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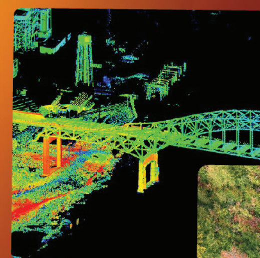
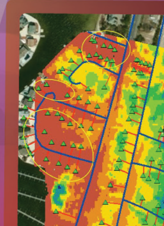


Commercial Remote Sensing & Spatial Information Technologies Program


2017

ACKNOWLEDGEMENTS

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COMMERCIAL REMOTE SENSING & SPATIAL INFORMATION TECHNOLOGIES PROGRAM

PROGRAM HIGHLIGHTS

U.S. DEPARTMENT OF TRANSPORTATION

OFFICE OF THE ASSISTANT SECRETARY FOR RESEARCH & TECHNOLOGY

OFFICE OF RESEARCH, DEVELOPMENT & TECHNOLOGY

2017

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PROGRAM OVERVIEW

The Commercial Remote Sensing and Spatial Information Technologies (CRS&SI) program was a congressionally mandated program authorized in the Safe, Accountable, Flexible and Efficient Transportation Equity Act: A Legacy for Users (SAFETEA-LU). Under this mandate, the Program was charged to validate commercial remote sensing products and spatial information technologies for application to national transportation infrastructure development and construction.

This Program focused on major national initiatives and validation of CRS&SI technology applications which deliver smarter and more efficient methods, processes and services for transportation infrastructure development and construction. The Program projects were competitively awarded to individual/consortia teams of university research entities working in partnership with industry and state agencies.

Remote Sensing includes remotely sensed imageries and data from satellites, aerial platforms, manned and unmanned vehicles. Spatial Information Technology includes Position and Navigation data from Global Positioning systems, Geospatial Information Systems etc.

Focus areas of the projects were chosen based on the Agency's priorities for CRS&SI technology applications for user services that had the potential to produce a high return on investment, in terms of saving costs and improving efficiency for practices of infrastructure development, planning, construction and condition assessment. Therefore, in order to ensure safe and efficient movement of people and freight within the national transportation infrastructure system, the program solicited projects dedicated to reduce inefficiencies, improve system performance, and assess infrastructure condition through implementation of applied research. Some specific focus areas of applied research were as follows:

- Risk assessment & evaluation: network level risk assessment and evaluation of transportation infrastructure associated with natural calamities such as floods, storms, hurricanes, earth quakes etc.;
- Post-hazard response: network-level inspection and evaluation technologies for bridges, large culverts, tunnels, sign structures, etc. that provide quantitative data for planning, maintenance, and management;
- Planning, operations, maintenance & program development: infrastructure systems to include waterways, highway facilities, freight, public transportation, intelligent transportation systems and railroads; and
- System deficiency detection & damage prevention: all modes of surface transportation.

The objectives of research efforts were focused to:

- Apply and validate CRS&SI technologies to collect data and provide a framework for analysis in studies and projects related to infrastructure development design, planning and construction;
- Apply spatial-based technology applications to increase efficiency and safety, and reduce congestion;
- Apply concepts of CRS&SI technology integration and products to monitor the condition of constructed infrastructure systems and provide quantitative data to reduce/supplement components of current visual inspection procedures and practices;
- Develop and apply decision support systems using CRS&SI data and visualization techniques to effectively monitor/assess the condition of existing/new infrastructure systems;
- Develop tools/products and effectively disseminate the results to relevant transportation user-communities such as academia, private sector and public sector agencies; and
- Develop and execute comprehensive project outreach programs to effectively inform and disseminate project results and products to relevant transportation user-communities such as academia, private sector and public sector agencies.

Advanced Imaging of Transportation Infrastructure Using Unmanned Aircraft Systems

University of Alaska – Fairbanks

Executive Summary

Pipeline operators are required to continuously monitor their infrastructure for safety and integrity. Federal regulations require surveillance patrols 26 times per year—patrols that may be on foot, in a vehicle, or from an aircraft. In the near future, unmanned aircraft systems (UAS) are likely to be a technology integrated into the business of pipeline operations.

The project research focused on:

- Right of Way Monitoring
- Close-Range Inspection
- Geotechnical Assessments
- Beyond-Line-of-Sight Flights

The project Team partnership for the research comprised of the University of Alaska and the Alyeska Pipeline Service Company, (operator of the Trans Alaska Pipeline System – Figure 1). The research was conducted from the spring of 2014 to the autumn of 2016 near Fairbanks, Alaska. This location represents some of the most austere environments for UAS operations, not only environmentally, but also because of its very sparse communications infrastructure.

Findings & Outputs

Anticipated findings were confirmed and new findings discovered. These findings contributed to a refocusing of the research during the project and an effort launched toward rapid commercialization of the project outcomes.

A need for future research emerged concerning optimization of both training and operational costs. Successful integration of the technology into the pipeline market would demand fewer supporting personnel than are now used for flight operations and data analysis. Until the UAS could operate autonomously in conjunction with the automated sensing of intrusions along a pipeline, operational cost will be set by the number of support specialists piloting the aircraft, operating sensors, monitoring airspace, and analyzing the data.

A robust radio telemetry system to carry pilot commands and real-time data such as video for analysis was developed and tested as part of this research application. Radio telemetry is a backbone of communications infrastructure, one that is only now maturing in the United States and likely to be based on existing cellular data networks. In locations across rural America, and especially Alaska, such coverage can be poor to non-existent. Therefore, supplemental communications systems will be required for future command and control applications, especially when UAS are operating at low altitudes beneath the view sheds of radio networks.

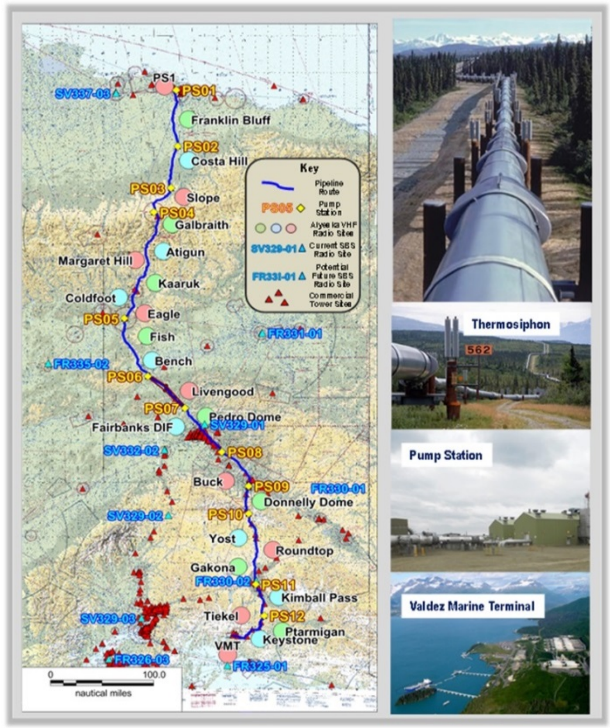

Figure 1: Trans Alaska Pipeline System

Promising findings related to commercialization of the project outputs centered on the ground control station (GCS). Using open source programming, researchers created a GCS that works with open source UAS autopilots. Unlike others currently marketed, this GCS can be customized for specialized applications such as the persistent surveillance of critical infrastructure locations, e.g., pipeline river crossings. We anticipate the future of UAS operations most likely will involve specialized applications that follow a planned script for the majority of flights and data collection.

Products & Outcomes

Several products were developed and their outcomes tested. First among these was three-dimensional modeling of infrastructure from highly overlapping images collected from drones. This type of photogrammetry—called structure from motion—is now a commercially mature technology in use by many markets around the world, though it was not at the start of the project. For pipeline operators, the results are "as-built" image-models with fine details suitable for inspection.

The second area of product development is an open source video integration with the UAS to generate full motion video (FMV). FMV utilizes metadata from the aircraft position, orientation, and speed with the camera-gimbal pointing data to overlay the streaming FMV on top of an existing base map. Other users will be able to modify the FMV open source code for custom cameras and for later applications involving change detection. This is a step needed for future automated image analysis and change detection.

Operating a UAS beyond line of sight, typically defined as less than a half-mile from the pilot, will be an area of vigorous research. This is due to the need to safely integrate the UAS into the National Airspace System, where manned aircraft fly. The project Team successfully tested an aircraft transponder that operates below air traffic radar to show its location to air traffic controllers and even to other aircraft.

Post Project Initiatives

This research has resulted in follow-on activities with continued UAS research and the commercialization of the ground control station.

Data collection has expanded to incorporate not only imagery, but also in-situ sampling. In-situ collection of aerosol data can include "sniffing" for methane leaks. Some sampling methods require weather and aerosol data, such as smoke and particulates, taken at differing altitudes. This points to the evolution of remote sensing into a real-time dynamic system that links data with spatial and temporal dimensions in a manner now possible only with low-flying UAS.

Several proposal opportunities for research and commercialization have been identified to develop tools for data collection and surveillance.

One of the significant post-project initiatives is cultivating the community of UAS software developers now using the open source GCS. The first tier of developers includes other universities adopting software algorithms for research and scientific purposes. UAS operators with aircraft whose autopilot the GCS supports represent the next tier. Finally, another important segment of the community is the manufacturers of aircraft and sensors. This group would want to build more tightly integrated systems that are flexible to be repurposed by their users.

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Monitoring and Analysis of Frozen Debris Lobes Using Remote Sensing

University of Alaska – Fairbanks

Executive Summary

Frozen debris lobes (FDLs) are slow-moving landslides within permafrost on slopes located in the Brooks Range of Alaska. Forty-three FDLs are located within the Dalton Highway corridor, with 23 occurring less than one mile uphill of the Dalton Highway and the Trans Alaska Pipeline System. Although slow-moving for landslides, their size and close proximity to infrastructure make FDLs geohazards. This project used remotely sensed data from multiple acquisition methods to monitor and analyze FDLs at different temporal scales, thereby increasing our understanding of rates and episodes of movement of these geohazards. Each technique was evaluated for its overall cost, ease of use, and applicability to assess the flow dynamics of FDLs. This research involved: 1) measuring surface movement in the field with a differential GPS unit; 2) analyzing remotely sensed data using multiple data acquisition methods (i.e., historic optical imagery, LiDAR data, InSAR data, and UAS-acquired photography) to monitor and analyze the FDLs at different temporal scales; and 3) summarizing and synthesizing the research results, making them available to the public and to the agencies with a vested interest in FDLs through several different deliverable formats.

Figure 1: Photograph of FDL-A, the largest and closest of the FDLs to the Dalton Highway. Here it is shown as of August 2016, view to the north

Findings & Outputs

The results of this integrated research indicate:

- The rate of motion of FDLs has increased over the last 60 years, with the eight FDLs investigated moving asynchronously to each other.
- In the last 40 years, scarps have developed in the catchments of the investigated FDLs, which may indicate increasing instability.
- The movement dynamics across the surface of a given FDL vary significantly throughout the year.
- All of the investigated FDLs demonstrated a maximum rate of movement in late October, and a minimum rate of movement in late February.
- The closest FDL to the Dalton Highway is FDL-A (Figure 1). Key observations at the location indicate that:

  a) As of October 2016, FDL-A was 32.2m from the toe of the highway embankment.
  b) It moved at an average rate of 6.4m/yr over 2015/16, and its rate has steadily increased over the period of analysis.
  c) Based on these values, FDL-A will reach the Dalton Highway by 2021.
  d) FDL-A is impacting the subsurface ahead of its toe, possibly shearing deeper that the original ground surface.
  e) When FDL-A impacts the highway, its narrowest portion will deposit over $19m^3$ (or $25yd^3$) of material on the highway every day. This equates to about two dump truck loads a day, and does not consider that FDL-A becomes wider uphill.

Products & Outcomes

The results of this research were disseminated through a variety of sources, including two peer-reviewed journal papers and eight conference papers. Links to the documents available from the internet are provided on the project website (fdlalaska.org). Discussions with personnel from the agencies with a vested interest in FDLs indicated that 3D visualizations of these features are important. Based on these discussions, two short videos were developed, which describe the relative scale and shape of FDLs, and illustrate their downslope progression through time (Figure 2). Both videos are available on the project website.

(a)

(b)

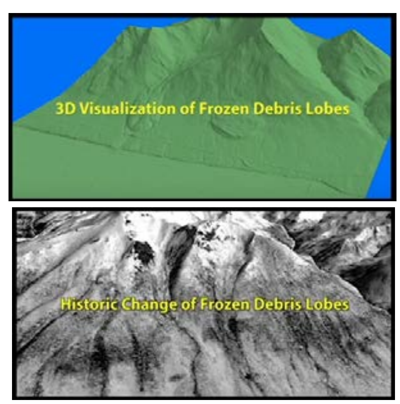

Figure 2: Screen shots of the two short videos explaining (a) the relative scale and shape of FDLs, and (b) illustrating their downslope progression through time

While the work focused on these slow-moving landslides within the Brooks Range of Alaska, the results of the remote sensing evaluation are more wide-spread, as the successful techniques may be applied to other regions with forested mass-movement features having similar rates of movement. As such, this project also evaluated each of the methods used in this research. The evaluation is summarized both in the final report and in a short, "best practices guide", which provides an at-a-glance summary of the pros and cons of each method. Examples of results from each method are depicted in Figure 3.

Post Project Initiatives

The Principal Investigator and her research Team have been monitoring and analyzing FDL movement mechanism and rates since 2012. The research results directly led to the Alaska Department of Transportation and Public Facilities' decision to realign the Dalton Highway in the immediate vicinity of FDL-A. While this is not a permanent solution for this specific geohazard, it provides additional time to develop appropriate mitigation techniques that can be applied to FDL-A and other FDLs in the Dalton Highway corridor.

In order to determine appropriate mitigation techniques, we must first develop a slope stability analysis technique that incorporates the temperature-dependent nature of the frozen soils' strength and phase change. Results from this and previous research indicate that pore-water pressure is a key element of FDL-A's movement. Thus, additional drilling and sampling and/or employing geophysical methods will help to define variations in soil strength and the pore-water pressure distribution, both of which will contribute to the modeling and analysis effort.

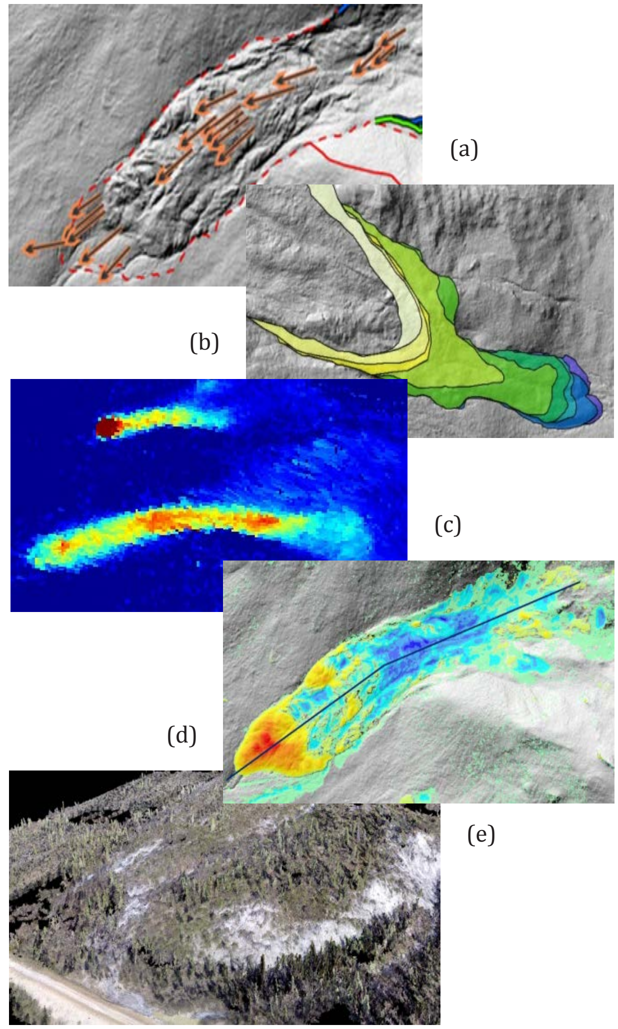

Figure 3: Examples of results obtained from various methods employed: (a) DGPS field measurements, (b) historic imagery analysis, (c) InSAR analysis, (d) LiDAR data set comparison, (e) UAS analysis

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Multi-Level Adaptive Remote Sensing Package for Bridge Scour Health Management

Arizona State University

Executive Summary

Over the past few decades, various fixed scour monitoring instruments such as sonar, manual sliding collar, tilt sensors, and sounding rods have been installed on bridge structures for measuring bridge scour depth. Typical issues reported of unmanned detection techniques are either vulnerability or survivability of the device under harsh conditions.

In this project for the U.S. Department of Transportation, our overarching objective was to develop an integrated means for reliable monitoring, inspection, detection, and prediction of local scour for bridge structures (Figure 1). Our Multi-level, Adaptive, Remote Sensing System (MARSS) integrates remote sensing and wireless technology with adaptive information processing, Gaussian process and particle filtering for prognosis, and a decision support system to assess different modes of scour (i.e., clear-water vs. live-bed scour) as well as their extent in terms of depth and volume near bridge structures.

Figure 1: Local bridge structure

Findings and Output

Radio Frequency ID (RFID) was developed for online detection of local scour around bridge piers during scour critical events. The key component of the RFID system is the reader. The reader not only emits the initial radio signal to activate the RFID transponders, but also receives and processes the return signal from the transponders. Three readers for the RFID systems were constructed by assembling the various electronic components, which included the circuit boards, attached wires, and connection ports for the computer and RFID antenna. RFID detection software PAPTSAK was developed. This software was needed for the integration of the RFID system into the MARSS package. The software calculates the inclination angle of the RFID sensor with respect to the excitation antenna.

One of the critical components of detection in MARSS is the critical scour depth. A scour estimation equation was developed based on the available filed data as a threshold scour depth. Detection in MARSS has two components: (i) Detection during data collection: a data examination procedure has been added into the data-gathering software of the gateway. If scour is detected, then an alert procedure is activated. The alert procedure can perform actions according to the preferences of the operator, e.g. can enable an audible signal at the gateway, initiate more frequent data sampling, or send in a notification to a control room if connectivity to it is available. (ii) During the loading of data from the database, the MARSS software (Figure 2) reviews the values and runs a scour detection technique, which in the simplest form is a value comparison to a preconfigured threshold. Once scour above threshold is detected, then a message dialog box is displayed and a warning message is issued to the user of the detection

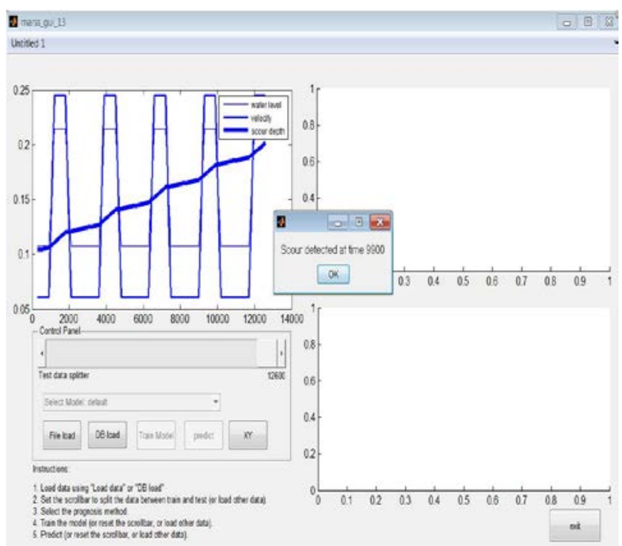

Figure 2: MARSS software user interface – Sample Screen 1

The evolution of scour is highly stochastic in nature. Therefore, in order to capture this uncertainty, probabilistic prognostic methods were developed to predict scour depth. A Gaussian process based prognosis model was developed to predict temporal scour using laboratory and field data sets. A stochastic filtering approach (particle-filtering) was developed and integrated with the Gaussian process prognosis model to: (i) include the uncertainty in measurement data from the RFID sensors and (ii) to predict the scour depth using training data.

A Decision Support System with a robust database, which covers bridges and piers information along with the RFIDs attached to each pier and their dependents like transmitters and their activities was designed for MARSS (Figure 3). In MARSS, we have managed to bring multiple uses into one, easy-to-use interface.

