Using Big Data to Make Our Infrastructure (*i.e.* Bridges) Safe
A Peter Kiewit Institute Integration Project

1. The Threat

There is an urgent need to develop and deploy a highly reliable, robust, cost effective system for 'real-time' monitoring of our nation's infrastructure to protect human lives, save our capital assets, and ultimately ensure the stability and quality of our nation's economy and way of life.

The nation's infrastructure, including roads, bridges and water treatment and distribution systems, continues to deteriorate at an alarming rate. In Nebraska alone, it is estimated[§] that 25% of the State's bridges are structurally deficient or functionally obsolete and 59% of its roads are in poor or mediocre condition. It is further estimated that an investment of ***$4 billion*** is needed to address Nebraska's aging waste and drinking water infrastructure.

For many key assets, such as bridges, visual inspections, nominally by trained personnel, are still the primary method of health monitoring. In spite of advances in sensor and computing technologies, this process has not changed since the initiation of a national bridge inspection standard in 1968. In many instances, similar approaches are used to determine the condition of other infrastructure assets, such as pavements, dams and large water and sewer lines.

For the most part, this approach has been effective in identifying structures needing attention, particularly for transportation assets. However, using humans to assess infrastructure and to predict remaining functional life is a costly, dangerous and highly subjective enterprise that can be adversely affected by extraneous factors from weather to accessibility to inspector fatigue.

The cost of failure can be catastrophic. The 2007 collapse of the I-35W Mississippi River Bridge in Minneapolis is a dramatic example of what can happen when important "health" indicators are missed. In this case, it was an undetected crack in a steel connection plate that killed 13 and injured 145, cost hundreds of millions of dollars in damage, not to mention the disruption to the lives and economy of Minneapolis.

These types of issues are not limited to larger-span structures. Collapses of shorter span bridges, commonly defined as having spans less than 140 feet, happen more frequently but rarely receive the same level of media attention. As recently as July 2014, a culvert in New Jersey collapsed forcing a road closure. Fortunately no one was injured.

2. The Opportunity

Imagine blanketing every infrastructure asset (e.g. bridges) in the country with sensors that communicate with a Big Data computer to accurately assess the safety of each bridge in real time.

Over the past few decades, advances in high performance computing, in particular, have permitted greater modeling and prediction capabilities for complex engineering systems. Examples of past civil engineering health monitoring successes include bridge and pavement health monitoring systems, intelligent transportation systems, automated storm and sanitary sewer assessment systems, and smart buildings. In addition, advances in supporting technologies, from satellite

[§] *American Society of Civil Engineers (ASCE) 2013 Report Card for America's Infrastructure*; http://www.infrastructurereportcard.org/a/#p/home imaging to nano-devices to wireless communications, are creating opportunities for unparalleled transformations in sensor development and infrastructure monitoring.

At the same time, the emergence of Big Data as a powerful tool for understanding and controlling highly dynamic and non-linear systems is both critical and timely. We are in an age where the amount of data produced far outweighs our ability to effectively digest and comprehend its content and quality, a phenomenon the National Science Foundation calls the 'data deluge'. In response, there has been rapid development and growth of Big Data technologies and of 'smarter' sensors and sensor systems.

However, comprehensive Big Data initiatives focused on transportation infrastructure are largely nonexistent. The opportunity then is to develop 'smart infrastructure' systems that would effectively and efficiently collect, interrogate and act upon vast quantities of health data produced from ubiquitous sensors located within, on and beneath bridges, road- and railways, dams, sanitary and storm sewer lines and other entities comprising our civil infrastructure.

The Big Data system, and the sensors it employs, would need to be seamlessly integrated into new infrastructure assets but also easily deployable on existing assets. Economic viability of this enterprise would dictate that the cost of instrumenting and monitoring each structure in the system should be a small fraction, *e.g.* ‹ 5%, of that asset's replacement cost. Successful development of such a system, then, would require a highly multidisciplinary team involving extensive basic and applied research in partnership with key industries. Critical research and development thrusts will entail: sensor development, structural and environmental modeling, life prediction modeling, low cost communication and data transmission, and Big Data analytics.

