needs interdisciplinary teams to invent solutions in which **CPS meets big data**. Overall, transportation infrastructure has to be seen as a huge control loop that includes construction, usage and deterioration, as well as maintenance. Due to the long latencies this control loop has been overlooked despite its criticality, and has led to the current disastrous state [1].

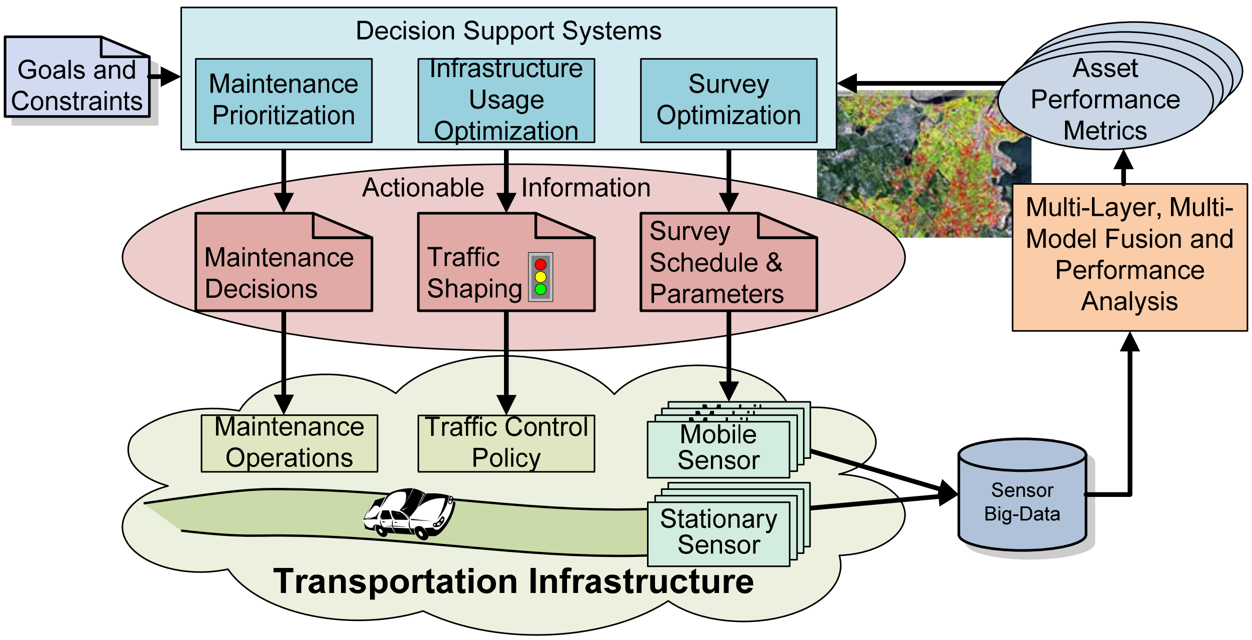

Figure 2 Transportation Infrastructure Control-loop

Figure 2 shows a conceptual solution, which requires a diversity of sensing applications that combine *roadside sensors* (stationary) and *roaming acquisition systems* (mobile). Huge amounts of data is collected by the 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*, *traffic control*, and *maintenance operations*. Understanding this control loop, and formalizing of the asset performance metrics in the same way as we do performance analysis for e.g. computer architectures will dramatically help reducing the cost of transportation infrastructure while improving the quality.

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.

The asset performance metrics can become part of the infrastructure utilization optimization. It can 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. Potential *traffic shaping* outcomes include policies for routing heavyweight equipment via alternate lanes or routes, or incentivize alternate usage through tolls.

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 will establish a personalized healthcare for civil infrastructure.

CPS Challenges and Research Opportunities

Many multidisciplinary challenges including essential CPS challenges need to be addressed on the road to realizing the transportation infrastructure lifecycle management. Embedding a sensor network into the roadway infrastructure, augmented by roaming sensor systems poses secure and reliable communication challenges. At the same time, sensing tasks need to be distributed and solved in collaboration with heterogeneous sensors 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.

An additional level of challenges is introduced when considering the lifecycle as a control loop. It uniquely presents itself as a multidimensional optimization problem that on one hand has to optimize sensing and information input given the limited set of sensing resources, and on the other hand has to trade-off traffic shaping with maintenance decisions. In addition to the global optimization across these three categories, local optimization potential exists within each category.

In addition to the CPS challenges, the success of the lifecycle management hinges also on big data challenges. Here, the basic 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 heterogeneous 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. As sensors advance, we further intertwining of big-data and CPS is needed to enable distributed anomaly analysis that is spread across a set of sensors.

Overall, creating a transportation infrastructure lifecycle management sparks a new set of research that intersects CPS, civil engineering and big data challenges. Interdisciplinary ideas and solutions will improve infrastructure health monitoring, will identify mechanisms to guide utilization (traffic shaping) and guide maintenance – all in order to satisfy the public demand for high-quality infrastructure despite funding shortfalls.

References

[1] American Society of Civil Engineers (ASCE), "Report Card for Americas' Infrastructure: American Society of Civil Engineers," 2013. [Online]. http://www.infrastructurereportcard.org

[2] John Stankovic Janos Sztipanovits, "Cyber-Physical Systems: A National Priority for Federal Investment in Infrastructure and Competitiveness," The Computing Research Associaation, 2008. [Online]. http://www.cra.org/ccc/resources/ccc-led-white-papers

[3] Federal Highway Administration (FHWA). Map21. [Online]. http://www.fhwa.dot.gov/map21/