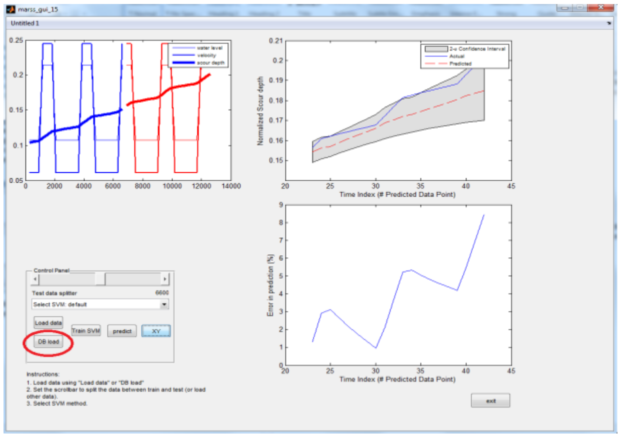

Figure 3: MARSS software user interface – Sample Screen 2

Products & Outcomes

RFID and MARSS system was implemented in two sites in Iowa and Arizona. In Iowa, a geodetic survey was conducted using a Total Station of a 350-m long reach of Clear Creek near Camp Cardinal in Johnson County, IA where the RFIDs were installed. A series of four RFID transponders were placed at 2, 4, 8, and 12 ft. depths below the bed surface at the Clear Creek site. They were secured to a chain that ran along the stream bed and up the bank to a ground anchor. A field test was also conducted at N Bush Highway Bridge at Blue Point picnic area in Arizona. A detection distance of 24 ft. was achievable with at least 50% success rate or higher and 32 ft. with 37% success rate. The prognosis software can predict scour depth with a minimum of 90% accuracy.

Post Project Initiatives

In future projects, a few minor updates can be done before vast implementation of MARSS for scour detection and prediction. In doing so bridges located at places with very poor connectivity should be studied and the source of power to be used to charge the device to which the base station is connected needs to be researched. Solar energy stands as an option to charge the device for many states in the country; at the current status, the sensor network for data collection must be entirely under the bridge as it was observed that the bridge concrete top deck had a fast fading effect on the signal and hence reduced the signal strength by a great extent. Effect of concrete and metallic structures on the performance of MARSS needs to be studied.

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Improved Satellite and Geospatial tools for Pipeline Operator Decision Support Systems

California Polytechnic State University, Cal Poly Corporation

Executive Summary

California Polytechnic State University, San Luis Obispo (Cal Poly), in partnership with, Pipeline Research Council International, Inc., MacDonald, Dettwiler and Associates (MDA), C-CORE, and Electricore, Inc. developed a program to use satellite remote sensing, geospatial data information, and readily available web-based datasets to enhance existing pipeline operator Decision Support Systems (DSS) for pipeline integrity management. The DSSs and associated tools and methods could also be used by federal, state, and local government agencies.

Findings & Outputs

The overall technical approach is broken down into the following three areas:

1. Enhanced Data Models

Based on an extensive open source GIS software and data base literature review, the Team designed and implemented a geospatial data service, REST API for Pipeline Integrity Data (RAPID) (Figure 1) to improve the amount and quality of data available to project partners.

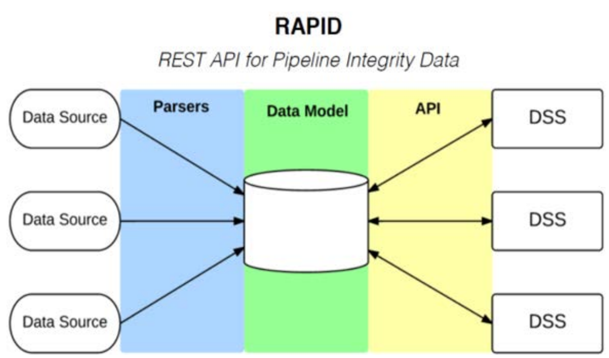

Figure 1: REST API for Pipeline Integrity Data

The RAPID system was built with PostgreSQL's PostGIS extension spatial database and the Python-based Django web framework and allows third-party software to manage and query an arbitrary number of geographic data sources through one centralized REST API. RAPID was built with permission management capabilities for DataLayers and GeoViews, thus a multi-tenant system allowing scalability for multiple proprietary data users. The Team successfully integrated the RAPID data model with the OGC compliant GeoServer web-platform. GeoServer automatically provides web coverage service, web map service, and web feature service, all OGC-compliant data formats and was set up with the PostGIS database.

2. Encroachment Monitoring & DSS

The Team examined the capabilities of a new generation satellite-based synthetic aperture radar (SAR) systems that have higher resolution modes to provide all-weather, day or night monitoring of a specific geographic location. This monitoring, dubbed Encroachment Management Service, was achieved using computerized change detection to identify potentially hazardous activities, combined with analyst quality control of the computerized results to create an output product of activity. This task evaluated optimizing detection algorithms and reducing false detections to make the service 'more practical and cost effective. A Bayesian belief network was designed incorporating both change detection output from the satellite-based SAR, and GIS-based vector data as inputs.

This network was implemented within C-CORE's Coresight framework, a web platform that has been designed for operational services derived from satellite imagery. By considering other data sources in addition to satellite imagery, potential encroachment events can be refined to reduce the number of false positives requiring manual assessment.

3. Ground Movement & DSS Development

The objectives of the ground movement assessment & DSS development task was to examine the utility of the techniques established by MDA for land classification, deformation and change analysis utilizing SAR data from the RADARSAT-2 satellite program, and then effectively uploading the derived information into a DSS (Figure 2) for easy access and action by pipeline operators.

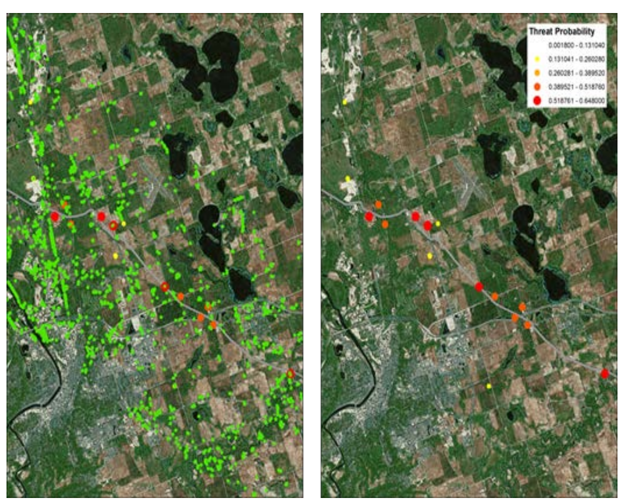

Figure 2: Images show an automated threat assessment calculated by an early version of the DSS. The right-hand image has had low probability targets automatically removed

The Team identified the reliability of slope stability risk mapping using the combined approaches of polarimetric change detection and ground deformation mapping. This resulted in the creation of a product that would easily portray the information needed for pipeline operators to identify areas of risk. RADARSAT-2 Ultra-Fine (3-m ground resolution) data was collected starting one ascending and one descending image collected on a 24-day basis throughout the project. In addition to the above data, WorldView-2 (WV-2) high-resolution 8-band multispectral (1.85 m) and panchromatic (46 cm) data was collected coincident to the ground-truthing campaign. The WV-2 data was used primarily for terrain and ground cover assessment and interpretation.

A 13-location Dual Corner Reflector (CR) (Figure 3) study was conducted over a segment of a pipeline in Washington State. The CRs were used to provide a field of monuments for exact slope monitoring by Interferometric Synthetic Aperture Radar (InSAR) methods in the pipeline area of interest (AOI). The CRs were aligned to the RADARSAT-2 ascending and descending satellite passes. The CRs experience precisely the same motion as the underlying ground and serve as measurement points to capture the overall deformation of the reservoir.

Figure 3: Dual Corner Reflector #9, Washington. © MDA Geospatial Services Inc., (2017)

The CR study (Figure 4) confirmed trends in subsidence and ground movement in the AOI. MDA's ground movement mapping from InSAR provides information necessary to both measure surface deformation and identify potential geohazards occurring at the operator's selected AOI.

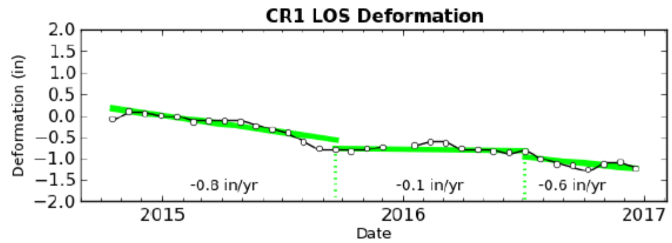

Figure 4: Westward CR1 ground movement profile. © MDA Geospatial Services Inc. (2015)

Products & Outcomes

Three primary products were developed by the individual project partners under this project: 1) Cal Poly's geospatial data service - REST API for Pipeline Integrity Data (RAPID) 2) C-CORE's Coresight software decision support system and 3) MDA's InSIGHT mapping index system. The products and services developed by C-CORE and MDA will be commercialized as part of existing services to customers worldwide. The Cal Poly data model is available to C-Core and MDA to incorporate, as needed, into their existing service offerings.

Two master's thesis reports were generated as part of this project. Other public presentations were made at national and international conferences, including industry workshops hosted by the Pipeline Research Council International.

Post Project Initiatives

The Team will continue to develop the RAPID system and add functionality based on user/customer demands. This open source GIS software product developed as part of this U.S. Department of Transportation sponsored project complements and adds to the growing body of research and demonstration of open source GIS software systems, such as those catalogued by The Open Source Geospatial Foundation (OSGeo)

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Advanced Space-Based InSAR Risk Analysis of Planned And Existing Transportation Infrastructure

Stanford University

Executive Summary

Stanford University and MacDonald, Dettwiler and Associates have developed a suite of cutting edge algorithms to derive mm-level surface displacement from space-borne Interferometric Synthetic Aperture Radar (InSAR) imagery. A prototype comprehensive InSAR displacement monitoring system was developed in collaboration with State Department of Transportations (DOT) to guide the evolving prototype to provide efficient and robust unstable ground risk analysis in the planning phase of new transportation infrastructure development as well as monitoring the stability and integrity of existing infrastructure.

The flexibility and robustness of the advanced InSAR methods contained in this system make it adaptable to specific infrastructure problems and particular environments throughout the United States. The system thus allows partnering State DOTs to greatly reduce their costs and improve the timeliness for monitoring new and existing transportation infrastructure. Cost benefits above the status-quo of road infrastructure monitoring are achieved through the system's superior spatial coverage allowing timely reconnaissance monitoring and identification of problem hotspots to efficiently direct on-the-ground monitoring to where it is warranted.

Findings & Outputs

The methodologies were applied to several sites in three different states. In Pennsylvania, for example, rural roads were analyzed in the Bushkill Creek and Lewiston Narrows regions. Figure 1 shows persistent ("reliable") pixels in regions with possible subsidence in Lewiston Narrows.

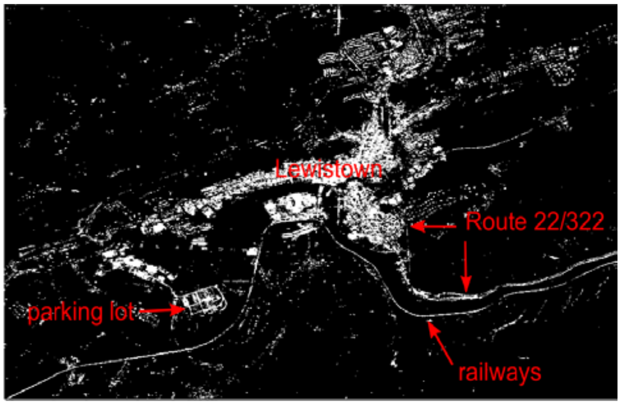

Figure 1: Subsidence Levels

Figure 2 presents subsidence vs. time for these points as derived from our model. While there is subsidence over a year in the labeled areas, it rarely exceeds 2 cm and thus is not a significant hazard.

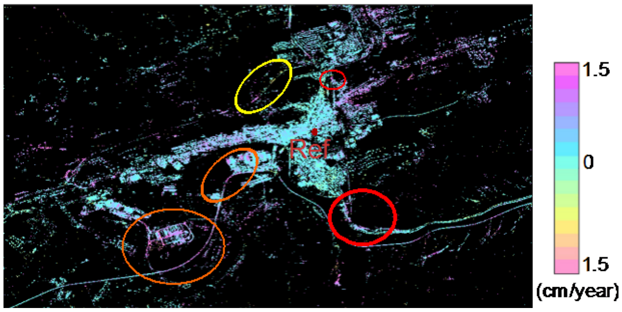

Figure 2: Subsidence vs time

A detail of subsidence in this area (Figure 3) shows clearly where the roads were affected by changes in deformation that could indicate future hazard.

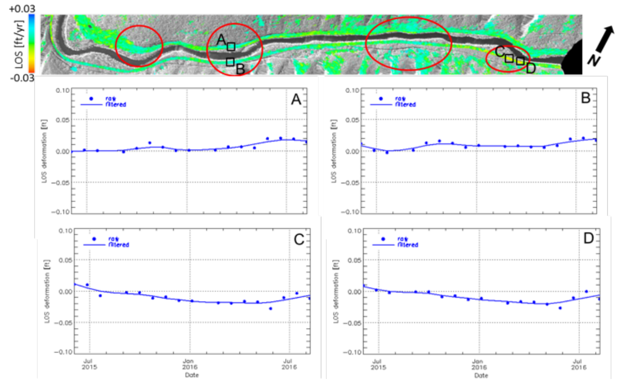

Figure 3: Deformation Locations

Subsidence due to the digging of a corridor tunnel in Seattle during 2012-16 was also examined, where much of the subsidence was caused by dewatering of the tunnel proper. The tunnel route is shown in Figure 4.

Figure 4: Tunnel route

The deformation is readily observed in the system as shown in Figure 5. Similar analyses were conducted over parts of California as well. A visualization tool was developed based on using Google Earth, so that any state DOT may easily exploit the capabilities developed here.

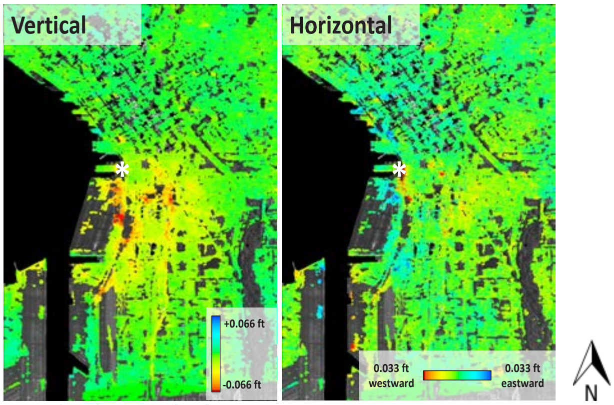

Figure 5: Deformation levels

Products & Outcomes

The products resulting from this work include:

- Technical report summarizing requirements and needs specific to State DOT partners, including experiment sites, measurements, and analyses.
- Dual scale point scatterer analysis over selected test sites. as of the effective date of the Agreement (Del – 3A).
- A study of deformation of ground surface over selected test sites.
- Report describing tools that visualize InSAR analysis results in a manner that can be interpreted and exploited by State DOTs.
- Report summarizing feedback from the State DOTs on the project technical results presented to them at Workshops.
- Project website for public dissemination of project results.

Technical analyses were completed over the following sites:

- SR99 Tunneling project (Seattle, Washington)
- Lewistown Narrows project Mechanically Stabilized Earth retaining walls (Lewistown, Pennsylvania)
- Bushkill Creek area limestone karst sinkholes (Northampton County, Pennsylvania)
- The Geysers geothermal field (California)

In each case, any subsidence was documented, measurements were presented, and results were presented using the visualization tool. Literature papers are being submitted as the technical conclusions are completed.

Post Project Initiatives

The project Team is in the process of continuing discussions with state DOTs to further adapt and evolve the system into a useful tool for assessment and planning. These discussions should lead to develop better and more responsive tools enabling the agencies to better examine the roadway conditions across the country.

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A Remote Sensing and GIS-Enabled Asset Management System (RS-GAMS)

Georgia Institute of Technology

Executive Summary

An intelligent Remote Sensing and GIS-based Asset Management System (RS-GAMS) was developed in a two-phase research project (Figure 1). Commercial Remote Sensing and Spatial Information (CRS&SI) technologies, including 3D line laser imaging, mobile Light Detection and Ranging (LiDAR), video log imaging, differential GPS, Inertial Measurement Unit (IMU), and Distance Measuring Instrument (DMI), are integrated on the Georgia Tech Sensing Vehicle (GTSV) system. GTSV can be operated at highway speed to improve the inventory, condition assessment, and management of pavement and roadway assets including asphalt and concrete pavement distresses, traffic signs, pavement markings, and roadway geometric characteristics.

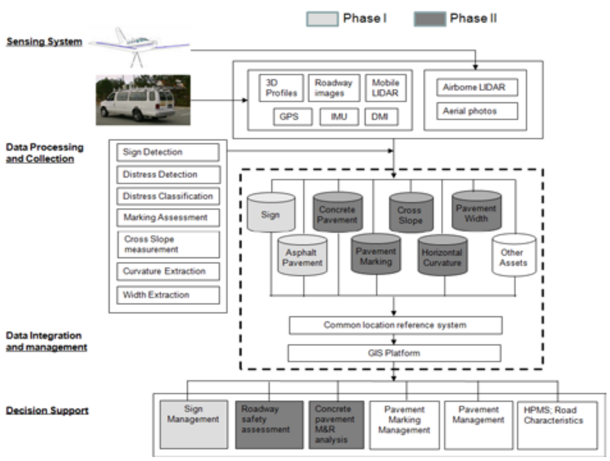

Figure 1: Remote Sensing and GIS-based Asset Management System

The research results, e.g., automatic pavement distress detection and recognition, automatic traffic sign inventory, etc., have been successfully implemented on Georgia's interstate highways. The research results were disseminated through numerous national and international conference presentations and journal article publications. The pioneering work has also promoted the use of 3D line laser imaging technology in nationwide state Departments of Transportation (DOT).

Findings & Outputs

Major validation research results and findings have been published in conferences and journals:

- The accuracy of point-based laser measurement methods was evaluated. Results show that point-based laser measurement methods (e.g. 3-point rut bar) are reliable for rutting measurement due to vehicle wandering, variation of rut locations, and rut shapes.
- A detection of isolated ruts using 3D line laser imaging technology was tested. Results show that 3D line laser data can be used to detect isolated ruts for determining adequate localized treatment.
- A novel quantification method based on the buffered Hausdorff distance was developed to evaluate the performance of pavement cracking segmentation algorithms. The proposed method accurately reflected the observed performance of the segmentation techniques and outperformed the other three quantification methods.
- The test results on automatic pavement crack detection and classification showed that 3D line laser data along with advanced signal processing and machine learning technique can be reliably used to automate crack detection and classification process, which would significantly improve pavement performance data accuracy and data collection productivity.
- The automatic traffic sign detection and recognition algorithms using video log images and mobile LiDAR were tested using real data acquired from different transportation agencies and the GTSV. Results showed that these technologies can be incorporated in an enhanced sign inventory procedure that can significantly improve data quality and productivity.
- A mobile LiDAR-based retro-reflectivity condition assessment method was validated for both traffic signs and pavement markings, which showed very promising results.

The research results have been presented in numerous national and international conferences, including the keynote speech on 3D technology for roadway asset management. 17 peer-reviewed articles have been published in some highly referred journals such as the Transportation Research Part C, ASCE Journal of Computing in Civil Engineering, ASCE Journal of Transportation Engineering, and the Journal of TRB. The above outcomes extensively disseminated the research results to nationwide transportation agencies and researchers, and promoted the use of CRS&SI technologies, especially the 3D line laser imaging technology, in transportation.

Products & Outcomes

A standard File Exchange Format for pavement surface laser data, including both 3D range and intensity data was developed. It can be implemented by vendors who provides data collection services. Thus, a highway agency will have the flexibility to use a third party for data processing. Also, data collected by different vendors can be easily combined and reused.

Post Project Initiatives

The following are some major initiatives resulted from the successful completion of this research project.

Invited and sponsored by the AASHTO pooled fund study with more than 20 state DOTs (TPF-5(299): “Improving the Quality of Pavement Surface Distress and Transverse Profile Data Collection and Analysis.”), a report on “Technology Overview on Validating 3D Transverse Profile Data and Measurement of Pavement Surface Distresses” has been completed in 2015. An innovative data validation board has been developed and proposed in the report. This report will help advance the application of 3D line laser technology in state DOTs, which has been successfully validated through this research project.

To study the pavement deterioration, the PI and his research team has been continuously monitoring and collecting pavement distress data on US 26 using 3D line laser imaging technology since 2011. An innovative, multi-scale crack fundamental element model has been developed for this study. The research outcome has been published in the Journal of Transportation Research Board (TRB) in 2016.

For the first time, a spatio-temporal study of 3D rutting deterioration has been conducted. The research outcome has been accepted for presentation at 2017 TRB Sponsored by Georgia DOT, the enhance sign inventory procedure along with the automatic sign detection and recognition using video log images and mobile LiDAR data has been successfully implemented on Georgia’s 2,500 survey-lane-mile interstate highways.

Georgia DOT has also sponsored the large-scale implementation of automatic pavement condition evaluation using 3D line laser imaging technology. The comprehensive pavement condition data on Georgia’s interstate highway has been completed and will be input into Georgia DOT’s pavement management system to support the statewide pavement maintenance and preservation.
The results of the successful implementation of automated inventory, condition evaluation, and management of sign and asphalt pavement assets on a large-scale interstate highway system (Figure 2) will be presented in 2017 TRB annual meeting.