Because of the level of public awareness coupled with the scale of the threat, the initial focus of this health monitoring enterprise will be on bridges, specifically small bridges than 140 feet long[†]. These are being selected for reasons of impact, scalability and multi-modal application. Currently, Nebraska maintains over 15,300 bridges, of which approximately 90% or 13,500 are shorter than 140 feet.

Selecting small bridges as the initial focus also has the added advantage of scalability. Modular design and construction techniques for small bridges typically involve a roadway deck supported by a repeating pattern of structural units (beams) running both parallel and perpendicular to traffic. These modular units are almost always employed in larger bridges, making the effort scalable to most of the larger bridges across the United States.

3. Technical Underpinnings of Big Data and Bridge Health Monitoring

Comprehensive, systemic solutions to health monitoring of bridge (or any infrastructure) network requires integration of three core areas: 1) ***DATA COLLECTION AND TRANSMISSION****, 2)* ***DATA ACQUISITION, MANAGEMENT AND ANALYTICS*** *and 3)* ***SMART AND SAFE ASSET MANAGEMENT****.*

A schematic diagram showing the inter-relationship between these elements is provided in Figure 1. The **DATA COLLECTION AND TRANSMISSION** research core focuses on developing robust sensing solutions that are inexpensive, smart and ubiquitous. Ultimately these sensors will replace humans as inspectors. In order for that to happen, they must be inexpensive to make, install and operate. And at the same time, they must be robust, accurate and reliable in harsh and

[†] It should be noted, however, that once fully developed, the proposed framework is readily adaptable to address virtually any other infrastructure network.

variable environments. More broadly, this core can be further categorized into ***contact*** and ***non-contact*** sensors:

Non–Contact Sensors, in a sense, are the ideal solution in that they do not interact directly with the structure. They can also monitor entire structures with a single sensor (*i.e.* a camera) reducing hardware costs. This class of sensors can further be subdivided into *optical* and *acoustic*:

- *Optical Sensors* typically use video-based imaging, though infra-red, fiber optic, or other technologies can be explored. The opportunity space here can be categorized by the imaging platform, *i.e.* space based or land based:
  - *Satellite Imaging* has not been rigorously examined in the context of bridge health monitoring though it has begun to be used in monitoring construction site preparation. If proven feasible, this opens possibilities for monitoring multiple bridges from existing satellite(s).
  - *Earth-Based Optical Sensors* have the advantage of imaging single bridges (or major parts thereof) with much higher resolution than satellites. Weather would be less of a limiting factor, but there would likely be much greater data acquisition and analytics demands.
- *Acoustic Sensors* are generally less costly than imaging techniques and are not constrained by line-of-sight. Data and power requirements are concomitantly lower as well. The research challenge lies in developing them to provide health information at specific points within a bridge.

In-situ Contact Sensors provide the bulk of the health monitoring instrumentation today. While the sensors themselves may be inexpensive, power requirements for operating them and transmitting data are not. Sensor placement and intelligent analysis of data are major challenges. Work in this area can also be divided into two groupings:

- *Current Sensors* are going to be the mainstay of monitoring instrumentation for some time to come. As noted, the challenges are to reduce power and data transmission costs, as well as to develop better computational structure models so that data from these sensors can provide a more comprehensive picture of the state of the bridge.
- *Next Generation Sensors* can be developed in tandem with advances in nano-structured materials. One could also think generically of methodologies in which the bridge itself becomes its own sensor. Work in this area would likely have longer range development and implementation timelines, but could be the source of the transformative breakthroughs necessary for long term viability.

The **DATA ACQUISITION, MANAGEMENT AND ANALYTICS** core would focus generally on the complex problems associated with acquiring, managing and meaningfully analyzing massive amounts of data. Recall that the vision is to be able to include *every* asset in a regional or national network for *real time* health monitoring. This will be, no pun intended, a massive undertaking. Specific areas for research and development include:

Mining Existing Archival Data Sets is undoubtedly one of the very first efforts that needs to be undertaken by this center. Though not necessarily the same types of data that will be available in the future, existing data provide both insights into existing threats, as well as understanding the types of analytics and modeling that can/will need to be done into the future.

