ADVANCED SENSING TECHNOLOGIES FOR THE INFRASTRUCTURE: ROADS, HIGHWAYS, BRIDGES AND WATER

Technology Innovation Program
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The Technology Innovation Program (TIP) [1] at the National Institute of Standards and Technology (NIST) was established for the purpose of assisting U.S. businesses and institutions of higher education or other organizations, such as national laboratories and nonprofit research institutions, to support, promote, and accelerate innovation in the United States through high-risk, high-reward research in areas of Critical National Need (CNN). Areas of Critical National Need are those areas that justify government attention because the magnitude of the problem is large and societal challenges that need to be overcome are not being sufficiently addressed. TIP seeks to fund transformative research targeted to address key societal challenges. Funding selections will be merit-based. This white paper discusses the process and motivation behind selection of the Tip focus for this year's competition.

AN AREA OF CRITICAL NATIONAL NEED

The area selected as the Critical National Need is "Advanced Sensing Technologies for the Infrastructure: Roads, Highways, Bridges and Water Systems." This CNN was selected from a larger field of areas where transformative research could be expected to have large societal impact. Input regarding potential areas of CNN was obtained from government agencies and advisory bodies (such as the National Research Council, the National Academy of Sciences, the National Academy of Engineering and the Institute of Medicine), the Science and Technology Policy Institute (STPI), industry organizations, leading researchers from academic institutions, and others.

The desired output of work funded through this competition is an implementable, usable, and accurate sensing system for the effective measurement of explicit infrastructure performance characteristics such as fatigue, corrosion, stress, usage, damage, etc. Current sensing technologies, while well developed in controlled laboratory environments, have not yielded tools for producing real-time, in-situ data that are comprehensible for infrastructure decision-makers. Given this fact and the continuing and accelerating deteriorations of a large fraction of our nation's infrastructure, the creation of operationally-effective, accurate means for measuring and monitoring infrastructure integrity requires a leap in technology that can only be acquired through transformative research, rather than continued incremental advances of the current state of the art.

The need for advanced sensing technologies is *national* because every municipality and state in the nation faces infrastructure management challenges. The need is *critical* because portions of infrastructure are reaching the end of their life-spans and there are few cost-effective means to monitor infrastructure integrity and to prioritize the renovation and replacement of infrastructure elements.

MAGNITUDE OF THE PROBLEM

Civil infrastructure — the framework of interdependent networks and systems required to provide social services and support the public sector social activities — consists of transportation systems (e.g., highways, roads, rail systems, ports), utilities (e.g., water, power, communications), and public facilities (e.g., schools, recreation, prisons, postal facilities). As the economy grows, we become even more dependent upon larger and more complex networks of civil infrastructure that require ever increasing expenditures to maintain their safety and security. Each year Federal, state, and local governments spend billions of dollars to upgrade and repair transportation systems and water resources.

Public (Federal and state) expenditures on infrastructure have grown by 1.7% per year from 1956 to 2004 and in recent years, have been growing even more rapidly, rising by 2.1% per year, after adjustment for inflation.[2] This rate of growth translates into a constant fraction of GDP, about 1% to 1.2%, being spent on infrastructure. The Congressional Budget Office reported that Federal and state governments spent $67 billion on highway infrastructure and $28 billion on drinking water and wastewater infrastructure in 2004.[2]

Despite these large expenditures the nation continues to suffer staggering consequences from infrastructure decay. A poignant example is the August 2007 collapse of the I-35W bridge in Minneapolis, Minnesota that cost 13 lives and is estimated to ultimately cause economic losses to the city's economy of close to $200 million. Our water systems are also failing; the Environmental Protection Agency (EPA) reported that there are 240,000 water main breaks per year in the nation. In 2003 alone, Baltimore, Maryland, as an example of an older urban area, suffered almost 1,200 water main breaks.[3] In addition, it is reported that the Washington Suburban Sanitary Commission, which manages a pipe system about twice the length of the U.S.-Mexico border, in suburban Washington, D.C., recorded 2,129 pipe breaks in 2007.[4] Leakages and breaks in water distribution systems are estimated to waste up to 6 billion gallons of drinking water each day.[5]

Damaged infrastructure also directly impacts the daily lives of a large number of Americans. The American Society of Civil Engineers (ASCE) estimates that Americans spend $54 billion each year in vehicle repairs caused by poor road conditions.[6] Drops in water system pressure, resulting from water main breaks, lead to microbial contamination of drinking water. Each day, one can find news reports that a half-dozen or more communities are affected by "boil water" alerts due to water main breaks or other failures within their water-delivery system.