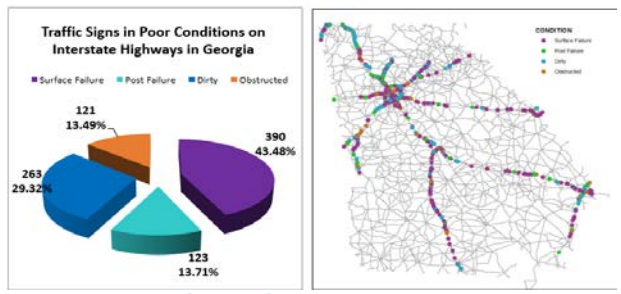

Figure 2: Pavement and Sign condition Inventory

Sponsored by University Transportation Center, an innovative research has been completed for automatic crack sealing cost estimation and planning. Furthermore, research results from automatic crack sealing planning will be applied in another Georgia DOT sponsored project for studying the performance of crack sealing. The research outcome has been accepted to present in 2017 TRB.

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Development of a Self-Sustained Wireless Integrated Structural Health Monitoring System for Highway Bridges

University of Maryland – College Park

Executive Summary

Fatigue-induced cracking is a common failure mode in many steel bridges reaching their original design life. These aging bridge structures have experienced increasing traffic volume and weight, deteriorating components as well as a large number of stress cycles. Despite years of research in overcoming these challenges, catastrophic failures (e.g., the interstate 35W bridge collapse in Minneapolis, MN in 2007) still occur, which is mainly due to various difficulties in detecting bridge health conditions under highly uncertain operational conditions and also our limited understanding of the failure mechanisms in these systems. This project addresses this issue by establishing an Integrated Structural Health Monitoring (ISHM) System for remote infrastructure sensing, diagnostics and prognosis. The ISHM entailed a few recent innovations that transformed the current state-of-the-practice in remote sensing and management of highway infrastructures.

The novelty and uniqueness of the technologies of this project are summarized into the following five thrust areas:

Thrust 1: Reconfigure sensor dots (sensor technology)
Thrust 2: Passive interrogation of evolving damage (AE diagnostics)
Thrust 3: Hybrid-mode energy scavenger (energy harvesting) to power wireless sensor
Thrust 4: Multi-media wireless smart sensor (wireless sensing)
Thrust 5: Prognostics

Findings & Outputs

Based on the five thrust areas, there are five tasks involved in this project, which are:

Task 1: Establishing weak point identification maps and conducting baseline field tests
Task 2: Fabrication and characterization of piezo paint AE sensor with reconfigurable sensing dots
Task 3: Development of a time-reversal (T-R) method for AE source identification
Task 4: Development of a wireless smart sensor with a hybrid-mode energy harvester and embedded T-R algorithms
Task 5: Developing ISHM in both laboratory and field environments and implementation with Bridge Management System

Findings by tasks are listed here:

- All activities under Task 1 (finite element model, sensor placement scheme, environmental variable data, etc.) were all accomplished timely.
- All activities under Task 2 (piezo paint sensor with improved sensitivity, reconfigurable piezo paint sensor dots) were all accomplished timely.
- All activities under Tasks 3 and 4 (onboard diagnostics method based on the T-R algorithm, self-sustained wireless smart sensor and hybrid-mode energy harvester) were completed in the extended third year.
- All activities in lab tests and field tests of the ISHM system under Task 5 (integrated piezo paint AE sensors with wireless smart sensor and hybrid-mode energy harvester) were completed in the extended third year.
- Finding of strategy to incorporate remote sensing and prognosis of bridge components into bridge management system under Task 5.3 were considered and reported.

Products & Outcomes

In summary, a functioning wireless ISHM System with remote sensing, diagnostics and prognosis was developed, tested in the lab as well as in the field, deployed and validated (Figure 1).

Figure 1: Wireless AE Sensor (Left) and Crack (Right)

The ISHM system is a sensor driven approach which yields multi-dimensional information about the reliability evolution of the monitored bridge structure in future operation years. Figure 2 illustrates the flowchart for the improved application of condition ratings.

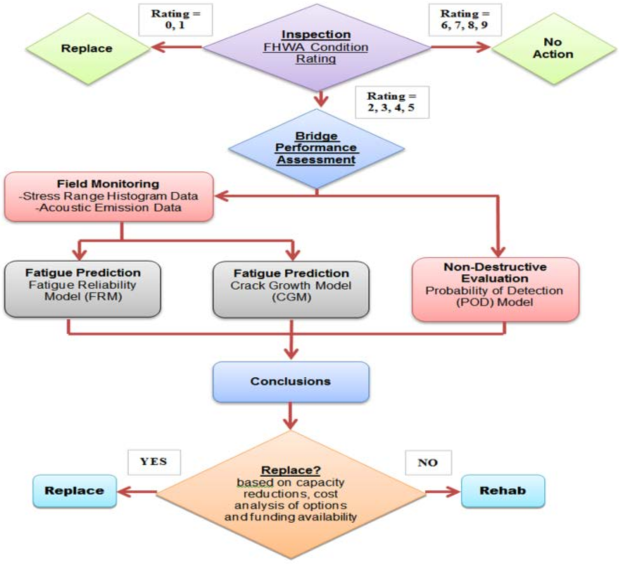

Figure 2: Application of condition ratings flowchart

Post Project Initiatives

Professional staff from the Maryland Department of Transportation (Figure 3) was invited to the demo site at I-95 (Figure 4) over Patuxent River, Laurel, MD. The whole process was performed to showcase the wireless smart sensor system with piezo paint AE sensors and hybrid-mode energy harvester. Also demonstrated were the pencil break tests to simulate the fatigue cracks to different groups of guests from Maryland State Highway Administration and Maryland Transportation Authority to demonstrate the AE sensor and crack detection technology and explain the benefits of the system to the bridge owners. It was a very successful event.

The UMD research team met with the staff members from the Office of Technology Commercialization (OTC) of the University of Maryland. During the meeting, the UMD research team presented the project research work/outcomes and potential sensor and crack detection technologies for licensing. The OTC demonstrated the procedure for technology licensing and encouraged the project team to discuss with potential technology transfer partners for licensing. Strategy of commercialization has been consulted to the OTCs of UMD and NCSU, and other DOTs.

Figure 3: Professional Staff from Maryland Department of Transportation

Figure 4: I-95 Bridge site and the solar-wind hybrid power

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Radio Frequency Identification (RFID) Sensors for Roadway Seasonal Load Restriction (SLR)

University of Massachusetts – Dartmouth

Executive Summary

A radio Frequency (RF) wireless subsurface sensor, internet of things (IoT) network system and intelligent GIS-Based roadway seasonal load restriction decision support system (SLR-DSS) was developed in a two-phase research project. The project's second phase developed new technology for wirelessly RF sensing of underground environmental conditions (e.g. temperature, moisture, etc.). Collected data is retrieved from the underground sensors using a radio frequency channel. The retrieved raw data is packaged and sent through an IoT RF hop network to a backend database system (Figure 1). The database system is interrogated daily by the web hosted DSS which decodes data, computes various SLR forecast plans and renders these results onto a web hosted graphical user interface (Figure 2).

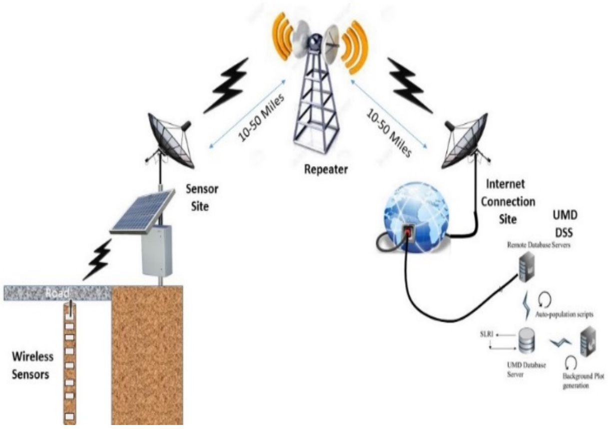

Figure 1: Wireless Subsurface Sensor and Communications System

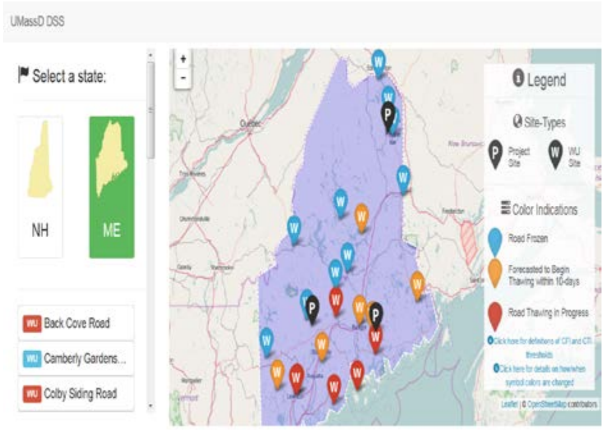

Figure 2: SLR Decision Support System User Interface Page

Research and development results, have yielded products successfully installed on secondary roadways in numerous northern states. The project's research results were disseminated through numerous conference presentations and publications.

Findings & Outputs

The project's transportation infrastructure monitoring system (TIMS) resulted in six major outcomes and products published in conferences and journals:

- The radio frequency wireless sensors proved to be significantly more robust than originally envisioned. Sensor depth was increased from a proposed six feet to twelve with no loss of fidelity. The RF wireless sensors implemented measured temperature, moisture, pressure and deflection, though only temperature and moisture are presently in use.
- The Primary cost from the first phase of the project was recurring costs with satellite and cell links from remote sensor sites. The new design uses a RF hop network to link sensor sites to data sink sites. The network uses off the shelf IoT RF links integrated into a cost effective low power network design.
- Sensor raw and processed data storage provided during the first phase of the project was quite expensive, requiring a recurring cost due to the use of an internet data storage firm. During phase two, the team examined various storage models and solutions before deciding upon a cloud-hosted approach that could be custom designed and provided at a much more reasonable cost.
- The redesigned DSS provides ease of use, maintenance and growth all in one package. The team went to great lengths to redesign the system for the long haul. The system is fully automated in terms of data extraction, formatting, processing and graphical rendering. Users simply select sites of interest and can then examine surface and subsurface conditions and can also retrieve stored data in either excel or text delimited formats for additional processing.
- The team examined numerous frost-thaw models for inclusion into the DSS. In addition, the team developed new models to provide a variety of solution to the SLR problem.
- The hardware and software system is undergoing continuous testing, verification and validation at the University of Massachusetts – Dartmouth (UMD) testbed housed on campus. This facility has been enormously helpful in developing and realizing working systems and supporting TIMS system innovations.

The project's research results have been presented in numerous national conferences, workshops and industrial shows. Numerous peer-reviewed articles have been published in some highly referred conferences such as the IEEE Sensors conference, ASCE cold regions conference, Massachusetts DOT technology transfer conference, and the Transportation Research Board . The project's outcomes disseminated the research results to nationwide transportation agencies and researchers, and promoted the use of RF sensors, DSS and forecast models for data driven SLR decision making.

Products & Outcomes

TIMS sensor designs and enclosures were completed during the project along with installation manuals and quick start manuals. System documentation has been uploaded to you tube to make them accessible by any interested party.

TIMS System IoT designs, implementation and installation procedures are completed and described in various manuals and on-line videos. Setup is quite seamless and does not require UMD team members to accomplish. The TIMS IoT mesh network supports line of sight RF communications links supporting 10-mile link hops, enabling almost an infinite system communications range.

A web hosted DSS was designed and developed during the project and is available for use by various state and federal DOT's for use in SLR decision making. The web hosted DSS has the additional capacity to allow users to select a specific sensor site, range of dates and extract all raw data sets associated with the selected site.

Post Project Initiatives

The following paragraphs describe some major initiatives resulting from the successful completion of the UMD TIMS research project.

The research Team was invited and sponsored by the US Forest Service to implement 4 additional testing sites for roadway SLR management on US Forest service lands. Sites have been installed in New Hampshire (2 additional sites), Pennsylvania, and Oregon. Other proposed sites in Colorado and Washington are under review.

The research Team has been in contact with other state DOT's interested in using the technology. The intention is to follow up with these agencies using our industrial partners.

The Team is collaborating with numerous start-up companies looking to utilize our patented technology to construct systems to aid in the management and use of roadways, rail lines and other transportation assets.

The Team is looking into making an enhanced DSS tool available for use by transportation freight, lumber and mining companies for use in determining optimal shipping routes based on posted SLRs.

The Team has patented the RF underground wireless sensor technology prior to the start of this project. This patented technology is being used to further examine uses beyond the original intended design.

The Team is investigating the patenting of the DSS system as well as the forecast models and their use in an integrated fashion (Figure 3).

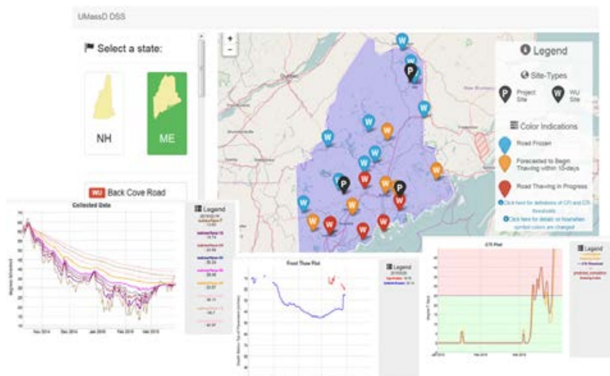

Figure 3: SLR DSS and Example Forecast Model Solutions

The project's completion is only the beginning; the Team is seeking out additional funding sources to continue this vital work and to expand the effort to examine additional transportation infrastructure assets. The outputs and products from the project have been useful to the state DOT partners as well as to other federal, state and local collaborators and users.

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An Automated System for Rail Transit Infrastructure Inspection

University of Massachusetts – Lowell

Executive Summary

A critical aspect of the transit state-of-good repair is the inspection of rail transit infrastructure. The current rail transit inspections are primarily based on visual observation (Figure 1), which is time-consuming and labor-intensive. Also, they cannot effectively identify subsurface hazards. For instance, ultrasound is usually used for rail inspection twice a year, and an inspection vehicle is used to check the rail geometry every few months. For all other structures and facilities (e.g., ties and fastening systems), they are inspected manually on a weekly or monthly basis, which requires considerable time and efforts. This practice is typical for most transit agencies in the United States.


Figure 1: Manual inspection of railway tracks

This project developed an integrated system to automatically collect and georeference surface and/or subsurface data for rail, concrete ties, fastening systems, and ballast (Figure 2). It consisted of Ground Penetrating Radar (GPR), 3D laser, Geographic Information Systems (GIS), encoder, accelerometer, and Global Positioning System (GPS).


Figure 2: Concrete ties, fastening systems and ballast

Advanced algorithms and software tools were developed to interpret the data and to identify rail infrastructure surface and sub-surface defects and safety hazards, such as broken ties (e.g., cracks in ties), missing fasteners, fouled ballast, and wide rail gauge. Also, a WebGIS-based decision support system with user-friendly interface was developed to help rail transit employees with no GPR and laser background utilize the data.

Rail transit agencies in the U.S. rely heavily on visual observation for track inspections. This manual method is time-consuming, costly, and unsafe and cannot effectively identify subsurface safety hazards. With the aging rail infrastructure, this proposed system is expected to substantially benefit the rail transit industry by improving track inspection efficiency, accuracy, and the safety of both the rail transit systems and track workers.

Findings & Outputs

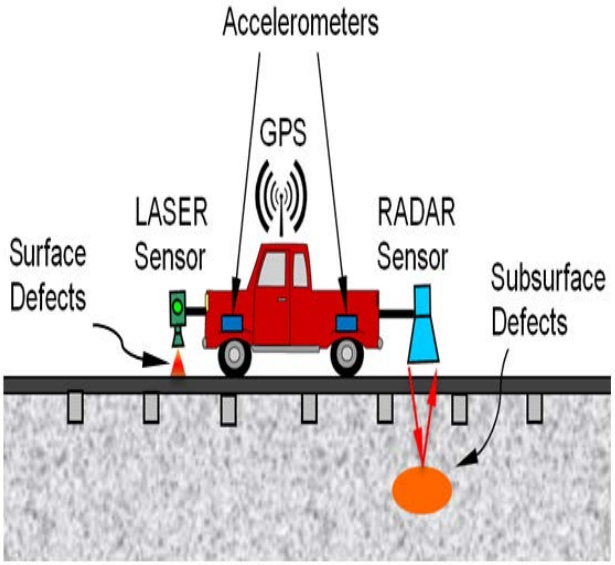

Figure 3: Automated rail transit infrastructure inspection framework

Each major component (e.g., GPR, laser, GPS, and accelerometer) of the system (Figure 3) was developed/tested first in the lab to ensure that they worked properly. For testing the performance of the GPR subsystem, a wooden box was constructed in the lab and filled with soil, sand, and clean and fouled ballast. The results suggested that the developed GPR subsystem was able to accurately identify the locations of fouled ballast and subsurface pipelines. The team also conducted lab tests to evaluate the accuracy of the laser subsystem and found that its horizontal accuracy was less than 0.3 mm and its vertical accuracy was less than 0.5 mm.

The integrated system was then used to collect surface and sub-surface data from Metro St. Louis and the Massachusetts Bay Transportation Authority during the summer of 2013. The system was designed to be easily mounted on a high-rail vehicle (Figure 4) and performed reliably during the field tests.

Figure 4: Automated system

Products & Outcomes

The research team also developed a set of algorithms and software tools to interpret the collected data, including:

- A laser software tool for measuring rail gauge, identifying rail positions, cross-ties and fasteners, and detecting cracks in concrete cross-ties. A 3D template matching algorithm (Figure 5) was developed for detecting missing fasteners;

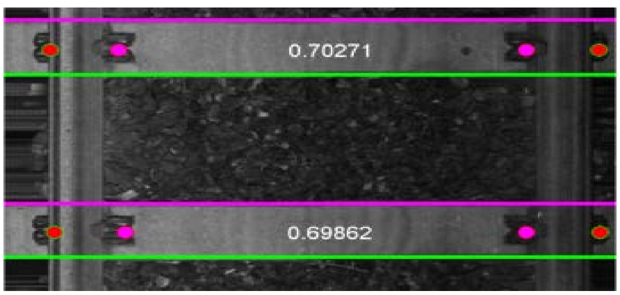

Figure 5: 3D template matching algorithm for detecting missing fasteners

- A GPR data analysis software package was developed that is capable of identifying and marking suspicious subsurface regions, including: 1) a 2D entropy algorithm to automatically identify regions of interest; 2) a method for calculating the depths of subsurface anomalies, and 3) a graphic user interface for the developed signal processing package;
- A track dynamic model for analyzing the collected accelerometer data. The team also developed a spectrum analysis model to identify hanging-ties based on the accelerometer data; and
- A WebGIS-based decision support system (Figure 6) for managing, visualizing, and analyzing the collected and processed GPR, laser, and accelerometer data. A mobile App was also developed to facilitate data collection and field inspection trips.

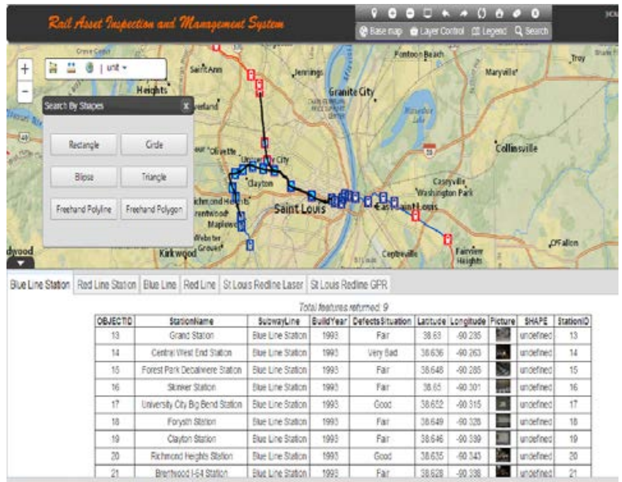

Figure 6: WebGIS-based decision support system

Manuals and tutorials for the developed tools have been prepared. The research has generated three peer-reviewed conference publications and has been presented 5 times at international, national and regional conferences.

Post Project Initiatives

Based on the results of this project, a Laser Rail Inspection System (LRAIL) has been developed and successfully commercialized by Pavemetrics Inc., a member of the project team. In addition, some of the team members are exploring other innovative technologies for railroad infrastructure inspections, including unmanned aerial vehicles (UAV), ultrasound, Digital Image Correlation, and infrared. The concept of using UAVs for railroad inspections was funded by the US Department of Transportation.

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Multi-modal Remote Sensing System (MRSS) for Transportation Infrastructure Inspection and Monitoring

University of Massachusetts – Lowell

Executive Summary

Managing the growing population of deteriorated transportation infrastructure systems (i.e. highway bridges) and being able to accurately inspect them in a timely and cost effective manner is a major societal challenge within the U.S. today. Traditional nondestructive testing, inspection, evaluation methods for highway bridges cannot currently provide an accurate and rapid evaluation (independent of human biases and interpretation) on a routine basis to prevent deteriorated bridges from sudden collapse (Figure 1). Automated, low-cost, efficient bridge inspection techniques for interrogating critical bridge components are needed. Existing highway bridge inspection techniques are typically time consuming, labor intensive, and cost inefficient. Safety issue, interference with existing traffic, and subjective evaluation of visual inspection are additional disadvantages in such inspections.