Managing Incoming (New) Data Sets will also be a critical part of the overall health monitoring enterprise. Given that existing data is heavily built on human inspections and that new data will be from remote sensors, the types of information and subsequently the way in which that information is collected, organized and stored will also be very different.

Big Data Analytics is ultimately at the core of expanding health monitoring to a system level enterprise. A distinction is drawn between the physical science based computational modeling and analysis of bridges, and the broader and more powerful methodologies associated with being able to recognize important events in an infinite sea of data. The former is included as part of the third core area, **SMART AND SAFE ASSET MANAGEMENT**. Research and development work in this topical area addresses the problem of identifying data anomalies that are reliable early warning signs for future bridge failure.

User Interfaces are the vitally important means by which critical bridge health information is conveyed to the human decision makers. A simple concept would be a cell phone app that would provide the bridge health monitor with a red, yellow or green indicator for any bridge of interest. If a bridge were to be indicating problems (yellow) or imminent danger (red), the user would then require specific, accurate, real-time information as to what the problem was. Presenting such critical information in intuitive and meaningful ways is another essential element of this program.

The **SMART AND SAFE MANAGEMENT OF BRIDGE ASSETS** core represents the place where sensors with big data analytics are integrated into a comprehensive bridge health monitoring paradigm. While big data was called out as a separate core area, it plays a major role in the modeling, analysis and decision making of bridge management. The three sub-categories in this core are:

Bridge System Modeling encompasses the underlying physical sciences and engineering of the bridge system (*i.e.* the structure, supporting foundation, and interactions with the environment). Through a combination of state-of-the-art experiments and high performance computing, advances in rigorous, science-based computational models of the bridges in the network will be made. A by-product of this work will be parallel advances in bridge design and construction.

Life Prediction is an area of research that is critically important from aircraft safety to bridge health monitoring. The current state-of-the-art in life prediction is still heavily empirical with unacceptably high levels of uncertainty. These are offset by imposing safety factors with tremendous economic (and safety) impacts. Integration of the science based ***Bridge System Modeling*** work will significantly advance this field and bridge safety in particular.

Decision Making is the culmination of all of the research and development activities articulated throughout this section. Ultimately, all of this work comes down to real-time decisions being made for every bridge (or infrastructure asset) in a network. Because health monitoring has been so heavily dependent on human inspectors making assessments on individual bridges, this is a paradigm that will have to be virtually created from scratch.

4. The Research Center Concept: Organization and Cost

A comprehensive bridge health monitoring research center is proposed consisting of highly coupled and collaborative university-industry-government teams focusing on the three core focus areas and their interconnectivity.

A schematic drawing showing the three core focus areas and their component elements appears in Figure 2. For simplicity, it can be assumed that each sub-group within the three core areas, a total of twelve in all, will include five faculty experts (with an appropriate cohort of postdoctoral researchers, graduate students and undergraduate students) and industry/government collaborators. If fully funded, each of these groups would be funded at annual levels between $500K - $1M. The total center would then operate at approximately $10+M per year.

There is extensive expertise already resident in the Colleges of Information Science & Technology (UNO) and Engineering (UNL). Relevant areas of strength include, but are not limited to structures, imaging, acoustic sensors, nanomaterials and technologies, telecommunications, high performance computing, big data analytics and modeling, and infrastructure health monitoring. Because of the national/international stature of our faculty, there are collaborative networks to key research groups around the country with expertise not resident in the NU system. These partners will be brought into the center as it grows and federal funding is solicited. The concentration of design/build and transportation industries in Omaha, and eastern Nebraska in general, along with Nebraska Department of Roads' national presence in transportation research and development, combine to create a powerful base for this center.

The NU system is fully committed to this initiative. At this writing, the NU central administration just sent word that $800K in new faculty salaries specifically to support this nascent center. Over the next five years, this adds up to $4M in senior investigators who will contribute to this critically important problem. There is also ~$2M in cash that the leadership of the Peter Kiewit Institute will commit to this center.

The full center, including major block funding from state and federal sources, may take up to three to five years to develop. However, with strategic choices of start-up projects, it is possible to have immediate impact. Specific areas where work can be started include satellite sensing, acoustic sensing, mining existing data sets, managing new data sets, big data analytics, and life prediction. These are areas where expertise and potential for industry-university-government collaboration is already extant, and there are opportunities for near term, high return. At the same time, these areas represent essential building blocks in the development of the full health monitoring paradigm.