The amount of infrastructure to inspect is enormous. The nation has 1,000,000 miles of water mains, 600,000 bridges, and 4,000,000 miles of public roadway. Public safety professionals and engineers responsible for this infrastructure strive to maintain these systems. They seek to prioritize repair schedules and to avoid premature replacement of infrastructure. Better technologies have the potential to provide invaluable input to these recommendations by making the monitoring of processes and conditions that affect structures more quantitative, more thorough, and more frequent. Technologies that achieve the goal of continuous monitoring of structural integrity with costs low enough to permit wide-scale, permanent deployment, require transformative research.

SOCIETAL CHALLENGES

Societal challenges are defined as problems or issues confronted by society that when not addressed could negatively affect the overall function and quality of life of the nation, and as such justify government attention. In order to address the Critical National Need of addressing the deterioration of our nation's civil infrastructure, there are several Societal Challenges that need to be overcome, including inspection issues, monitoring issues, the development of novel materials, "smart" structures, green and sustainable construction, among others. TIP has decided to focus on the challenges of inspection and monitoring civil infrastructure. This decision was based on an analysis of the size and complexity of the challenges, and the expected benefits if the challenges are surmounted.

Inspection issues

A lack of predictability of infrastructure failures is understandable. All engineered structures, including the entire nation's civil infrastructure, have usable life-spans. Structures approach the end of their life spans through a complex process that involves long-term environmental degradation, wear, and episodic events like impact or fire. All engineered structures must be maintained, including periodic repair and renovation, in order to reach their usable life spans. Because the factors that affect the integrity of engineered structures cannot be perfectly predicted, the process of the degradation of the integrity of the structure must be sensed in some form. Today, the most common form of assessing the integrity of a structure is visual inspection. The visual inspection provides a qualitative assessment of damage caused by the various degradation processes that affect the particular structure. Visual inspection is sometimes supplemented with other non-quantitative methods like judging the sounds produced by dragging chains or hammering to detect delamination of structural surfaces.

The current state-of-the-practice for routine establishment of the integrity of bridges, roads, and water mains is typically a visual inspection, augmented with some physical aids like the sounds made by chains dragged across a road surface. Technology applied to infrastructure inspection is limited, existing as aids to the human-based inspection. For example, closed-circuit television is used to provide for human visual inspection of the interiors of wastewater and water mains. Visual inspections, used since the first builders, especially when coupled with chain-dragging, hammer soundings, and the removal of core samples, are time-consuming and require skilled operators, making them expensive. In addition to the expense, the finite supply of skilled inspectors/engineers necessarily limits the frequency of inspection. As a result it is typical for bridges to be inspected perhaps every other year and for deficient bridges to be inspected once a year. Beyond the infrequency of inspection, these types of personnel-intensive inspections are subjective. The insufficiency of current infrastructure condition and quality assessment practices has been studied and reported. In the most recent study of principal bridge inspection methods (the NBIS[1]), FHWA concluded that the condition ratings that the NBIS generates are subjective, highly variable, and not sufficiently reliable for optimal bridge management.[7] The FHWA also reported that in-depth inspection, assigned for deficient bridges, might "not yield any findings beyond those that could be noted during a routine inspection."[7]

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[1] The National Bridge Inspection Standards is used by bridge inspectors in state departments of transportation. Many states expand upon the NBIS.

Visual inspection of the interiors of installed water mains and wastewater pipe can be accomplished by dragging pipeline inspection gauges ("pigs") with cameras, eddy-current monitors, or an aid that provides an image for the inspector. Water mains provide an especially great challenge for inspection and monitoring technologies. There is a large variety of types of piping that have been used for water mains and these different pipe constructions have different degradation processes. Inspection and monitoring methods that work with one type of water main pipe (e.g. unlined iron), may not work with another (e.g., asbestos-cement). Water main inspections are often limited for different reasons. For example, water mains must be drained for some of the inspection technologies, and "pigs" dragged through undrained mains can disturb deposits within the mains which must then be flushed from them to prevent consumer complaints. In 2007, the EPA's Office of Research and Development reported with regard to condition assessment of water delivery infrastructure that "the technical and/or economic feasibility of measuring the right parameters, and/or the ability to interpret the data, are not adequate for high-risk mains."[8] With regard to wastewater pipe inspection methods, the EPA concluded "As the focus of condition assessment continues to broaden to include targets beyond the reduction of excessive hydraulic loading due to I&I (infiltration and inflow), sewer system inspection technologies and investigation approaches must evolve."[8]

Technology that could provide more quantitative data on integrity and condition of infrastructural elements is currently very expensive and is able to provide only a partial picture that is specific to the type of technology used. More advanced inspection systems involve ground-penetrating radars, sound-wave propagation methods, electrical impedance measurement, and other methods that can detect the presence of some subsurface defects. These methods are costly, requiring expensive equipment, significant amounts of skilled operator labor for setup, measurement and interpretation, and, in some cases, removal of layers of bridge decking or road surface. For example, ground-penetrating radar provides very detailed quantitative data on the integrity of examined subsurface elements like the condition of reinforcing bar embedded in concrete. However, the cost of these surveys is so prohibitive that they cannot be used routinely. For example, a quantitative ground-penetrating radar study on the I-35W bridge in Minneapolis was estimated in 2006 to cost $40,000.