Figure 1: Failures of highways bridges (a) Corrosion of the bridge (b) Collapsed I-70 Lake View Drive Bridge, Pittsburgh, PA

The objective of this project is to develop a multi-modal remote sensing system (MRSS) that will be used as the next generation of rapid, distant, interrogation technology for bridge inspection. The proposed MRSS combines advantages of Non Destructive Testing (local inspection) and structural health monitoring (global, continuous monitoring), using innovative continuous wave imaging radar (CWIR), digital image correlation (DIC), and fiber optic sensors (FOS) to deliver a cost-effective, robust solution for the inspection and monitoring of critical transportation infrastructure such as highway bridges. MRSS represents the next-generation of portable bridge inspection technology for efficient inspection, evaluation and rating of bridges.

Findings & Outputs

Findings from field activities and research results are summarized as follows:

- CWIR can identify the type of materials in both distant laboratory and distant field measurement schemes. CWIR can also identify and locate a #3 subsurface rebar inside concrete at a concrete cover of 3" from distant measurement (Figure 2).
- Background noise (electromagnetic) does not affect the performance of CWIR when conducting distant measurements within 100 ft. Detectability of CWIR is not jeopardized by background noise in the field when signal-to-noise ratio is higher than 1.5~2 in various applications. Denoising techniques are helpful in improving the detectability of CWIR in field applications.

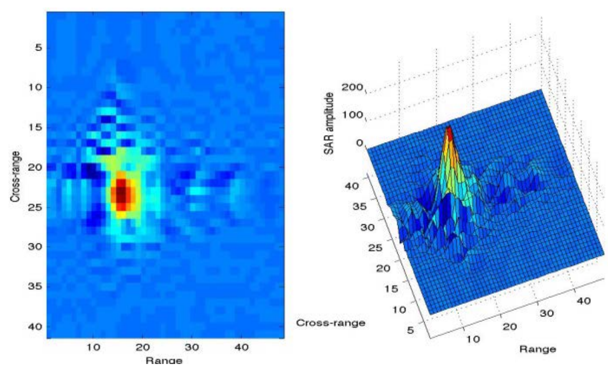

Figure 2: Subsurface CWIR imaging of a RC cylinder

- DIC is capable of monitoring the long-term displacement and reconstructing the surface stress/strain fields of (Figure 3) reinforced concrete (RC) highway bridges, from our 9-month field measurements. Using surface stress distribution, DIC can also indicate possible cracking areas of RC bridge elements, even though there is no visible surface cracking of concrete.

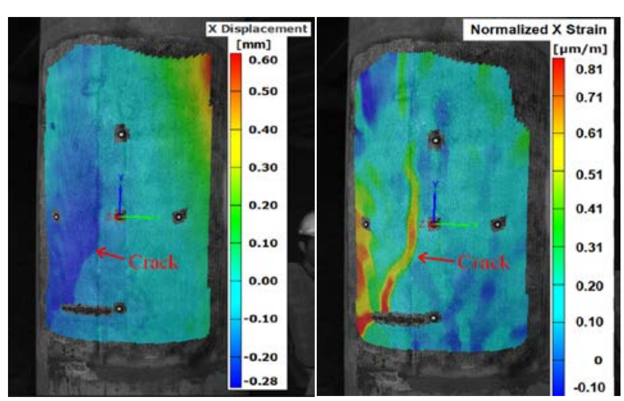

Figure 3: Displacement and strain of a RC highway bridge pier (a) X-axis displacement (b) Normalized x strain

- Calibration and pattern deployment are important to the performance of DIC. Various pattern deployment schemes (e.g., physical painting, optical laser projecting) were investigated and tested. Optical laser projecting scheme is applicable and uses only few reference marks on the surface of structures.
- Laboratory and field FOS measurements show good agreement with the DIC result, suggesting the robustness of DIC.
- Multi-modal laboratory RC beam tests using CWIR, DIC, and FOS demonstrated a consistent, repeatable coupling pattern (Figure 4) between the electromagnetic (CWIR) and mechanical responses of a RC beam. The local mechanical response (stress/strain) of a RC beam can be related to the global behavior of the beam.

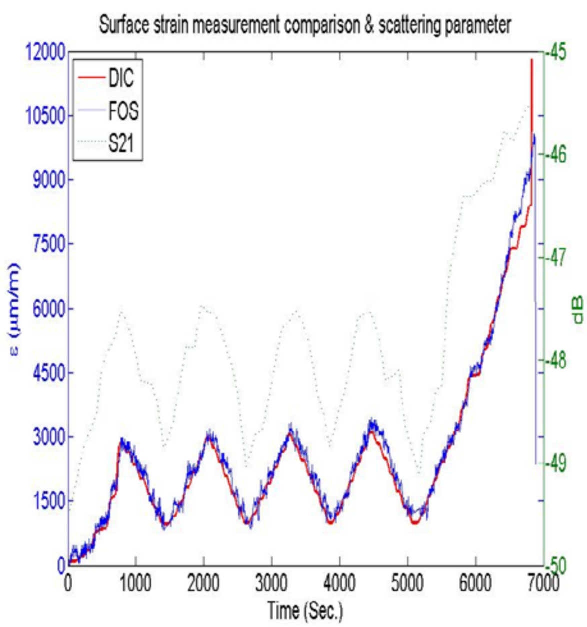

Figure 4: Coupling of CWIR, DIC and FOS measurements of a laboratory RC beam under cyclic loading

Products & Outcomes

Developed products from the MRSS project mainly include a portable CWIR/DIC system (Figure 5), a User's Manual, laboratory and field test reports of MRSS, numerical simulation reports (radar signal propagation), and CWIR software. We are also working with MassHighway (MassDOT) on applying our system to few selected damaged RC highway bridges.

Figure 5: Portable MRSS hardware (a) Portable CWIR (b) Portable DIC

Post Project Initiatives

The research team is in the process of applying for one or two patents (one for CWIR concept, one for mechanical/ electromagnetic coupling) incurred from the project. The team has worked with Trilion Quality Systems in commercializing the portable DIC system as a product (now available in the market), and we are also working with the Office of Commercial Ventures & Intellectual Property at UMass Lowell to convert the third generation of CWIR into a commercial product (fourth generation).

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Quantitative Sensing of Bridges, Railways, and Tunnels with Autonomous Unmanned Aerial Vehicles

University of Massachusetts – Lowell

Executive Summary

An unmanned aerial vehicle system (UAV) was developed to autonomously interrogate numerous areas on civil structures without requiring expensive, time consuming aerial lifts or inconsistent visual inspections. The sensing platform includes innovative continuous wave imaging radar, digital image correlation, and 3D photogrammetry to monitor structures or quantify damage. The sensing approach provides accurate large area interrogation of bridges, using a quad-rotor aircraft capable of operating in global positioning system (GPS)-available and GPS-denied environments. This project has enabled the next generation of rapid inspection and evaluation of bridges, railways, and tunnels. Figure. 1 illustrates the concept of this research.

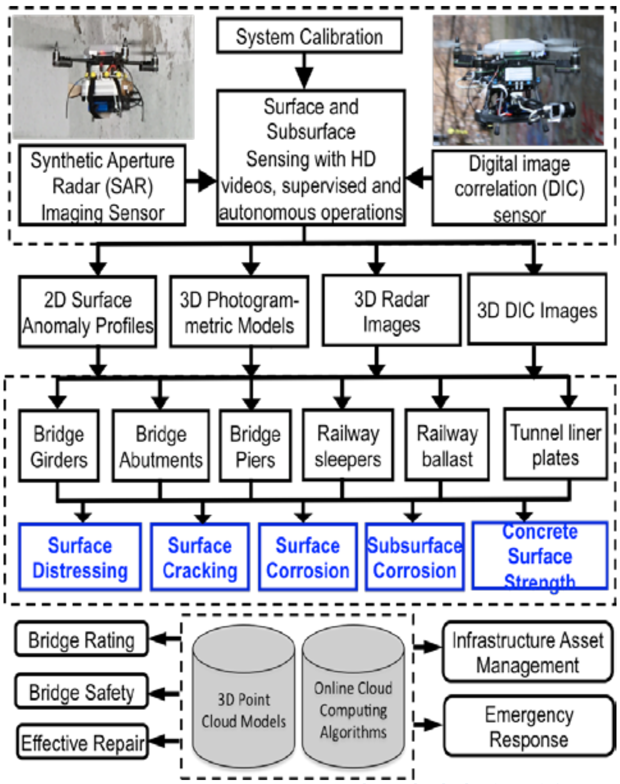

Figure 1: Quantitative Autonomous Unmanned Aerial Vehicles (QUAV) for Bridges, Railway, and Tunnels

The UAV sensing system was successfully applied to highway bridges, rails, and tunnels in Massachusetts. 3D point cloud models of inspected structures, containing surface and subsurface images for condition assessment, were developed for decision makers and stakeholders. This project was disseminated through numerous national and international conference presentations, as well as conference and journal publications.

Findings & Outputs

Major research results and findings are summarized in the following:

- The use of high definition videos to construct 3D point cloud models using 3D photogrammetry demonstrated as a promising tool for rapid prototyping and modeling of infrastructure systems.
- A wireless digital image correlation (DIC) sensor was applied to the long-term monitoring of local and highway bridges and successfully identified the locations of surface distressing and concrete spalling.
- A wireless synthetic aperture radar (SAR) imaging sensor was developed for the subsurface sensing of concrete structures. Experimental results on bridges demonstrated its capability to locate subsurface steel rebars inside bridge abutments and piers from 6 ft (2 m). The SAR imaging sensor was also applied for surface geometric characterization of concrete structures and to successfully detect and locate concrete cracking.
- The developed wireless SAR imaging sensor was also used for estimating the surface mechanical strength of concrete bridges. A semi-empirical model was proposed to predict surface strength of concrete using SAR images. This new finding has the potential to significantly accelerate conventional bridge rating procedures by surface strength mapping/profiling of concrete bridges.
- A new UAV platform (quad-rotor) was developed for enabling the autonomous inspection of bridges, railway, and tunnels, using a wireless SAR imaging sensor and a DIC sensor. This platform was field tested in both GPS-available and GPS-denied environments.
- Laboratory and field test results demonstrated that 3D photogrammetry can be used as a reliable tool to integrate SAR images with DIC images. 3D point cloud models of structures provide a versatile platform for integrating spatial results of different sensors. These can also be used in infrastructure asset management (e.g., Pontis).

The research results have been presented in several national and international conferences (e.g., SFR, SPIE SS/NDE, SAGEEP) and received many inquiries about system integration and data interpretation. Eighteen peer-reviewed journal and conference articles have been published from this work. The above outcomes extensively disseminated the research results to nationwide transportation agencies and researchers, and promoted the use of CRS&SI technologies (e.g., imaging radar, DIC, 3D photogrammetry) in transportation.

Products & Outcomes

2D SAR images and 3D DIC images of structures are integrated in 3D point cloud models rendered in commercially compatible formats (*.xyz, *.wrl, *.stl, *.3ds, *.obj). These 3D point cloud models can be easily accessed by AutoCAD, MicroStation, and BIM (Adobe) software packages, allowing state highway departments to adopt them into their existing inventory management systems. In addition, integrated 3D point cloud models can easily be converted into documents and multimedia (e.g., videos) files for better data visualization. Figure 2 provides examples of 3D point cloud models and radar and DIC images. A graphic user interface (GUI) was developed for end users to access the infrastructure inventory database and data visualization (Figure 3).

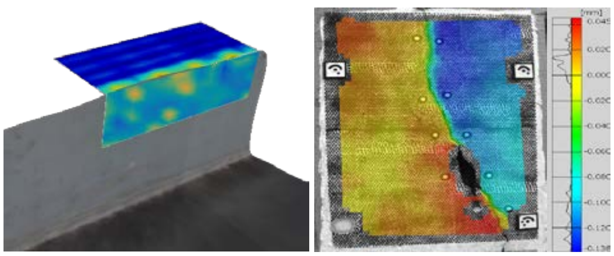

Figure 2: Integrated 3D point cloud model with SAR images (left); DIC image for crack growth monitoring

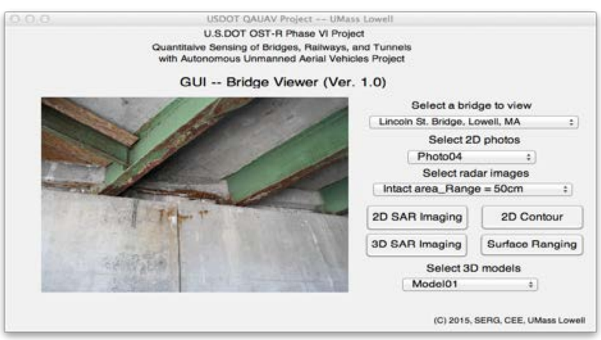

Figure 3: GUI – Bridge Viewer version 1.0

An integrated UAV sensor (Figure 4) designed to operate in a GPS-denied environment was also developed as part of the project.

Figure 4: Integrated UAV sensor operating in GPS-denied environment

Post Project Initiatives

Some major initiatives resulted from the successful completion of this research project are as follows:

The Team was invited by interested nondestructive testing and structural health monitoring companies including Simpson, Gumpertz, and Heger Corporation (Waltham, MA) and Nobis Engineering, Inc. (Lowell, MA) for possible collaboration on using UAV to inspect roadway pavements and bridges.

The Team was invited by Geophysical Survey Systems, Inc. (Nashua, NH) for possible collaboration on developing UAV for ground penetrating radar systems.

To study the long term deterioration of critical civil infrastructure in Massachusetts, the PI and his research team has been continuously monitoring and collecting SAR images and DIC images on US 3 since 2011. An aging model of concrete bridges will be proposed and reported in the near future.

The research outcome was presented at the 2017 TRB annual meeting and will be presented in SPIE SS/NDE conference in 2017.

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Automated Scour Detection Arrays using Bio-Inspired Magnetostrictive Flow Sensors

Michigan Technological University

Executive Summary

The project demonstrated the use of automated magnetostrictive scour sensor whisker arrays for bridge piers, bridge abutments, and for monitoring of bank stability. Data collected by the sensors were processed remotely and information about the state of scour determined by the sensors was then relayed to bridge owners via cellular data link. Data retrieval and visualization tools were intrinsic to the project to support decision making by bridge owners in management and maintenance decisions. This project tested the ability of the system to detect scour and develop the decision support engine to aid bridge owner make cost effective maintenance decisions.

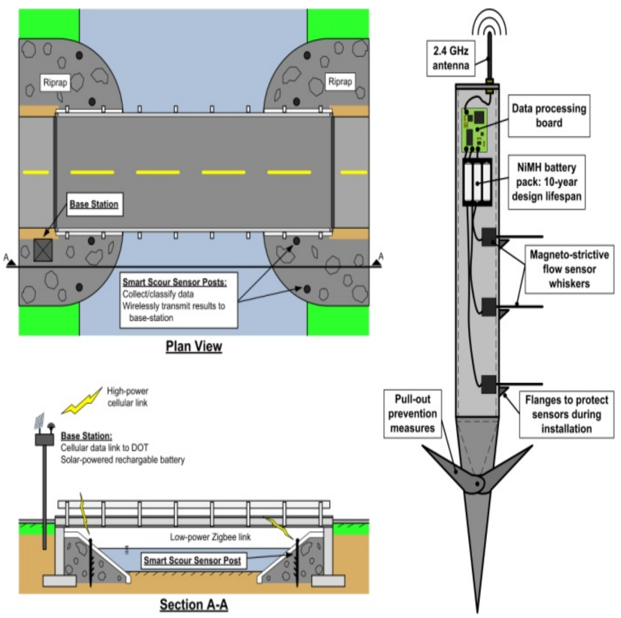

Figure 1: Modular scour detection system deployment around bridge abutments

The whisker-inspired flow sensors were constructed using the magnetostrictive Galfenol wire developed at the University of Maryland. One end of each Galfenol whisker was installed fixed, with the other end free to deflect under fluid flow-induced drag forces, as seen in Figure 1 above. The bending-induced stress near the fixed end of the whisker produces local changes the magnetic domain orientation, which is accompanied by a global change in the magnetic flux density in the whisker. This change was measured using a giant magnetoresistance sensor at the fixed end of whisker.

The objective of this project was to test and deploy an embedded array of sensors located on or near the outer surface of the bridge foundations, at varying heights, that could determine the sediment depth and profile around the foundation in real time. The sensor array was composed of bio-inspired, whisker-shaped magnetostrictive flow sensors that are highly rugged and detect water flow by bending. Those sensors located above the sediment level were free to move with the current flow and yielded dynamic flow measurements. Those sensors located below the sediment line were trapped and returned only static measurements. Knowledge of sensor depth was used to determine the sediment level in real time. An automated data acquisition base station monitored sensor signals from above the water line, differentiating between static and dynamic sensor readings, estimating the sediment and water line elevations, monitoring for sensor failure, and sending scour alerts to relevant authorities to be visualized using the decision support engine (Figure 2).

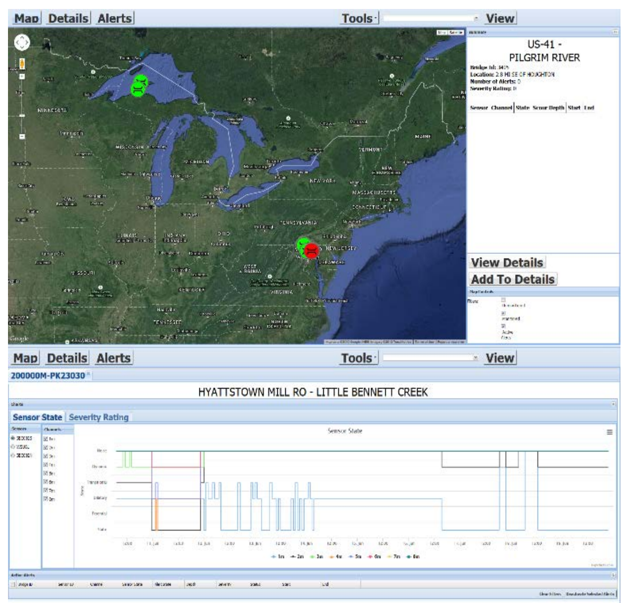

Figure 2: Remote data visualization decision support client

To make installation of scour sensor elements as practical as possible, modular sensor units, known as “smart scour-sensing posts” were used in this project. These modular units, shown in Figure 1, consist of several magnetostrictive transducer elements, embedded data collection and interrogation electronics, a wireless communication interface, and a long-lived battery pack packaged in a galvanized steel post that can be driven into the ground near abutments, culverts, and in embankments. These devices were made to be wireless to eliminate the need to run signal cables in the vicinity of the bridge. They utilized low-power wireless signal networks (*e.g.*, Zigbee) to communicate with local base stations that aggregated the data from multiple on-site posts and send it via cellular data link to remote users.

Findings & Outputs

Key components of the research program were to demonstrate the efficacy of the proposed system, understand user needs, and calibrate detection algorithms. A laboratory research test program to demonstrate the ability of the system to detect scour conditions and to provide initial calibration data was initiated in a controlled scour flume (Figure 3) environment. Transitions from buried to unburied conditions were initiated and detected by the monitoring system. Automated change detection algorithms were tested in the laboratory environment as well, establishing thresholds for signal levels to discern between low-level flow activity and electrical noise through examination of whisker output signals in the frequency domain. Remote hardware needed to aggregate field scour detection information was constructed and programmed to allow the system to communicate autonomously with bridge owners and provide information to be displayed in the decision support system. Whisker corrosion protection and robustness studies were also conducted to enhance the lifespan of whisker sensors.

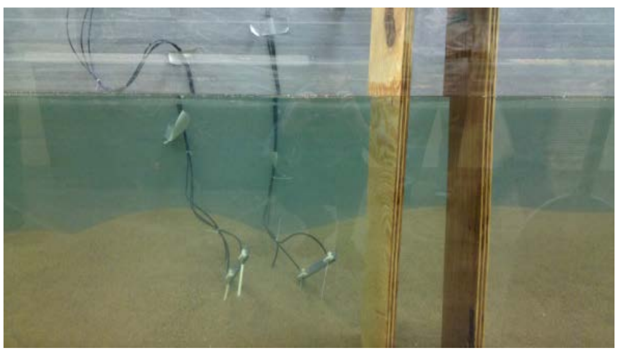

Figure 3: Laboratory scour flume study using magnetostrictive flow sensors

Products & Outcomes:

The project delivered a working prototype system installed in a number of bridge sites in Michigan and Maryland. The prototype system included a mix of whisker and seaweed sensor types, scour posts (Figure 4) using wired and wireless communication approaches, remote data collection base station hardware with necessary firmware, and a decision support interface to view scour information collected for the bridges in the instrumented network. Future work will focus on characterizing the longevity of the various transducers used and the ability of the system to measure scour in low-flow conditions.