5. Getting Started

A unique window of opportunity exists to be the 'first to market' in addressing infrastructure design and safety in a broadly systemic, yet highly rigorous and detailed way. The core partnership between Nebraska based, albeit national and global reaching, companies and universities creates a foundation for a premier national center around integrating big data with infrastructure health monitoring. By providing a reliable, real-time methodology for monitoring vital elements of the nation's infrastructure, this center will be transformational in how that infrastructure is designed, built and operated in the future. The lives saved, and the economic impacts, are immeasurable.

Ultimately, safety cannot be a proprietary pursuit; the majority of the methodologies and outcomes from this center must be in the public domain. However, there will, of course, be projects and products that can be commercialized or of a highly sensitive nature. Analyzing existing data from a single company, for example, is not something that should be shared. As such, the activities of the center will necessarily be a hybrid of proprietary and public activities. Funding and the partnerships that build the funding base are all an integral part of the founding discussions necessary to bring this vision to fruition.

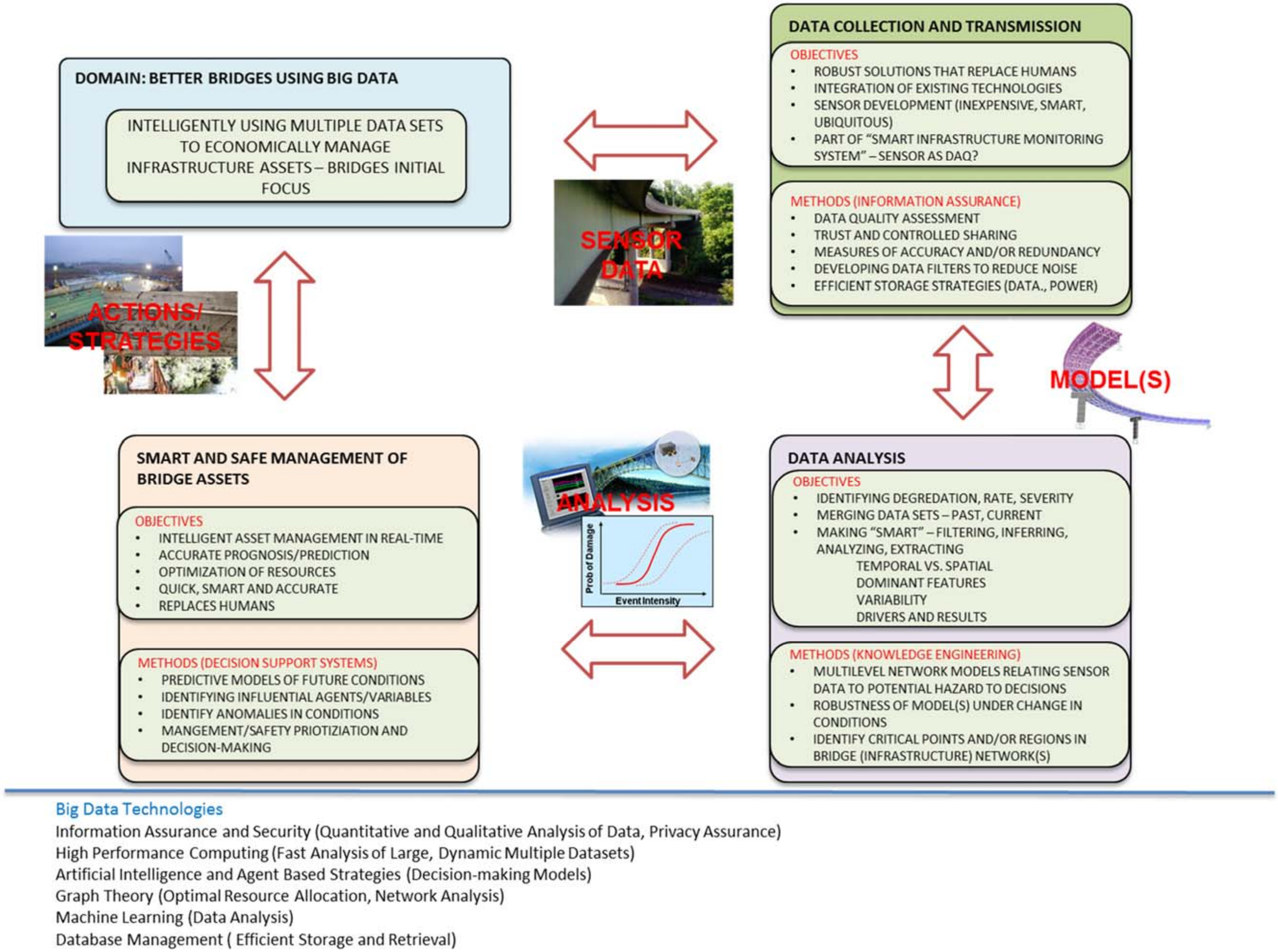

Figure 1. Research Concept

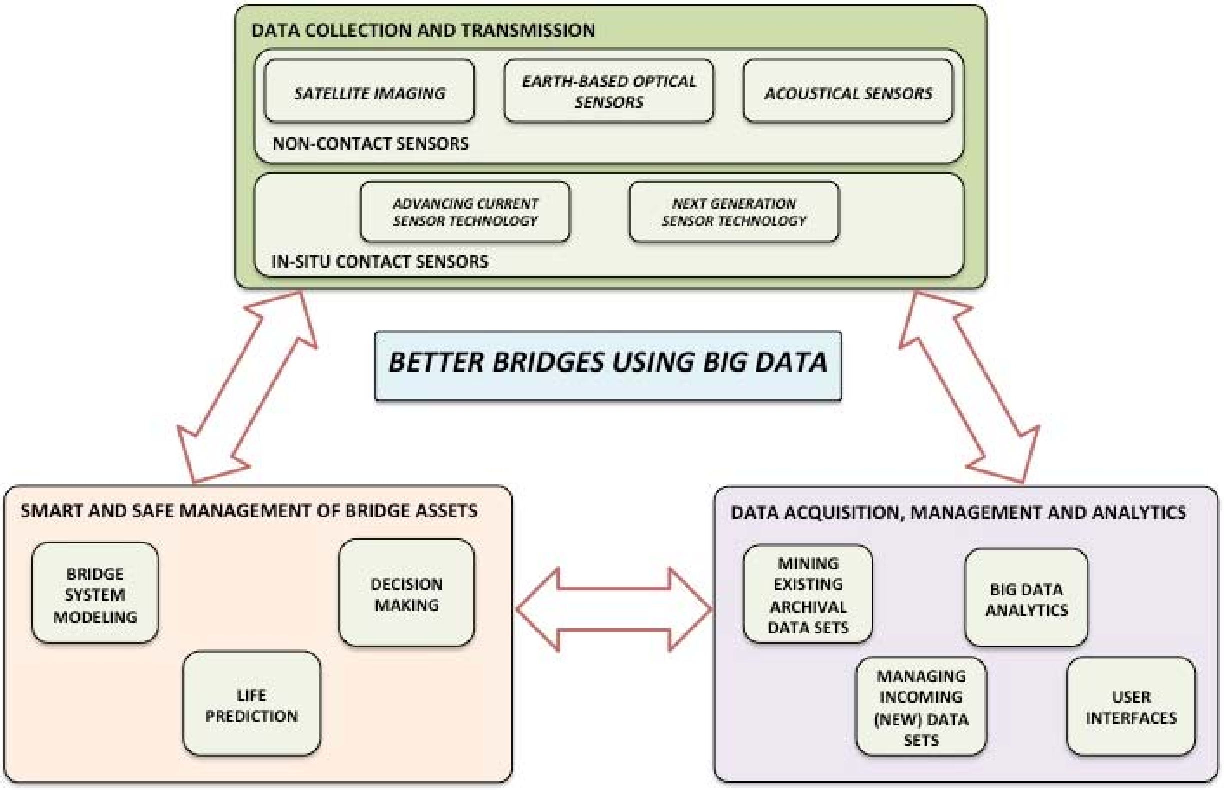

Figure 2. Organization