Monitoring Issues

Monitoring the condition and usage of infrastructure is also fundamental to its maintenance. Bridge and road surfaces are designed to accommodate a particular level of loading. Excessive loading puts a structure at risk in at least two ways. The first is catastrophic failure of the structure when its maximum load and safety factor have been exceeded. A second risk comes from fatigue.[2] Fatigue arises from load-cycling over very long periods of time. Fatigue develops microscopically, weakening structural elements over time, resulting eventually in catastrophic failure of an element. There are insufficient cost-effective means for monitoring the load history of infrastructural elements or of monitoring continuously and cost-effectively the fatigue state of the individual elements. In prepared testimony (2007) before the United States House of Representatives, Committee on Transportation and Infrastructure, Mr. King Gee, Associate Administrator for Infrastructure (FHWA), and Mr. Gary Henderson, Director, Office

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[2] Fatigue is a material degradation that occurs when the loading-unloading cycle occurs many times with loads beyond a certain amount. Fatigue begins as microscopic cracks that weaken the material's strength properties. The cracks often grow until the material fails.

of Infrastructure Research and Development (FHWA) stated, “Monitoring systems that are available today require routine maintenance and repair and continuous assessment to ensure that they are working correctly. In addition, they do not eliminate the need for regular visual inspections.”[9]

Monitoring issues also affect the water delivery infrastructure. Municipal utilities are not able to monitor the extent of leakages in their distribution systems. They know how much water they treat and they know how much water passes through customer water meters. The difference between those two quantities comprises leakages and unmetered uses, the latter of which includes, among others, firefighting and local government usages including irrigation of public land. Leakage rates vary across municipalities depending on the age and quality of the infrastructure. Nationwide, drinking water losses are estimated at 6 billion gallons per day or approximately 15% of the water sanitized and treated for use. Water lost due to system leakages is not just lost water, it is also the loss of the treatment chemicals and the energy required to treat and pump six billion gallons of water through water delivery system. Water leakages also create other infrastructural damage. They undermine structural and roadbed foundations, and they disrupt power grids and telecommunications that are in underground proximity to water mains.

Interaction of Critical National Need and Societal Challenges

The societal challenges — needed improvements in cost-effective inspection and monitoring of critical infrastructure systems, particularly those of bridges, roads, water delivery systems and wastewater collection systems — can potentially be resolved with better and more cost effective sensing technologies. Real time data on the structural integrity of bridge components is not only useful for determination of repair and renovation scheduling, but also for emergency evacuation in the event of impending catastrophic failure. There are currently no cost-effective, field-deployable sensing systems that are capable of providing continuous data with which to prioritize repair and renovation schedules and that provide sufficient warning of impending catastrophic failure. There has been progress in the development of embedded sensors for new construction; however, these systems are not deployable to existing components of the infrastructure. It is clear that both the EPA and the FHWA concur that current infrastructure inspection and monitoring systems are inadequate and that better infrastructure sensing systems, based on current state of the art technologies, are either not available or not economically feasible.

MAPPING TO NATIONAL OBJECTIVES

The focus upon Advanced Sensing Technologies for the Infrastructure: Roads, Highways, Bridges and Water Systems as a Critical National Need maps well upon national objectives, Administration guidance, Congressional testimony, and NIST's core competencies.

The National Academy of Engineering recently identified the restoration and improvement of urban infrastructure as one of their fourteen grand challenges in engineering.[10] These challenges were selected by a committee of distinguished leaders in science and engineering.

The Administration has consistently prioritized the security of the nation’s critical infrastructure; “All Federal departments and agencies shall work with the sectors relevant to their responsibilities to reduce the consequences of catastrophic failures not caused by terrorism."[11] More recently, Dr. John H. Marburger, Science Adviser to the President and Director of the Office of Science and Technology Policy, identified again the task of securing critical infrastructure as a national priority. [11]

Congressional committees are focusing more attention on the needs to secure, maintain, and improve critical infrastructure. Mark Funkhouser, Mayor of Kansas City, Missouri, appeared with mayors of other municipalities and testified before Congress on the problems their communities face with infrastructure maintenance and decay. "We're having a quiet collapse of prosperity," he testified. (June 12, 2008).