Figure 4: Modular scour detection posts

Post Project Initiatives:

Efforts have been undertaken to patent applicable technologies developed as part of this study in order to make them attractive as a commercial product. A start-up venture, Tarous Engineering, has also been initiated as a means to bring this technology to market and make it available for state DOT agencies to use. Integrated systems that can be installed and operated with minimal cost and effort to the bridge owner are envisioned and commercial products in the years following the conclusion of the project. Integration of the remote scour sensing and information collection system with other bridge and roadway information is also envisioned integrating traffic flow, bridge icing, SHM, and other time sensitive information into the decision support client in order to provide additional value to DOT agencies is a priority.

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Bridge Condition Assessment Using Remote Sensors: 3-D Optical Bridge-Evaluation System

Michigan Technological University

Executive Summary

Managing an aging infrastructure continues to be a challenge for transportation authorities as they align asset management and replacement priorities with limited funding. The United States is home to over 600,000 highway bridges, of which nearly 10% are structurally deficient. This project, funded by the U.S. Department of Transportation (USDOT) through the Commercial Remote Sensing and Spatial Information (CRS&SI) Program, focused on the applicability of low cost, commercially available remote sensing technologies for assessing the condition of bridges.

Numerous remote sensing technologies were evaluated for their ability to measure associated high priority challenges at specific superstructure zones. Ranking criteria included commercial availability, measurement capabilities, cost, ease of data collection, complexity of analysis, stand-off distance and traffic disruption. Remote sensing technologies that scored as most promising included optical photogrammetric methods, passive infrared (IR) thermography, Light Detection and Ranging (LiDAR), digital image correlation, ultra-wide band imaging of ground penetrating radar, synthetic aperture radar (SAR), and multispectral satellite imagery.

Based on these ranking results, promising technologies and systems were further developed, evaluated, and compared to ground truth (e.g., hammer sounding, chain drag) via laboratory and field testing on in-service Michigan bridges. Spall and delamination maps were generated from the optical and thermal IR images using commercial software and an automatic detection algorithm. Integration of the maps into ArcGIS allowed for a streamlined analysis that included integrating the results of the complementary technologies, including visual inspection and ground truth results.

There have been several successful outcomes, including a demonstration Decision Support System to integrate traditional inspection reports with remote sensing bridge condition data in a user-friendly, map-based interface. Another successful outcome has been development of the 3-D Optical Bridge-evaluation System (3DOBS), an easily deployable system used for rapidly assessing surface condition indicators such as the location, area, and volume of spalls. Several initiatives have been inspired and guided by these outcomes.

Findings & Outputs

As a result of lab and field testing, 3D optical technology could be applied to high-resolution, automated spall detection for concrete bridge decks. Early testing used a standard high-resolution digital camera (DSLR) to collect overlapping imagery, and 3D modeling software to create a sub-centimeter resolution Digital Elevation Model (DEM) of the surfaces (Figure 1). From this, the 3D Optical Bridge-evaluation System (3DOBS) was developed for demonstration and implementation.

Figure 1: High-resolution 3DOBS output of cracks and spalls

3DOBS was developed into a vehicle-mounted system that elevates the DSLR above a bridge deck so that at least one full lane width is within the field of view. Overlapping imagery is collected and processed through close-range photogrammetric software to produce DEMs of the bridge deck. The DEM is then run through an automated spall detection algorithm, which detects all spalls that are a minimum specified size and generates a GIS layer showing the location of the spalls on the bridge deck. This software allows the user to choose the minimum size of the spalls to be detected and to mask out bridge joints.

Products & Outcomes

All deliverables and reports from the original USDOT project are available at (http://mtri.org/bridgecondition/). The deliverables include reports on the "State of Practice", "Commercial Sensor Evaluation" and findings from the field demonstrations of each of the remote sensing technologies that have become frequently cited sources. The final report is also posted at the website. Included are summaries of the development and testing of the initial version of 3DOBS and the Bridge Condition Decision Support System (BCDSS), two major products that came out of the USDOT/CRS&SI project.

Post Project Initiatives

Following the successful outcomes of the USDOT/CRS&SI project, the Michigan Department of Transportation (MDOT) supported several additional initiatives in partnership with Michigan Tech. *Evaluation of Bridge Decks using Non-Destructive Evaluation at Near-Highway Speed* (MDOT Report RC-1617, 2015) continued development of the 3DOBS system so that it could operate at near-highway speeds (>45 mph) while integrating thermal IR bridge delamination detection technology as shown in Figure 2.

Figure 2: 3DOBS mounted alongside a thermal camera and GPS system on the BridgeGuard van

With upgrades to the RED camera, the system can capture imagery up to 60 frames per second at “8K” (33 megapixel resolution). Both the RED and thermal cameras are mounted underneath a high accuracy Trimble GPS. The GPS track log is used to geotag the extracted RED image frames to georeference a base ortho image on which all other data can be overlaid. Outputs include detected spalls and potential delaminations layers, an ortho image, a DEM of the bridge deck, and a mosaicked thermal layer. All of the outputs can be viewed in a GIS such as ArcGIS.

A follow-on initiative included a pilot study to evaluate six large deck bridges in southern Michigan with a deck surface area greater than 90,000 sq. ft. Data collection was completed on all six bridges within one week with minimal traffic disruption. Figure 3 is an example of the combined RED imagery of 8 Mile Rd, which is used as the base layer for other data outputs. Condition states are generated per span based on NBI deck rating criteria (MDOT Report RC-1617B, 2016). A third phase funded in 2016 includes field deployment at near-highway speed and training for MDOT inspectors on in-service bridges using the upgraded 3DOBS system.

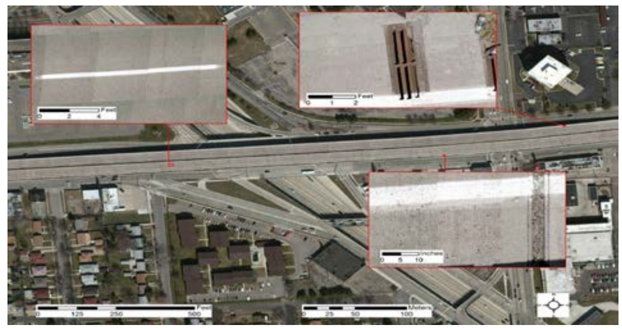

Figure 3: High resolution mosaicked image of the 8 Mile Rd. bridge over M-10 referenced over Bing Maps imagery

These remote sensing technologies have further been deployed through two unmanned aerial vehicle (UAV) research initiatives with MDOT. Five UAV platforms combined optical, IR, and LiDAR sensors to assess critical transportation infrastructure, including bridges, confined spaces, traffic flow, and roadway assets (*Evaluating the Use of Unmanned Aerial Vehicles for Transportation Purposes*, MDOT Report RC- 1616, 2015). The newest MDOT UAV initiative enhances the previous UAV project by developing near-time data collection and storage concepts for the most viable UAV platforms and sensing technologies. Activities also include pilot projects to deploy and implement on-board sensors for specific MDOT business practice applications.

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Sustainable Geotechnical Asset Management along the Transportation Infrastructure Environment Using Remote Sensing

Michigan Technological University

Executive Summary

This project developed a novel approach for the geotechnical asset management using remote sensing techniques. The project outputs provide a cost-effective solution for the transportation agencies to measure the state of geotechnical assets using remote sensing technologies, relate the acquired data to obtain information on the condition of the asset, and further utilize this for strategic investment to achieve life-cycle performance goals of the asset.

Current management practices for geotechnical assets along the transportation environment focuses on restoration of the asset after failure, instead of identifying and remediating hazardous conditions before their occurrence. The reason for the lack of proactive geotechnical asset management systems is because geotechnical assets are extensive, and assessing their condition using traditional site inspections by trained engineers is laborious and costly. However, recent advancements in commercial remote sensing (Interferometric Synthetic Aperture Radar (InSAR), Light Detection and Ranging (LiDAR), and optical photogrammetry) provide opportunities to obtain precise displacement measurements, which could provide a valuable alternative to traditional site inspections. These measurements, and asset conditions can be integrated into a decision support system to assist managers to make investment decisions.

Findings & Outputs

The findings and outputs are as follows:

- A survey of State Department of Transportation agencies indicated that: (1) asset monitoring and maintenance are conducted in a reactive way, and (2) the most common asset monitoring method is through visual inspection.
- Remote sensing techniques – such as InSAR, LiDAR, and optical photogrammetry – are capable of measuring displacement rates across geotechnical assets (Figure 1), but at different spatial resolution and temporal frequency.
- A wide range of surface displacement measures can be captured with different remote sensing methods. InSAR is capable of measuring ground motion at the mm/year-scale (Figure 2), while LiDAR and optical photogrammetry can detect 1-2 cm of movement between data acquisitions.
- Displacements measured across geotechnical assets provide indirect information about the asset's condition.

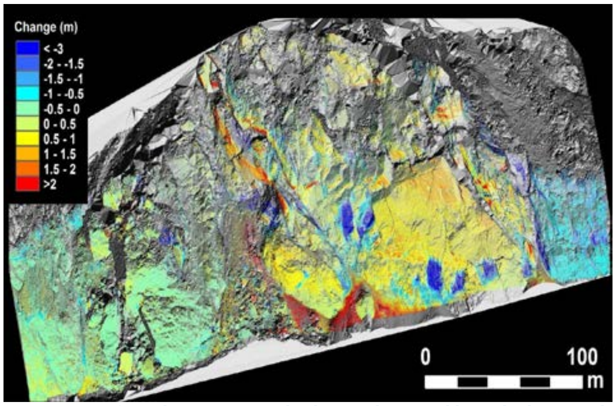

Figure 1: Surface changes perpendicular to the unstable rock slope at the Nevada test site, derived from LiDAR data

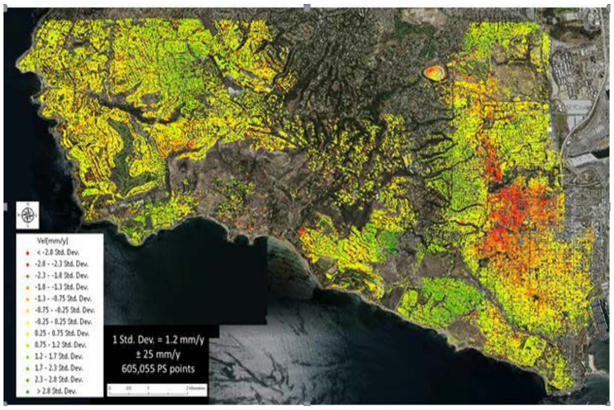

Figure 2: InSAR stacking results over the Palos Verdes Peninsula using 40 COSMO-SkyMed images (July 2012 – September 2014).

Products & Outcomes

The products and outcomes are as follows:

- A decision support system was developed to provide a useful tool for visualizing and analyzing data in a geographic information system environment (Figure 3).

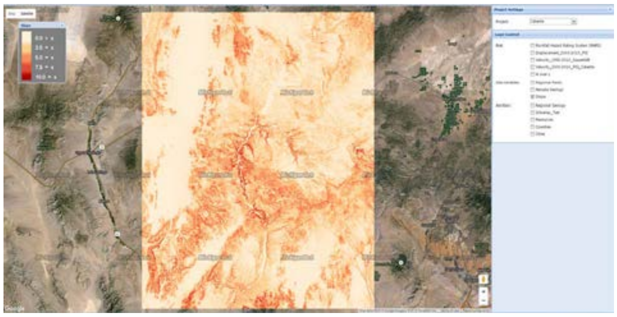

Figure 3: Slope map of the Nevada test site in a web interface decision support system

- A cost-benefit analysis was conducted to highlight how financial spending affects output data quality based on each remote sensing technique.

- A remote sensing implementation framework was created to demonstrate how remote sensing techniques can be used towards geotechnical asset management.
- Outreach activities were conducted to generate awareness about evolving geotechnical asset management approaches and the use of remote sensing technologies. These include:

  a) Developed video presentations to convey the use and benefits of remote sensing technologies and methods for geotechnical asset management:- http://www.mtri.org/geoasset/outreach/
  b) Published numerous technical journal and magazine articles to disseminate results and findings of the research work to the technical community.
  c) Trained 2 M.S, 1 Ph.D. student, and 1 Post-doc all from racial and ethnic minority groups to develop workforce for geotechnical asset management using remote sensing.
  d) A project website is maintained to disseminate the reports and deliverables at the following link:- http://www.mtri.org/geoasset/
  e) In excess of 15 conference presentations were conducted including two invited talks to share projects results with potential users in academia and industry, and to provide an alternative approach to disseminate the results to a broader audience.

Post Project Initiatives

The project Team is currently working with Washington State Department of Transportation, Alyeska Pipeline Company and the World Bank on advancing the commercial application of remote sensing for geotechnical asset management.

The World Bank organization has funded a pilot project to apply some of these techniques to landslide management along the Salang Highway and the Baghlan to Bamiyan road in Afghanistan.

Dr. Thomas Oommen is presenting an invited keynote to building resilience to landslide and geo-hazard risk in the south Asia region World Bank program, on "Geotechnical Asset Management and Tools: Global and U.S. Federal Highway Experiences." This is part of the First annual south to south learning workshop in Kandy, Sri Lanka, November 15-17, 2016.

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Characterization of Unpaved Road Conditions Through the Use of Remote Sensing

Michigan Technological University, Michigan Tech Research Institute

Executive Summary

The Federal Highway Administration stated in 2012 that there are over 1.4 million miles of unpaved roads in the United States, over 1/3 of the U.S. total. Unpaved roads are a critical transportation resource that provides both rural and suburban transportation networks, including farm-to-table transition of food resources, getting children to school, and emergency routing after natural disasters, among many other uses. Unpaved road management is often the responsibility of local governments and transportation agencies, which are in need of rapid, repeatable, and objective methods that are cost-efficient and easily deployable in a budget-limited environment.

The objective of the project was to first develop a remote sensing system which would automatically characterize unpaved road distresses such as potholes, washboarding, rutting, and measuring the crown.

This project lead to development of the Aerial Unpaved Road Assessment (AURA) system (Figure 1). AURA is an Unmanned Aerial Vehicle (UAV) based system which collects stereo-overlapping imagery (Figure 2) of the roads surface and then is processed into condition data which is easily displayed in a GIS.

Figure 1: The selected hexacopter Bergen Hexacopter UAV taking off to collect data

Figure 2: Example high-resolution image of unpaved road with pothole and washboarding distresses

Findings & Outputs

Based on recommendations from the project's Technical Advisory Committee outlined in the requirements, platform, and sensors deliverables, the AURA system was developed around the Bergen Hexacopter UAV and Nikon D800 DSLR camera. This combination resulted in the 3D models of unpaved roads being reconstructed with a ground sample distance of 1cm from a collection altitude of 25m (Figure 3).

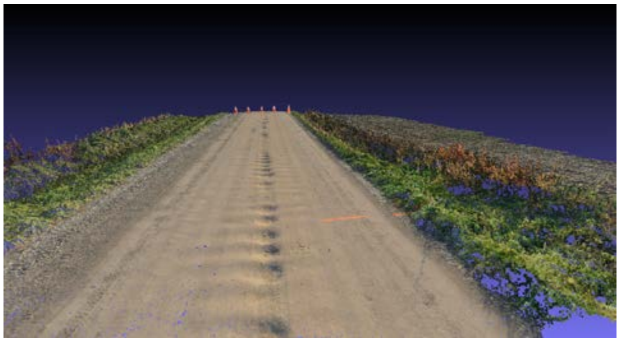

Figure 3: 3D point cloud of an unpaved road derived from UAV-enabled road digital photos

Collected imagery was processed through the Remote Sensing Processing System (RSPS) which created a 3D model of the roads surface using Structure from Motion algorithms and then ran multiple distress detection algorithms developed by project researchers to locate and categorize each road distress type. Figure 4 shows a Digital Elevation Model (DEM) in which potholes were automatically identified and then rated for severity.

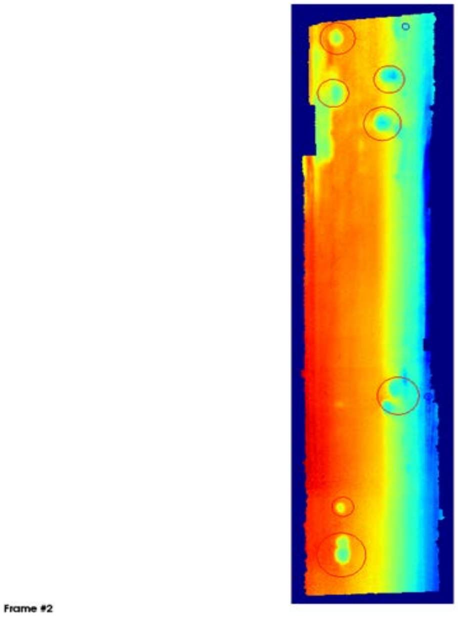

Figure 4: Detected potholes are identified by red circles on the DEM

The RSPS provides the user with a compact XML file of the distress type and severity results which can be easily imported into a Decision Support System such as the RoadSoft GIS software (Figure 5) and other GIS tools that can use linear referenced road systems.

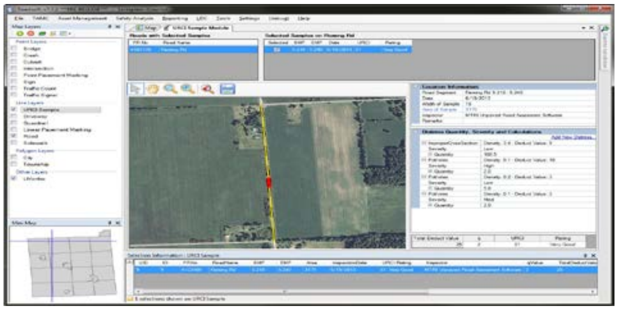

Figure 5: UAV-derived unpaved road condition data integrated into the RoadSoft GIS decision support and asset management tool

Outreach and commercialization were the focus of Phase II of the project. This included two technical field demonstrations, multiple web videos, handouts, and three webinars organized with the help of Integrated Global Dimensions. The field demonstrations were held in Salina, KS and Rapid City, SD (Figure 6). These demonstrations were attended by local and state transportation managers as well as businesses interested in commercialization. These demonstrations and webinars served to increase awareness and interest in the AURA system and to make contacts with companies which would be interested in commercializing the technology and offer it as a service.

Figure 6: Attendees at the technical field demonstration held in Salina, KS

Products & Outcomes

Several reports were developed on the state of practice, candidate platform and sensor evaluations including describing multi-rotor vs. fixed wing UAV options, commercial demonstrations and outreach activities. Phase I and II final reports were also developed and all 20 deliverables and reports from the project are available at http://mtri.org/unpaved/.

Post Project Initiatives

Due to the success of the field demonstrations, webinars, and related outreach activities, several companies have shown interest in licensing AURA. On the international market, Grupo Engemap of Brazil has licensed access to the AURA system for the South American market. Woolpert Inc. of Dayton, Ohio tested the AURA system for commercial evaluation of gravel mining haul roads in Ohio. Michigan Tech is currently (Dec. 2016) in negotiation with a North Carolina-based company for domestic and international access to the AURA system analysis capabilities through a web-based interface. Companies in Arizona and Nevada are looking for opportunities to apply the AURA system. In the fall of 2016, companies in India and Australia have reached out to the project team to start offering automated unpaved road assessment.

As part of these efforts, the project team is working on increasing the speed and flexibility of the distress detection and rating algorithms so they can be run commercially through the web. The project team remains committed to the long-term commercial implementation of UAV-based assessment of unpaved road condition.

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Health Assessment and Risk Mitigation of Railroad Networks Exposed to Natural Hazards using CRS&SI Technologies

University of Michigan

Executive Summary

The overarching goal of this project was to integrate data from commercial remote sensing and spatial information (CRS&SI) technologies to create a novel data-driven decision making framework that empowers the railroad industry to monitor, assess, and manage the risks associated with their aging bridge inventories, especially those exposed to natural hazards. Among the CRS&SI technologies explored, wireless sensing was a primary focus. As shown in Figure 1, wireless monitoring systems were designed and deployed to monitor railroad bridges exposed to train and environmental loads. Coupled with structural inspection data, wheel impact load detection data, and train location data, the wireless monitoring data was interrogated to assess train loads on bridges, assess the health and reliability of bridges, and quantify the consequences of exceeding performance limit states. A data-to-decision framework was established to automate the processing of the CRS&SI data to convert it into actionable information that empowers risk-based decision-making. The Team partnered with Union Pacific Railroad (UPRR) who provided access to operational railroad bridges, data and expertise. The project instrumented the Harahan Bridge and the Parkin Bridge in the New Madrid fault zone for demonstration of the system.

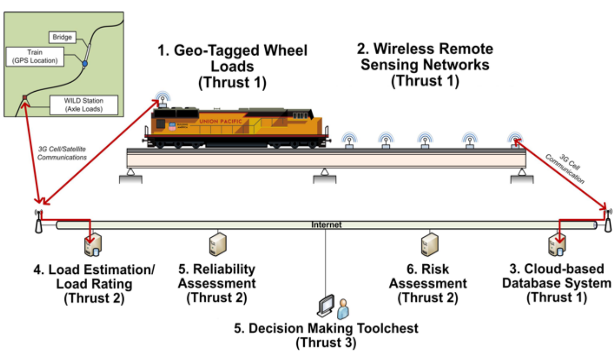


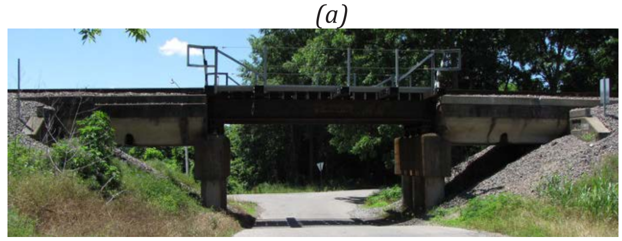
Figure 1: Overview of Project Framework

Findings & Outputs

This project produced a large number of critical findings that advanced the use of CRS&SI technologies for risk management rail bridges:

- Two permanent wireless monitoring systems were designed and deployed on the Harahan (Memphis, TN) and Parkin (Parkin, AR) Bridges. These bridges are critical elements of the Memphis sub-junction and were selected due to their exposure to natural (e.g., seismic, aging) and man-made (e.g., vehicular collisions) hazards. The Harahan (Figure 2a) and Parkin (Figure 2b) Bridges were instrumented with 36 and 30 wireless sensing channels, respectively, ranging from strain to acceleration measurements. As part of these monitoring systems, a real-time alert service was implemented to provide email alerts to UPRR engineers and inspectors regarding structural responses exceeding pre-defined response thresholds.

(a)



(b)

Figure 2: (a) Harahan Bridge (Memphis); (b) Parkin Bridge (Parkin, AR)

- A relational database was developed to provide a comprehensive data repository to store inspection data, CRS&SI sensor data and analytical models of railroad bridges. Unifying these three forms of data/information empowers more extensive data analysis to assess the health of railroad bridges and aid railroads with risk management of their networks.
- A reliability framework was created to assess the health of bridge components monitored. The reliability index calculated using the first-order reliability method was found to be an ideal scalar metric for assessing component health. Lower limit states were defined to trigger inspection and maintenance of bridge elements using monitoring data. The reliability index, when coupled with the consequences of exceeding defined limit states, allows owners to assess and manage the risks associated with their bridges and rail networks. The reliability framework was successfully validated on the Harahan Bridge.
- The loads imposed on short-span rail bridges were quantified using long-term monitoring data.

Specifically, the maximum static response and dynamic load factor as a function of train velocity were assessed for the Parkin Bridge. A novel approach to bridge load rating was developed using structural monitoring data; results indicated AREMA-specified load rating procedures are likely conservative for well-maintained rail and bridges.
- An extensive return-on-investment analysis was performed to assess the return rate for railroads that elect to invest in structural monitoring systems. Using the data-driven load rating methodology developed, the revelation of greater bridge capacity allows railroads to carry larger loads at higher train velocities. This ensures the return on investment is positive and reaped rapidly after technology adoption.

The research effort also resulted in scholarly publications including four conference proceeding and two journal papers. Members of the research team provided sixteen presentations in which aspects of the research effort in advancing CRS&SI technologies were presented to broad set of audiences across the United States.

Products & Outcomes

A key objective of the project was the development of a commercialization plan for the CRS&SI technologies developed. The commercialization plan was produced based: market analysis, interviews with prospective technology adopters, and feedback provided by the project Technical Advisory Committee. The market analysis indicated a robust market both domestically and internationally for data-driven risk management methods based on CRS&SI data. Specifically, Class I and II railroads were identified as prospective customers domestically. However, interviews with technology adopter revealed a strong preference for short-term monitoring due to the perceived high costs associated with placing permanent monitoring systems in the field. Based on this feedback, the team devised a go-to-market strategy centered on short-term monitoring. A rapid-to-deploy commercial solution based on Civionics' wireless monitoring system and the Prospect Solutions' Decision Making Toolchest was developed.

In partnership with the Transportation Technology Center, Inc. (TTCI) in Pueblo, Colorado, the Team validated the commercial system using a short-span steel girder bridge loaded under a controlled loading regime (Figure 3). A wireless monitoring system measuring bridge strain and accelerations was deployed in minimal time and at minimal cost. Monitoring data was used to assess the load rating of the bridge using the data-driven load rating method developed by the team.

Figure 3: Civionics Wireless Sensor Node on TTCI bridge

Post Project Initiatives

The Team is currently pursuing opportunities in the marketplace to recruit additional customers. In addition, the team is continuing to work with TTCI on technology refinement and adoption. Finally, venture funding is being sought by the commercial team members to accelerate the marketing of the system and to refine its analytical capabilities.

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Developing a Real-Time Incident Decision Support System (IDSS) for the Freight Industry

University of Minnesota

Executive Summary

Delays to truck movement are of particular concern to the nation. In this research effort an Incident Decision Support System (IDSS) was developed that uses GPS-equipped commercial trucks as probe vehicles on key freight corridors in Minnesota using an automatic incident detection algorithm. The objective of IDSS is to detect incidents and provide incident information in real-time to truck operators on rural corridors where infrastructure-based sensing is unavailable. A bivariate incident detection methodology was developed by using the travel time computed from raw GPS truck data and the travel time difference between the current interval and the previous interval for each roadway segment.

A pilot implementation was developed to demonstrate a concept of operations for the IDSS, in which incident information is provided to truck operators. The pilot implementation used available archived data for demonstration purposes. Many traveler information systems provide incident alerts to drivers based on reports by travelers, or by the incident responders. Most incident detection methodologies have been developed based on sensors at a fixed location. This approach based on probe vehicle data can detect traffic disruption automatically and alert vehicle operators of incidents ahead, especially useful for roadways without instrumentation and roads that are lightly travelled.

Findings & Outputs

Key research results and findings are highlighted as follows:

- An incident detection methodology was developed using bivariate analysis and outlier detection. On average, the probe vehicle based bivariate methodology tends to over-predict the occurrence of an incident as compared to the reported incident reports from the state patrol. The over-prediction rate ranges from 8 to 19% for the top 6 most frequent incident types. The over-prediction may result from scenarios when a shock wave occurred but no incidents were reported. The detection results using bivariate methodology improves when the sampling frequency of probe vehicles or the number of probe vehicles increases.
- A prototype IDSS was developed for pilot implementation. Figure 1 illustrates the functions and data flow for the pilot implementation. Block A represents a user's device (a smartphone or some other in-vehicle device) that has the capability to automatically determine the user's location and heading using GPS. Block B is a database and web server that hosts the incident information (timestamp, location, and heading) resulting from the truck GPS data processing and analysis as displayed in Block C. Block C will continuously process incoming GPS data for incident detection. If an incident is detected, the results will be sent to the incident database residing in Block B.

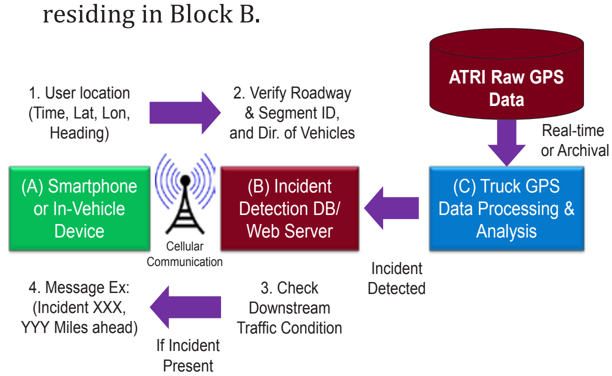

Figure 1: Functionality Block Diagram of Incident Decision Support System (IDSS)

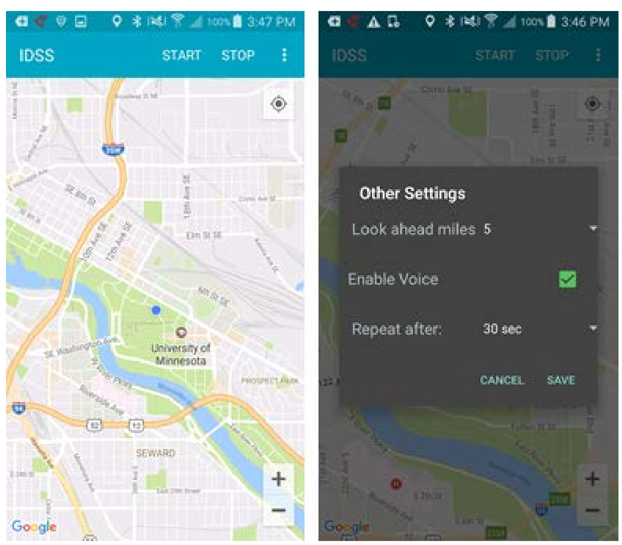

Figure 2: Screenshots of Smartphone App for IDSS

- A mechanism for providing the information to the user was tested. An Android application (Figure 2) and web services were developed to implement the IDSS. The smartphone determines its current latitude-longitude and heading. The information together with the current timestamp is submitted to a web interface to determine the roadway and segment where the user is currently located. Roadway ID, segment ID and direction information is used to query incident formation from the

database. The IDSS then checks the downstream traffic condition if there is any incident along the roadway on which the operator is traveling.
- The smartphone App was tested on a passenger vehicle driving on I-94 WB near the University campus in Minneapolis where an incident occurred according to the historical data. A few historical incidents were identified for testing and validation purposes. Time on the smartphone App was set to a timestamp based on the archived data when an incident occurred. As the test vehicle drove toward a location where the incident occurred, the App successfully detected the available incident information through the web server and announced the corresponding information (where and when) to the driver during the experiments. For example, when an incident is detected, the App announces "*incident occurred 5 miles ahead 19 minutes ago on Interstate 94*".

Products & Outcomes

An Android App shows the current location on a Google map and updates it positions as the current location of the user changes. As the location is updated, the application sends its location and date-time data to the server to get information about any incidents that might have taken place on the route that the user is travelling. The application provides settings to adjust date, time, look-ahead distance, test-to-speech settings etc.

A web service middleware and a database server were developed to support the Android application. The middleware receives the request from the App and then establishes a communication connection with the incident detection database server.

Post Project Initiatives

The following are some major initiatives resulted from the completion of this research project:

- A project titled "Measure Truck Delay and Reliability at Corridor Level"' was sponsored by Minnesota Department Of Transportation to use performance measures for assessing impact of truck congestions and identifying operational bottlenecks or physical constraints. Trucking activity nearby a congested area will be further examined to analyze traffic pattern and investigate possible causes of recurring congestions. Recommendations for potential mitigation solutions will also be developed to improve system performance for all users.
- As a result of previous freight related studies, Dr. Liao & Dr. Hourdos from the UMN Minnesota Traffic Observatory will be partners of the Freight Mobility Research Institute Team, recently awarded by the USDOT as a Tier 1 University Transportation Center led by Florida Atlantic University. Further freight related research to improve mobility and mitigate truck delay and congestion will be conducted in the next 5 years.

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Smart Rock Technology for Real-time Monitoring of Bridge Scour and Riprap Effectiveness – Design Guidelines and Visualization Tools

Missouri University of Science and Technology

Executive Summary

Scour is responsible for more than half of the bridges collapsed in the U.S. Scour monitoring with fixed and portable instrumentations have been considered as one of the most effective measures in dealing with scour effect on bridges. Fixed instrumentation with sensors installed prior to flood events is unable to detect scour other than the area instrumented and is vulnerable to harsh environments during a flood event. Portable instrumented sensors cannot be deployed during a severe flood event due to safety consideration and/or water condition.

The goal of this study was to explore and develop and install a new type of portable instrumented sensor system called 'smart rock' to monitor scour. One or two permanent magnets embedded in concrete as a smart rock fulfils two functions: 1) automatic roll-down function to bottom of a scour hole for monitoring and 2) provision of its position through remote measurement for determination of maximum scour depth. The smart rock can also be deployed at the toe of a riprap measure to evaluate the effectiveness of such a scour countermeasure.

To achieve the goal, this study was focused on movement characterization, design guidelines, field performance, and spatial display of smart rocks at three representative bridge sites. Spherical smart rocks were considered for easy rolling in field operation. Their design was based on the critical velocity of water flow as specified in Hydraulic Engineering Circular No.18 (HEC-18). To ensure a minimum effect of steel reinforcement in bridge piers and decks, a gravity-controlled Automatically-Pointing-Up System (APUS, see Figure 1) was designed to make the South pole of magnets always faced up. Smart rocks with an embedded APUS were deployed at three bridge sites (Gasconade River Bridge, MO, Roubidoux Creek Bridge, MO, and Waddell Creek Bridge, CA) for scour depth monitoring. The effectiveness of riprap countermeasure at the Waddell Creek Bridge was also monitored.

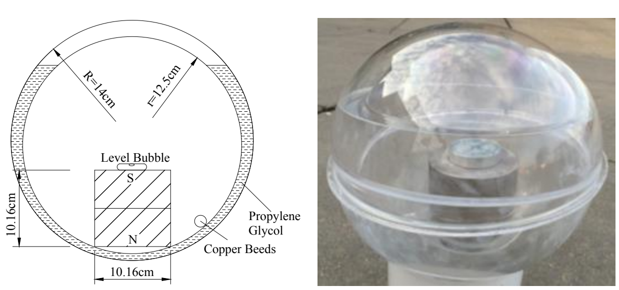

Figure 1: Schematic view and prototype of an APUS with two stacked N42 magnets

The smart rock deployed at the Roubidoux Creek Bridge was located successfully and satisfactorily during three field tests. Its movement was displayed on a three-dimensional contour map created in ArcGIS (see Figure 2) based on the riverbed survey data collected with a sonar device and a total station.

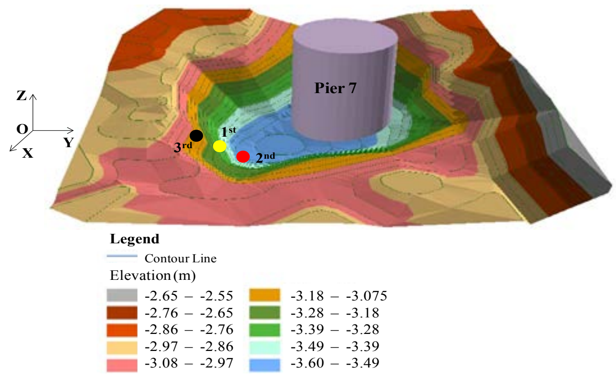

Figure 2: Smart rock movement during three field tests

Findings & Outputs

Research findings indicated the following main conclusions:

- The design guidelines of smart rocks developed with the critical velocity of water flow in HEC-18 were demonstrated to work well at the Roubidoux Creek Bridge site based on three field tests.
- The maximum prediction error in smart rock location at the Roubidoux Creek Bridge was 0.333 m in all field tests, less than a target of 0.5 m.
- The smart rock deployed at the Roubidoux Creek Bridge was successfully predicted to have settled down to the bottom of scour hole by 0.182 m during the Dec. 27, 2015, flood, which was underestimated by 0.158 m.
- A single neodymium N42 magnet can be accurately and reliably located at 6 m distance. With two stacked N42 magnets, the measurement distance can be increased to 7.5 m in open environment.
- When placed on top of the bridge footing, the gravity-controlled magnets were demonstrated to rotate for less than 0.5°, which is negligible in engineering application.
- It was verified that soil deposits on top of a smart rock had no effect on the magnetic field measurement from above ground.
- During the field tests, two smart rocks were retrieved for visual inspection. As expected, both indicated no sign of water leakage.
- The smart rocks that were simply deployed from a boat or bridge decks to the Gasconade River and Waddell Creek sites were washed away during

flood events. Subsequently, additional smart rocks were deployed with their top to flush with the riverbed for future measurement.

- Spherical smart rocks were not stable for the monitoring of riprap countermeasure effectiveness due to lack of their interlocks with natural rocks. Heavy smart rocks with a polyhedral shape were recommended for future study.

Products & Outcomes

This study has resulted in several deliverables: smart rock design guidelines, smart rock prototypes with an APUS, a rock positioning and scour depth evaluation algorithm, a time-variant mapping tool of spatially distributed smart rocks, and a field performance data sheet of smart rocks. They were reported in the following publications and presentations (partial list):

- G. Chen, Y. Tang, Y. Chen, Z. Li, L. Fan, C. Guo, Y. Bao, and X. Hu. *Smart Rock Technology for Real-time Monitoring of Bridge Scour and Riprap Effectiveness – Design Guidelines and Visualization Tools*, Final Report No. OASRTRS-14-H-MST submitted to the USDOT/OST-R, Dec. 31, 2016.
- Y. Tang. *Remote Sensing and Localization of Smart Rocks with Orientation-Controlled Magnets for Real-time Monitoring of Bridge Scour and Riprap Effectiveness: Concept, Characterization, and Validation*, Ph.D. Dissertation submitted to the Graduate Faculty of Missouri University of Science and Technology, Dec. 15, 2016.
- G. Chen. "Smart Rocks as Field Agents for Bridge Scour Monitoring in Real Time." Presented at the 13th US-China Workshop on Bridge Engineering, Xi'an, China, Oct. 26-31, 2016.
- Y. Tang, Y. Chen, Z. Li, Y. Bao, C. Guo, and G. Chen. "Design, Test and Field Validation of Sour Monitoring Sensors with Automatically Pointing-up System." Presented at the SPIE Annual Symposium on Smart Structures/NDE, Las Vegas, NV, Mar. 20-24, 2016.
- G. Chen. "Passive Smart Rocks for Bridge Scour Monitoring." Presented at the TRB Meeting - Committee AFB60 Hydrology, Hydraulics & Water Quality, Jan. 11, 2016.
- G. Chen. "Field Deployment and Validation of Passive Smart Rocks for Bridge Scour Monitoring." Presented at the TRB Annual Meeting - Workshop 160, Jan. 10, 2016.
- G. Chen, B. Schafer, Z. Lin, Y. Huang, O. Suaznabar, J. Shen, and K. Kerenyi. "Maximum Scour Depth Based on Magnetic Field Change of Smart Rocks for Foundation Stability Evaluation of Bridges." *Struct. Health Moni.*, 14(1): 86-99, Jan. 2015.

Post Project Initiatives

A pool-funded study with selected departments of transportation and University Transportation Center support is being planned to develop a mobile platform with an unmanned aerial vehicle (UAV) for the collection of a dense array of magnetic field intensity data for long term applications. Increased data acquisition will improve the accuracy of smart rock localization and movement prediction. UAV will replace current usage of test cranes and fork-lifts and would allow a rapid setup of field tests and would potentially eliminate the need for traffic lane closures or traffic interruption.

An implementation study with an industrial partner, such as SMARTSENSYS, is being planned to integrate the smart-rock positioning and displaying system into one of the existing commercial platforms for bridge monitoring.

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Mobile Hybrid LiDAR & Infrared Sensing for Natural Gas Pipeline Monitoring

Rutgers, The State University of New Jersey

Executive Summary

The natural gas distribution system in the U.S. has a total of 1.2 million miles of mains and about 65 million service lines. There is growing concern about managing this vast network of pipelines as weather systems become increasingly aggressive and natural disasters become more frequent (Figure 1).

Figure 1: Examples of natural disasters

Timely assessment of pipeline integrity after major natural disasters is a critical step to prevent post-disaster damages. However, such assessment is currently hampered by:

- the lack of data sufficient for quantifying changes in pipeline conditions and their built environment; and
- the lack of data-driven risk models that identify high risk pipe segments after a disaster.

The overall goal of this project is to:

- develop new remote-sensing capabilities for assessing pipeline performance after natural disasters;
- develop procedures to detect changes and anomalies in the environment which could indicate threats to pipelines; and
- develop data-driven risk assessment tools to identify and rank high risk pipeline segments.

The methodology integrates live spatially distributed threat information (terrain changes, flooding water, and displaced structures) gathered by remote sensing technologies with pipeline mechanistic models to estimate pipeline deformation or pullout potential. Specific parameters were used to screen pipeline systems at the network level in order to rank and detect high risk segments. The methodology is applicable to both above- and underground pipeline segments.

Products & Outcomes

Products include a mobile mapping platform that harnesses commercially available remote sensing technologies to provide new remote sensing capabilities for pipeline risk assessment, a point cloud and infrared imagery analysis system that semi-automates extraction of data to detect changes and anomalies in the built environment, and a GIS-based pipeline risk assessment tools to identify high risk pipe segments to prioritize repair and restoration activities.

These products together serve as an integrated system that starts with data collection and ends with actionable information for decision makers (Figures 2 & 3). The products can be readily implemented by stakeholders in pipeline safety. Several journal papers and conference presentation have been conducted to highlight research findings.