Sensing technologies also directly correspond to NIST's areas of technical competence of measurement science. NIST conducts research that affects the development of building codes and standards and that leads to new tools for evaluating seismic strength of new and existing buildings and communities. In addition, the U.S. Measurement System (USMS) at NIST [12] identified the need for developing new and innovative sensor technologies for in-line, real-time, and continuous monitoring in buildings and construction sites.

MEETING TIMELY NEEDS NOT MET BY OTHERS

Overview

TIP is directed to fund research areas that are not currently being addressed by others. Given the scale and importance of the problem of our nation's infrastructure, it is not surprising that there are other agencies that are working on challenges associated with infrastructure. Four Federal agencies were identified that operate twelve programs that might have shared commonalities with TIP's identified Critical National Need. Examination revealed that none of these programs has the scope, size, and potential impact that could be expected from a funding commitment from TIP to support innovative early-stage research in this area of Critical National Need.

TIP's Role

In general, local and state governments have significant knowledge gaps regarding quantitative assessment of infrastructure integrity, yet they do not have the funds and ability to develop more cost-effective advanced sensing tools that would eliminate the knowledge gaps. One Federal research program targets advanced sensing for infrastructure – the National Science Foundation's "Sensor Innovation and Systems Program." Total funding for this program is $5M per annum and innovation in sensing is only one of several categories of research supported under this program. Other programs were identified in which new sensing technologies might be funded, but none of the programs are targeted specifically at new or early stage sensing technologies. The civil infrastructure grants that are provided by the National Science Foundation (NSF) are primarily targeted for academic fundamental research and are smaller than the program envisioned. The Exploratory Advanced Research Program of the Federal Highway Administration (FHWA) is currently targeted at "Intelligent Transportation" projects. The Remote Sensing and Spatial Information Program of the Research and Innovation Technology Administration (RITA) is a university-focused program that seeks applications of existing technologies in a transportation context. Transformative impacts on infrastructure sensing from these and other programs are therefore expected to be limited.

CONCLUSION

New sensing technologies that produce real-time (time-effective) monitoring data, and that can also help or aid in the interpretation of the acquired data, therefore will enhance the safety of the public by issuing timely and accurate alert data on structural integrity. New sensing technologies will also allow more informed management of infrastructural investments by avoiding premature replacement of infrastructure and identifying those structures in need of immediate action.

TIP has selected as an area of Critical National Need, Advanced Sensing Technologies for The Infrastructure: Roads, Highways, Bridges and Water Systems. These new sensing technologies will provide increased security and safety of elements of critical infrastructure. The vision for this funding opportunity is:

- To develop new tools and techniques that will enable infrastructure managers to monitor the structural health of critical national infrastructure elements that are essential for the health of the nation, its economy, and its citizens.
- To develop the means to sense the safety, security, and integrity of engineered structures in the nation's highway, water, and wastewater infrastructure and that provide that information to managers of these systems in a timely and effective manner.

Those seeking further information should consult the Federal Funding Opportunity notice.

References

[1] "Technology Innovation Program," America COMPETES Act, P.L. 110-69, Sec. 3012, signed on August 9, 2007.

[2] "Issues and Options in Infrastructure Investment," Congressional Budget Office, May 2008.

[3] http://www.epa.gov/awi/distributionsys.html

[4] *Washington Post*: Under Pressure, p. A16, June 17, 2008.

[5] "Developments in Water Loss Control Policy and Regulation in the United States" G. Kunkel, Leakage 2005 – Conference Proceedings. (Data on national drinking water loss depends on the 1998 USGS Circular 1200 that identified "public use and loss." The USGS does not have the capability to separate the real loss from the apparent loss of unmetered public uses like firefighting. The statistic, however approximate, is supported by data from the Survey of State Agency Water Loss Reporting Practices, Beecher Policy Research, 2002).

[6] "Report Card for America's Infrastructure," American Society of Civil Engineers, 2005.

[7] "Reliability of Visual Bridge Inspection," Turner-Fairbank Highway Research Center, Federal Highway Administration, March 2001.
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[8] "Innovation and Research for Water Infrastructure for the 21st Century Research Plan," U.S. Environmental Protection Agency, April 2007.

[9] http://testimony.ost.dot.gov/test/pasttest/07test/gee1.htm

[10] "Introduction to the Grand Challenges for Engineering," National Academy of Engineering, February 2008.

[11] http://www.whitehouse.gov/news/releases/2003/12/20031217-5.html
http://www.whitehouse.gov/omb/memoranda/fy2007/m07-22.pdf

[12] http://usms.nist.gov/usms07/index.html