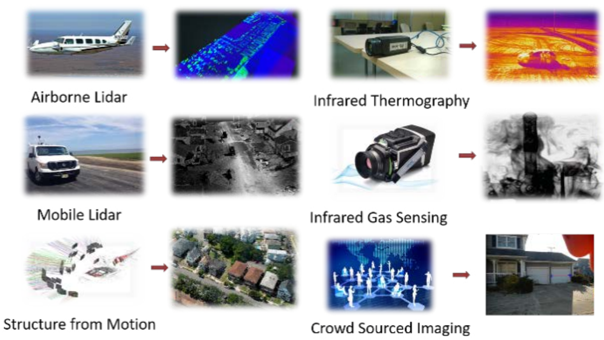

Figure 2: Remote Sensing Technologies

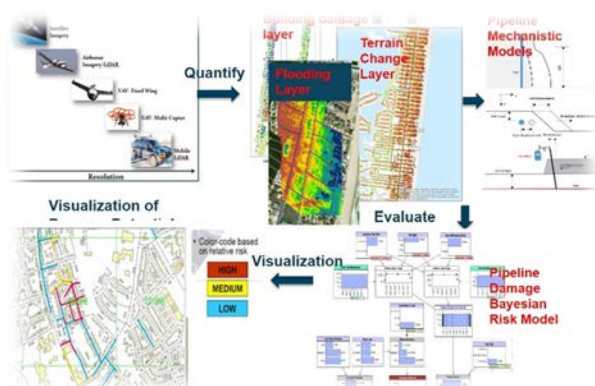

Figure 3: Proposed Spatial Sensing and Analytics Framework

Findings & Outputs

The project demonstrated integration of multi-sourced geospatial data, spatial data analytics, and pipeline risk models enables a data driven approach for large-scale post-disaster assessment of natural gas pipeline systems. The developed tools provide new geo-capabilities in collecting necessary geospatial data and turning these data into critical tools for rapid assessment of the integrity of natural gas pipeline systems. The system has been validated using data captured in several severely impacted coastal communities during Hurricane Sandy. Information from this project can be used to enhance the safety of gas distribution and system and provide gas system operators with an improved ability to manage their pipeline systems. While research resulted in an integrated approach to assess natural gas distribution pipelines subjected to earth movement, landslides, and flooding (commonly associated with hurricane forces), the procedures developed in this project are also applicable to other threats and associated risk parameters (Figure 4).

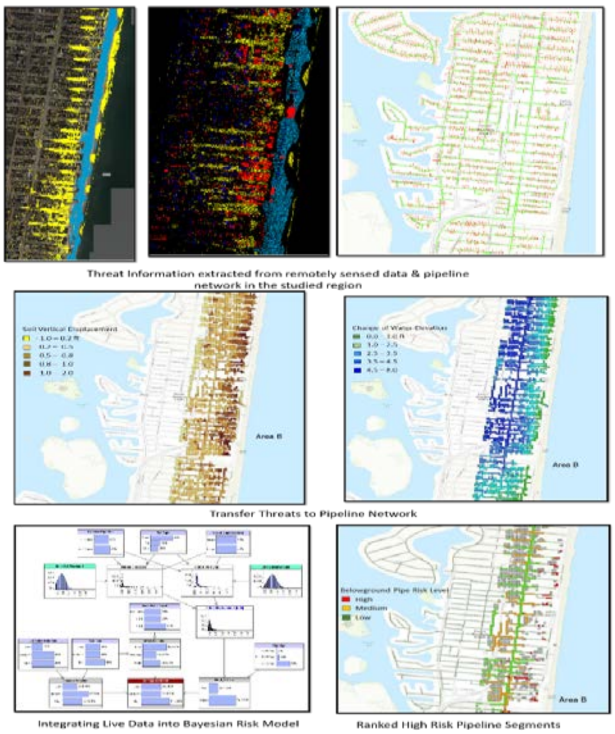

Figure 4: Remote sensing data and interpretation

Post Project Initiatives

The products developed in this project have been applied in multiple projects. The hybrid mobile mapping system has already been deployed in a Federal Emergency Management Agency funded Rebuilding with Greater Resilience project to scan nearly 800 miles of coastal roads, utility and building structures. The data will serve as the foundation for hurricane risk mitigation in the region for the years to come. In addition, the spatially resolved infrared thermography method has been deployed in several emergency infrastructure inspection tasks including assessing and evaluating the health condition of several deteriorating bridges in the state of New Jersey and assessing the condition of a critical tunnel in California. We have also applied our system to accomplish scanning of the iconic Port Authority Bus Terminal in New York City and provided models for terminal simulation. Lastly, a notice of invention has been filed to the office of commercialization at Rutgers University.

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A Time Sensitive Remote Sensing System (TSRSS)

University of New Mexico

Executive Summary

This project developed a remote sensing system – TSRSS, capable of rapidly identifying fine-scale damage to critical transportation infrastructure following hazard events (Figure 1). Such a system must be pre-planned for rapid deployment, automate processing routines to expedite the delivery of information, fit within existing standard operating procedures to facilitate ready use during a hazard response scenario, and the tools need to be commercially available to Department of Transportations (DOT). The project Team designed an airborne remote sensing system based on a network of collection platforms. An automated image co-registration and change product is now commercially available from BAE Systems Inc.

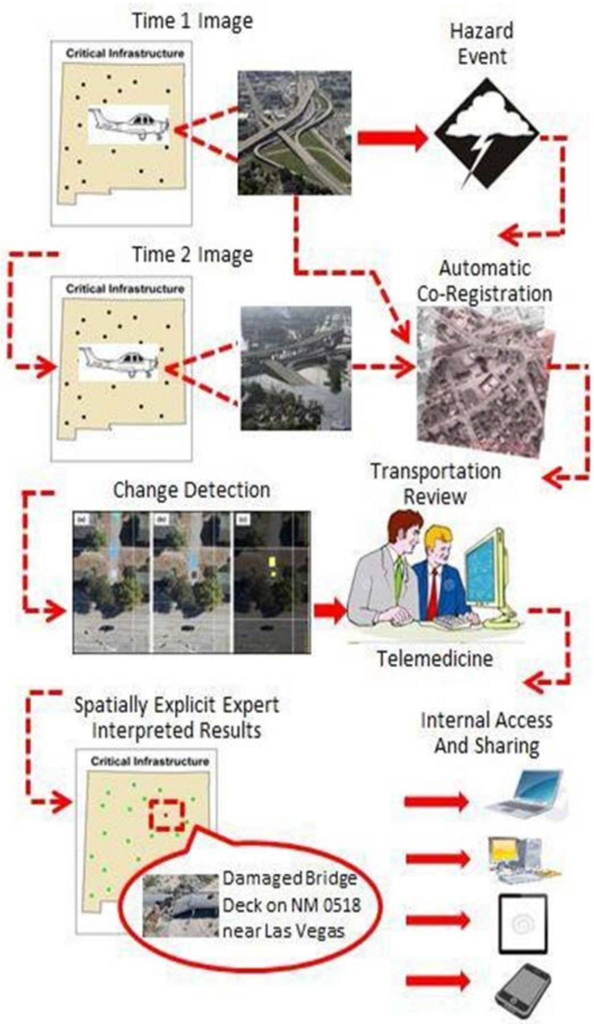

Figure 1: Overview of TSRSS Process

The design approach was based on the Remote Sensing Communication Model, which dictates that the design of time-sensitive remote sensing systems be based explicitly on the needs and properties of the user. The Team worked closely with the New Mexico Department of Transportation (NMDOT) during the design of the system, including ongoing consultation, attendance of NMDOT workshops and conferences, and two formal surveys.

Six critical elements were adopted and implemented within the remote sensing system:

- Pre-Event Planning and Baseline Data Preparation: Critical infrastructures are identified and baseline imagery is collected.
- Decision to Deploy: Available aircraft are deployed to predefined image stations based on desired coverage and required response time.
- Automated Pre-processing: Precise co-registration (alignment) of pre- and post- images for comparison enabled through Repeat Station Imaging.
- Automated Change Detection: A change detection (binary change/no change) and change enhancement product are produced.
- Remote Inspection by Engineers: Engineers can access pre-hazard, post-hazard, change detection, and change enhancement images simultaneously (Figure 2). They can locate, mark and annotate potential damage of concern and share their interpretations to a central database accessible by decision makers.

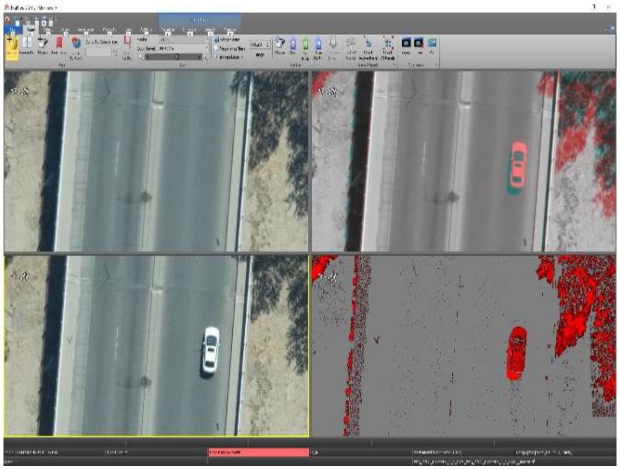

Figure 2: Remote inspection interface accessed through a web browser

- Decision Making: Transportation and emergency managers have expert interpreted information about the post- hazard status of critical transportation infrastructure such that they can safely route evacuees, support personnel, and relief resources.

Findings & Outputs

The team has conducted several presentations at national conferences and published technical papers in peer-reviewed journals to include:

- Transportation Research Board 2015, 2016, and 2017
- 9 presentations at various other academic conferences.
- 5 journal publications
- 3 peer reviewed conference papers

On October 28, 2016 a demonstration of the system was held at the University of New Mexico. The demonstration included a thorough review of the design, development, and overall functionality of the TSRSS. The demonstration, attended by members of the DOT, Federal Emergency Management Agency (FEMA), Department of Homeland Security (DHS), and the Civil Air Patrol, included a hands-on demonstration using the engineer-review interface and a field trip to the Civil Air Patrol (CAP) (Figure 3) hanger at Kirtland Airforce Base to inspect the system hardware and an overview of CAP's capabilities.

Figure 3: Civil Air Patrol Sensor Platform

Products & Outcomes

A standard File Exchange Format for pavement surface laser data, including both 3D range and intensity data was developed. It can be used by vendors who provide data collection services. Thus, a highway agency will have the flexibility to use a third party for data processing. Also, data collected by different vendors can be easily combined and reused.

The research Team has developed additional products and established interagency relationships to further effort:

- An open source tool (i.e., ADAPTEE) for estimating the time of information delivery from a network of aerial imaging platforms, including estimation of collection, transmission, and processing time.
- Automated image co-registration, change enhancement, and change detection without human intervention required.
- Web based tools for review of raw imagery, change enhanced, and change detection images by distributed engineers through a web browser. Engineers can provide image clips with annotations and text to report their findings to a central common operating picture
- Software tools to access and supplement interpreted results during field inspections.
- Relationship with US Air Force Auxiliary Civil Air Patrol, who operate a nationally distributed network of aircraft and have as part of their existing mission hazard response and other rapid deployment missions.

Post Project Initiatives

Current post project priorities are commercialization of the system and continued improvement of change detection algorithms. Interactions with NMDOT engineers at the demonstration suggested the system would be of value if provided in the form of an automated service, something BAE is prepared to do through and existing contract with the Department of Homeland Security. The project Team is submitting white papers and pursuing engagement with State DOTs and multiple other potential users of automatic change detection (e.g. DHS, Department of Defense, National Geospatial-Intelligence Agency, and FEMA).

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Integrative Freight Demand Management in the New York City Metropolitan Area: Implementation Phase

Rensselaer Polytechnic Institute

Executive Summary:

This project, also known as the Off-Hour Delivery (OHD) project is an innovative example of receiver-centered freight traffic demand management. This uses incentives (financial or otherwise) to induce receivers to accept deliveries in the off-hours (7PM to 6AM). Since the incentives remove the opposition of the receivers, and the carriers are generally in favor, entire supply chains can switch to the off-hours, and provide numerous benefits. This project has been implemented in stages. After a successful pilot phase that concluded in 2010, the Office of the Assistant Secretary for Research and Technology (OST-R) sponsored implementation phase was launched in June 2011 and concluded in September 2013.

Findings & Outputs:

The OHD program is a win-win solution that benefits carriers, receivers, and urban communities at all hours, enhancing quality of life, economic development, and environmental sustainability. It is estimated that in excess of 400 businesses in Manhattan shifted some of their deliveries to the off-hours (Figure 1). The businesses are predominantly located in Midtown and Lower Manhattan. The estimate includes businesses of various sizes that shifted after the pilot phase and through the implementation phase. It also includes businesses that did and did not receive financial incentives. It is estimated that 40-50 daily delivery tours in Manhattan have switched as a result of this project, for a total carrier savings of over $2,250,000/year.

Figure 1: Regular hour vs Off-hour traffic conditions

The table shown in Figure 2 illustrates the environmental savings for shifting various levels of deliveries to the off-hours. It shows the total yearly savings, based on the percentage of deliveries shifted to the off-hours. In essence, if 20.9% of the deliveries in Manhattan were shifted to the off-hours, each receiver would be responsible for an annual reduction of about 551 vehicles miles traveled (VMT), 195 vehicle hours traveled (VHT), CO of 12 kg, HC of 1.9 kg, NOx of 0.7 kg and PM10 0.004kg. This translates to a total reduction of 202.7 tons of CO, 40 tons of HC, 11.8 tons of NOx and 70 kg of PM10 per year.

TOTAL/YEAR

Scenario % OHD	CO (tonnes)	HC (tonnes)	NOx (tonnes)	PM_{10} (kg)
6.49%	101.196	24.047	3.004	20.29
14.10%	169.582	28.535	8.223	48.81
20.90%	202.749	39.972	11.824	69.99
25.34%	253.141	56.559	15.044	90.09
29.07%	383.813	55.764	26.333	149.86

Figure 2: Environmental savings estimate

To analyze fuel consumption and emissions, road segments with high trip frequencies were selected, on which the second-by-second GPS trajectory (time-velocity) data were extracted. The segments include three highway segments with a length of 0.25 mile (400 meters), three segments on a toll road with a length of 0.19 mile (300 meters), and three arterial segments in Manhattan with a length of 0.06 mile (100 meters). The differences are generally greater than 20% for highway and toll road segments, and greater than 50% for urban arterial road segments. For illustration purposes, the fuel consumption rates and CO2 emission rates for the road segments are plotted in different grey scales, as shown in Figures 2 and 3 below.

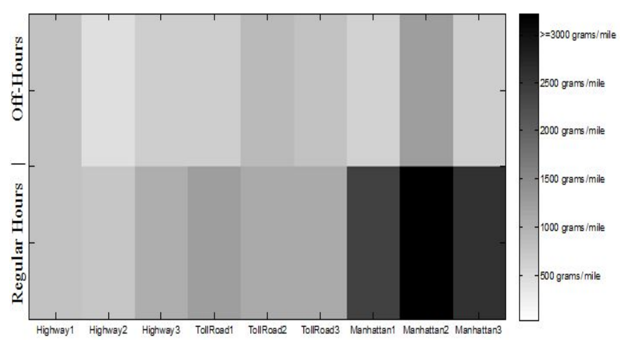

Figure 2: Fuel consumption rates

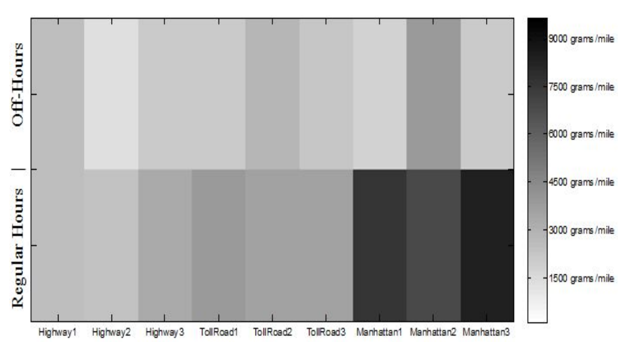

Figure 3: Carbon Dioxide emission rates

Products & Outcomes:

The project has demonstrated the potential that exists for paradigmatic change when the public, private and academic partners collaborate to find solutions to freight issues. The results indicate the potential economic impacts are enormous; savings in NYC estimated at $100-$200 million/year. The findings also confirm dramatic reductions in both the congestion and associated pollution produced by regular-hour traffic, and the pollution produced by the trucks in the off-hours. Experience shows that economic and operational benefits for receivers and carriers drive their continued participation; initial incentives may become less necessary as word about the program, and participant experience spreads. Financially sustainable, the program is socially and politically sustainable; if properly implemented, its impacts are positive for all involved enhancing urban quality of life, economic development, and environmental sustainability.

Additionally, several key products were developed including:

- Creation of an **Industry Advisory Group** (IAG). The IAG is a group of businesses representing carriers, shippers, receivers and trade groups all of various sizes. The IAG was provided useful insight into freight issues including OHD.
- **Building access technology** information. This serves as a resource to receivers on technologies available for unassisted deliveries.
- **Noise reduction technology** information for urban deliveries. This was particularly useful for carriers to learn about possible technologies available to install on their trucks to make the quieter in the off-hours.
- A **behavior micro-simulation (BMS) model.** The BMS reproduces the main characteristics of freight in an urban environment by considering the relationship between carriers and receivers, matching the freight-trip generation pattern, and considering the characteristics of each industry segment.

The project has transformed NYCDOT's relations with the freight industry and the private sector. The project has clarified the potential that exists for paradigmatic change when public and private sector and academic partners work collaboratively to find solutions to freight issues. The institutional support for, and commitment to, the OHD program--now branded "NYC deliverEASE--is made clear by these and other factors including the adoption of OHD as part of NYC's Sustainability Plan (PlaNYC) and the creation of the Industry Advisory Group that provides ongoing input to the city on freight matters.

Post Project Initiatives:

Both RPI and NYCDOT have been proactive in gaining support from other both the public and private sector to grow this program. Additionally,

- This project has led to the creation of a grant program, jointly funded by the Federal Highway Administration (FHWA) and the Environmental Protection Agency (EPA), to foster OHD programs in other cities.
- In 2013, $500,000 was obligated by NYCDOT to support the expansion of OHD. These funds will help participants shift and help to fund a quiet truck demonstration project with private sector participation.
- The New York State Energy Research and Development Authority (NYSERDA) funded a project to support noise reduction to support OHD. Funding was provided to NYCDOT to offer assistance to help purchase and evaluate noise reduction equipment to be used in OHD.

These programs and others being implemented by NYCDOT will ensure this program continues to be implemented on a larger scale. The support from the business community demonstrates their willingness to be proactive in solving urban mobility problems and these changes are transferable to other urban areas throughout the country.

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Commercial Remote Sensing & Spatial Information Technologies for Reliable Transportation Systems Planning

The University of North Carolina at Charlotte

Executive Summary

Reliability is the most viable performance measure with potential to be widely used for transportation system planning, project prioritization, and allocation of resources. However, the quality of travel time data to accurately assess reliability, for links with varying traffic and network characteristics, is still unclear and merits investigation. The first part of the project focused on collecting, processing and comparing the accuracy of link-level travel time estimates from selected technologies / data sources for both freeway and arterial streets.

Travel time based performance measures yield varying outcomes that could be applicable for different purposes (quantify level of congestion or reliability, before and after studies, or compare one link with another link for prioritization). The second part of the project focused on 1) evaluating relationships between travel time based performance measures, 2) establishing and identifying performance measures based on application and purpose, and, 3) demonstrating the use of a multi-dimensional performance measure.

Decision support tools (DSTs) help develop performance-based congestion management plans, identify links (to divert traffic due to an incident) for incident management and re-routing traffic over time (say, up to 2 hours after a fatal crash), and assist planners and engineers in their day-to-day activities (mobility and safety improvements at link- or corridor-level). The third part of the project focused on the development and implementation of DSTs that would help practitioners to:

- Examine spatial variations in the condition of the transportation network (Figure 1) based on various performance measures,

Figure 1: Spatial Distribution of Link-level Performance

- Assess the performance of links along a selected corridor in the transportation network,
- Identify and rank top "N" unreliable links in the transportation network,
- Assess the performance of a link by time-of-the-day and day-of-the-week during a year,
- Retrieve and report performance measures data for further analysis, and
- Evaluate the effect of an incident on nearby links in the transportation network.

Findings & Outputs

Travel time data for the Charlotte region in the state of North Carolina, for the years 2009 to 2013, was gathered, processed and used for research, analysis and illustration of the working of the of DSTs. The findings and outputs of the project are:

- The travel time data from Bluetooth detectors and INRIX are reasonably close to manually captured travel time data along the freeway corridor than when compared to arterial street corridors. For arterial streets, travel times from INRIX are observed to be more promising when compared to the travel times from the Bluetooth detectors.
- The average travel time was observed to be correlated with all the travel time and travel time variations related performance measures. It can be used as the expected travel time and to quantify the effect of a transportation project (before-after evaluation).
- Buffer time was observed to be correlated with almost every other measure, while buffer time index was observed to be correlated with most of the reliability indices considered in this project.
- Buffer time index can be used for evaluating the condition of the facility as well as comparing the performance of any two links in the network. It also provides adequate information about the congestion or level of reliability of the link.
- The proposed reliability measure, Cronbach's α, was observed to be a better estimator of expected travel time when compared to traditional travel time performance measures.
- Four web-based DSTs were developed to assist practitioners make decisions pertaining to transportation system.

Products & Outcomes

Four interactive web-based DSTs with analytical and visual capabilities were developed to assist practitioners make decisions pertaining to transportation system. They are:

- Reliability Mapping DST: The Reliability Mapping DST has seamless transition from macroscopic level (transportation network-level) to details at a microscopic level (link-level). The macroscopic level details assist decision-makers and practitioners in transportation planning and development of performance-based congestion management plans. The microscopic level details help engineers in identifying site-specific solutions and improvements. This DST also helps identify top 'N' (10, 25 and 50) unreliable links in the transportation network for prioritization and allocation of resources.
- "HeatChart" Visualization DST: The "HeatChart" visualization DST helps visualize the intensity and duration of the selected performance measure by time-of-the-day and week-of-the-day (Figure 2).

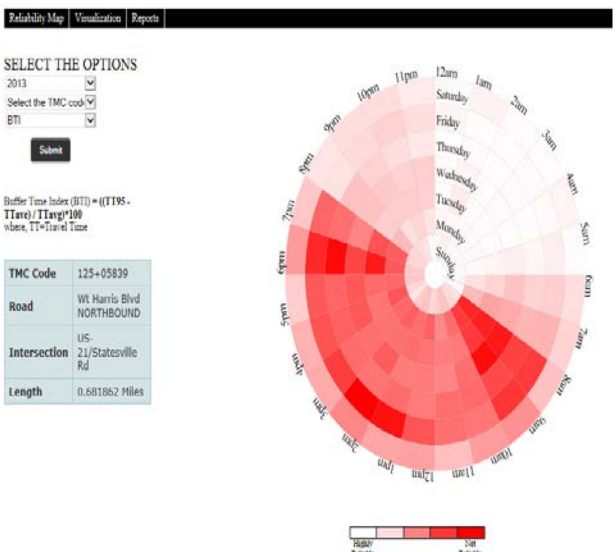

Figure 2: Link-level Performance by Time-of-the-day and Week-of-the-day

- Reports DST: The Reports DST retrieves, disseminates and reports travel time and reliability measures by time-of-the-day and day-of-the-week.
- Effect of Incident DST: The Effect of Incident DST shows the effect of an incident over time and space (Figure 3). This DST helps identify critical links to divert traffic due to an incident; incident management & re-routing traffic.

Figure 3: Effect on Link-level Performance 30 Minutes after the Incident

Post Project Initiatives

Selected post project initiatives are outlined next:

- The research outcomes from this project led to 5 conference proceedings publications and 9 presentations at international, national, regional & local meetings/conferences.
- North Carolina Department of Transportation (NCDOT) sponsored a project titled, "Monetizing Reliability to Evaluate the Impact of Transportation Alternatives", to define thresholds based on users' perception of reliability and to illustrate the application of monetized reliability to assess transportation alternatives and efficiently allocate resources.
- The Principal Investigator of the project participated in NCDOT's evaluation and selection of a vendor to procure travel time data for real-time monitoring as well as for performance and project assessment.
- Plans are being developed to expand the scope of the DSTs to research the effect of developments and construction/maintenance activities on travel time reliability.

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Improving Hydrologic Disaster Forecasting and Response for Transportation by Assimilating and Fusing NASA and other Data Sets

University of Pittsburgh

Executive Summary

Scour-critical bridges typically need to be inspected after severe storms to assess any potential damage. Similarly, the transportation infrastructure requires timely response to related threats such as floods, snow storms, icy roads, fog, etc. The research Team developed the Hydrologic Disaster Forecasting and Response (HDFR) system, which is a fast and reliable tool capable of obtaining and combining information from the National Weather Service, USGS, and NASA to determine the hydrological threat of scour and flooding that affect distributed infrastructure over large regions. The system was developed using the Geographic Resources Analysis Support System (GRASS), an open-source Geographic Information System (GIS) which allows rapid execution without requiring extensive technical know-how or sophisticated computational resources.

Extreme event severity analyses on the HDFR can be done using various levels of complexity, each suitable for different deployment scales. The simplest scenario, which can be executed simultaneously for thousands of locations, relies on precipitation inputs alone. A prototype tested by the Pennsylvania DOT (PennDOT) is currently able to save considerable time and provide bridge inspection priority lists for the entire state in only a few minutes.

A complex series of state-of-the-art companion tools were created to perform detailed forecast simulations of critical watersheds within the HDFR. These tools were developed to mitigate the substantial level of uncertainty in the spatially-distributed parameters and initial conditions of the soil, by combining information available from multiple sources (e.g., stream gauges, satellite soil moisture estimates, and snow cover measurements) and advanced algorithms.

Findings & Outputs

Important findings resulting from the development of the HDFR include the following:

- The severity of precipitation events can be efficiently analyzed using windows of multiple durations to account for events of different nature.
- Current storm severity approaches at PennDOT incur in increasingly large errors when applied to larger watersheds due to not accounting for the spatial structure of typical storms.
- The severity levels of high flows can be roughly estimated very efficiently using a data-driven regression approach that only uses the most general characteristics of the target watershed. This method is an interesting alternative to detailed modeling when fast results are required.
- The best characteristics of the two most popular data assimilation approaches (Bayesian and variational) can be combined together while mitigating some of their inherent weaknesses. The result was a novel assimilation algorithm called OPTIMISTS (Optimized PareTo Inverse Modeling through Integrated Stochastic Search) which showed promising improvements in streamflow forecasting tests.
- Accurate data assimilation in models with high-dimensionality can be achieved by implementing optimized dimensionality reductions based on *k*-means clustering. A prototype of such method was included in OPTIMISTS.
- The uncertainty in the parameters of models cannot be adequately counter-balanced through the adjustment of the model's initial conditions alone. Tests conducted by the team strongly suggest that a more integral approach to model uncertainty is required for effective hydrologic prediction.

Some of these findings have already been presented in multiple hydrologic and geoscientific conferences through both poster and oral presentations. A series of articles are being prepared or planned for publication in leading hydrologic science and application journals.

Products & Outcomes

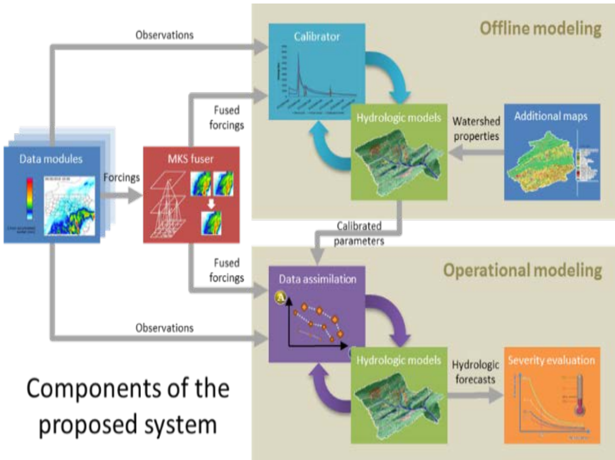

Figure 1: Components of the HDFR system and information exchange between them (grey lines)

Figure 1 shows the main components of the developed HDFR system. Data modules allow automatic retrieval of observed, modeled, and forecasted meteorological and hydrological data. The Multiscale Kalman Smoother fuser allows combining this information with multiple resolutions and error levels for improved accuracy. The calibrator and data assimilation components use advanced multi-objective probabilistic algorithms for determining the adequate parameters and initial conditions of distributed watershed models. These watersheds can be simulated with models such as "Large-scale land-surface model for hydrologic simulations" (for continental and regional scales) or "Distributed Hydrology Soil Vegetation Model" (for catchment/high-resolution scales). The severity evaluation component translates simulated quantities to actionable severity information by contrasting the observed or forecasted conditions with the history of the relevant variable.

The HDFR was developed as a series of modules for the GRASS GIS, and each module is accompanied by a graphical element that allows users to specify the desired inputs. All information is stored as GRASS shapefiles and all the tools available in the GIS for data import, export, transformation, and visualization are available for any further manipulation of the produced datasets. Figure 2 shows screenshots of some of the HDFR's modules in GRASS.

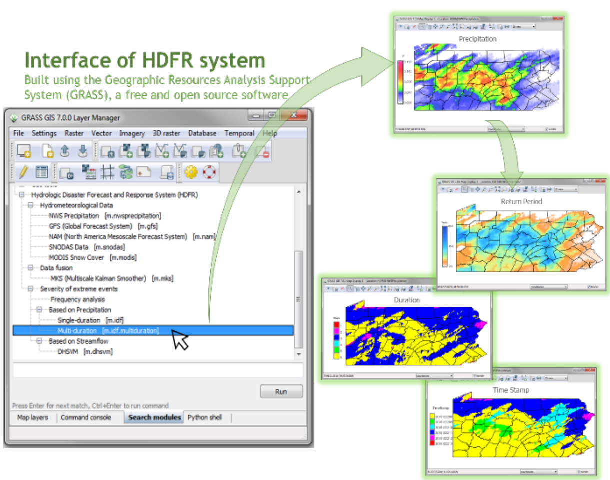

Figure 2: Screenshots of HDFR's modules in GRASS GIS

Post Project Initiatives

Through the execution of this project, the Team (led by the University of Pittsburgh) initiated an ongoing collaboration with PennDOT that comprises of technological transfer of the HDFR system to achieve operational deployment in the state of Pennsylvania. Test versions with cumulative functionality will continue to be delivered to PennDOT's highway engineering team throughout 2017. All feedback will be taken into account to create a mature version of the system that will complement or replace the agency's current software for bridge scouring emergency response. Moreover, we expect the HDFR to be used as a decision-support tool for other operations at PennDOT which involve additional types of infrastructure and hydrologic-related threats.

As the HDFR proves to be a valuable and robust asset at PennDOT, we will work towards its further implementation for deployment at other state DOTs. Additionally, we are currently formulating extension plans for the system to enhance its functionality.

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GPS Excavation Encroachment Notification System

University of Houston

Executive Summary

The University of Houston (UH), in partnership with the Gas Technology Institute (GTI), undertook a pilot project to mitigate pipeline damage due to excavation by developing a real-time excavator encroachment notification system. The system used Global Positioning System (GPS) technology, smart phone motion sensor devices, two-way messaging, and Internet GIS services to monitor pipelines, in real-time, for encroachment from excavation activities.

In cooperation with several pipeline industry commercial partners, the team, led by UH undertook a pilot study to assess the effectiveness of the prototype low-cost encroachment notification system to monitor encroachment in real-time and actively pursued commercialization opportunities for the resultant hardware and software products. The primary market for the GPS Excavation Encroachment Notification System (GEENS) is the utility market and a secondary market is utilities that operate and maintain electric, telecommunications, and water centric infrastructure.

Commercialization and outreach activities included 13 demonstrations and presentations at industry events such as the American Gas Association Annual Operations Conference; exhibitions at industry conferences such as national and state trade association shows; direct outreach to utilities as well as excavator manufacturers and insurance agencies; and advertisements in trade journals and informational webinars to the targeted industries. Partnerships with excavation contractors and with consulting and service organizations in the industry were also developed.

Based on the results from pilot testing and from benefit-cost analyses, it is concluded that GEENS represents a *smarter and more efficient* method for reducing pipeline damage incidents and that the benefits from GEENS far outweigh the cost of technology implementation.

Findings & Outputs

The objectives of the project were successfully met. The research team was able to build a working prototype system using sensor augmented smartphones that satisfied the requirements for low cost installations. Real-time situational awareness software was developed along with a user operations dashboard for tracking and monitoring all excavator devices and providing real-time warning to a simulated user base. The system not only will detect the location of the excavator in proximity to pipelines but will also be able to ascertain the status of it; whether it is digging or not. Because of the proliferation of smart phones and advances in the technology they contain, it is now possible to utilize a common mobile device to deploy the GEENS system. Similarly, software advances are employed in the GEENS through cloud computing and the use of ESRI software without the need for a costly software license. As the project progressed, feedback from demonstration and the two successful pilot tests was incorporated into the software to improve functionality.

Products & Outcomes

The final outcomes of the project were working prototype hardware and software systems with a design that was able to be implemented for pilot projects (Figure 1).

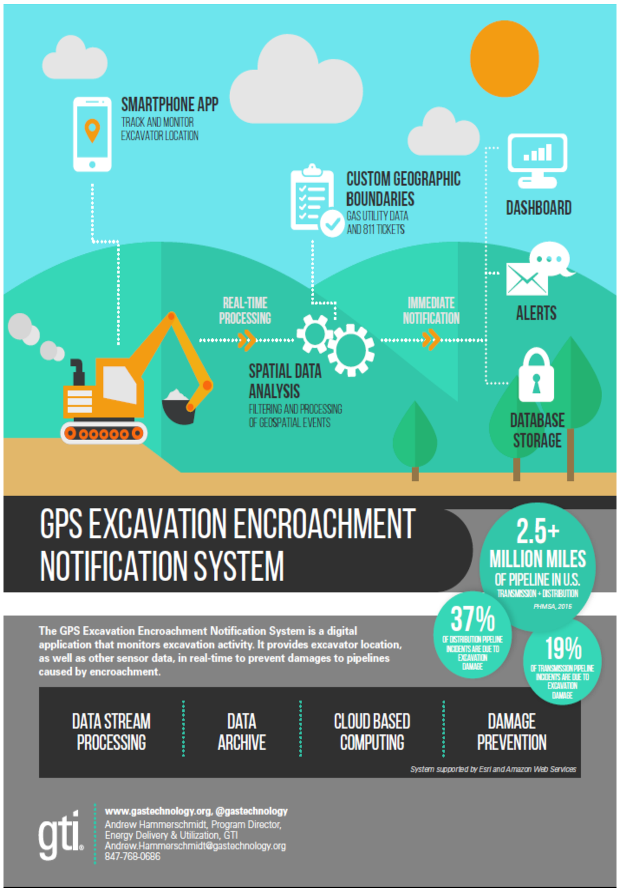

Figure 1: GPS Excavation Encroachment Notification System

In addition to the two pilot projects undertaken for the project, GTI also conducted two pilot projects of GEENS at National Fuel in Buffalo, NY and at New York State Electric and Gas Corporation in Binghamton, NY in the Fall of 2015. More than 140,000 data points were recorded of excavator movements and verified to actual events. Overall, the system performed as expected and provided a much higher level of awareness or visibility regarding the activities of construction contractors within the service territory of the utility.

The project has allowed the research team to prove the technology and learn from the initial implementations. Based on the success of the pilot projects, GTI is actively searching for a commercialization partner for the technology. The results of the project have also led to the development of a product commercialization plan and potential market assessment. GTI has been actively advertising the technology in trade journals and through marketing materials distributed at industry events.

Post Project Initiatives

GTI, via a California Energy Commission Grant, will be performing a 100 to 150-unit implementation of GPS EENs over the next 18 months. With an expectation of continued growth of GPS EENS, GTI will be seeking formal partnerships for the manufacturing and distribution of the sensor package, as well as partnering with organizations such as ESRI for continued support of the applications and server environments.

GTI, and the selected commercialization partner, will also continue to seek opportunities to expand GPS EENS through other complimentary service providers. An example of this is Opvantek, Inc, and specifically their Optimain xDR product, which integrates utility pipeline damage records, risk classifications, and geospatially driven 811 locate information to ascertain risk in an excavation zone. GPS EENS would be a natural complement to this product by combining the excavator situational awareness and operation state to the risk profile generated by Optimain xDR. This will provide additional insight and prioritization capability to the utility operator.

Efforts are also being made to expand GPS EENS to other critical infrastructure industries that endure third party excavation damage such as electric, telecommunications and water utilities.

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Rapid Exploitation of Commercial Remotely Sensed Imagery for Disaster Response and Recovery

University of Vermont

Executive Summary

Natural disasters can severely impact our nation's transportation network. Commercial remote sensing data are increasingly being used in disaster response and recovery, but obtaining actionable information from imagery is still hampered by slow and cumbersome workflows. This project designed, developed and deployed an automated system capable of identifying damaged portions of a road network from commercial satellite imagery. To estimate the amount of fill required to repair these damaged roads a workflow was developed that used 3D models generated from Unmanned Aircraft Systems (UAS).

Findings & Outputs

Automated approaches can accurately assess road damage from satellite imagery and offer substantial time savings compared to manual assessment. Nevertheless, such techniques are sensitive to the local landscape, type of damage, and image properties. UAS provide a readily deployable solution for assessing damage and estimating the amount of fill needed to repair affected roadways that is faster than more traditional approaches, and has the advantage of being able to operate over inaccessible areas. We found volumetric estimates from 3D to UAS to be within 5% of the actual volume.

Products & Outcomes

The Automated Damage Detection (ADDS) developed as part of this project allows a user to harness the power of automated feature extraction while providing the flexibility to adjust to differing sensors and conditions through an intuitive user interface. ADDS provides a means by which to screen large amounts of satellite imagery and rapidly identify portions of a road that have been damaged (Figure 1).

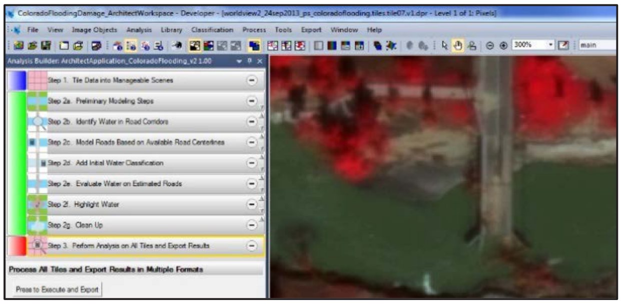

Figure 1: The interface for the Automated Damage Detection System

The workflows developed for UAS operations and volume calculations allow transportation analysts to quickly and accurately estimate the amount of fill needed to repair damaged roadways (Figure 2).

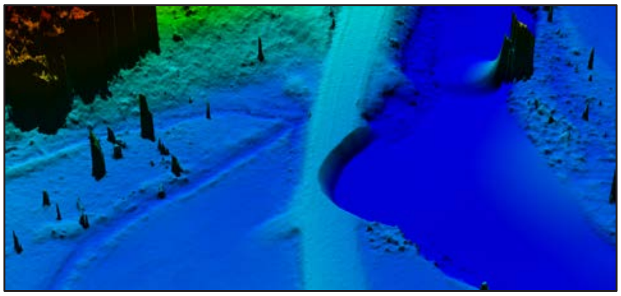

Figure 2: 3D surface model simulation of a damaged roadway used to compute estimated fill volume for repairs

In addition to developing technical workflows focused on volume estimation our team developed extensive expertise in UAS operations and the applications of UAS technology to the transportation decision-making. We developed detailed UAS standard operating procedures and carried out a number of proof of concept studies (Figure 3) for state and local transportation agencies.

Figure 3: UAS mapping of an active construction site

Post Project Initiatives

Following the conclusion of the project The Team established a UAS Team at the University of Vermont. The UAS Team assists state and local transportation agencies, transportation consulting firms, and emergency responders in harnessing the power of cutting-edge UAS technology. Highlights include:

- Development of a stream woody debris budget for the Great Brook in Plainfield, VT (Figure 4). Woody debris in the stream caused extensive damage to one of the town's bridges during summer flooding. The woody debris budget was a key piece of information used by the consulting engineers in justifying a new bridge design.

Figure 4: Woody debris damage to one of the bridges in Plainfield, VT caused by severe storms that hit the area in July 2015

- Participating in FEMA's Hard Knox disaster response exercise in September of 2015 (Figure 5). Due to cloud cover the UAS Team was the only imagery asset capable of collecting data to support the exercise.

Figure 5. A FEMA official holding the UAS used to capture imagery during Hard Knox 2015

- Responding to the October 5, 2015 Amtrak train derailment in Northfield, VT. UAS imagery was used by state and federal agencies as part of the accident investigation (Figure 6).

Figure 6: The UAS Team at the mobile incident command center following the Amtrak train derailment

- Working with five consulting engineering firms in Vermont who do contractual transportation work for the state to integrate UAS into their project scoping and planning process (Figure 7).

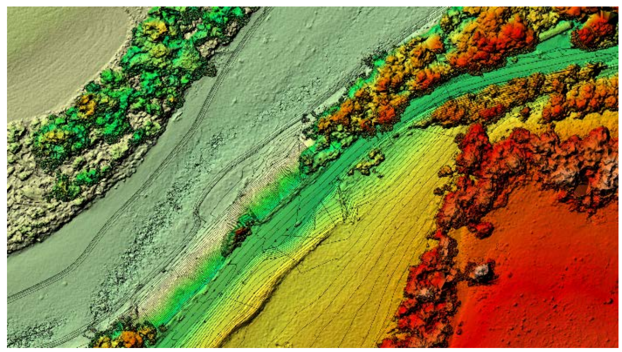

Figure 7: UAS 3D surface model integrated with survey data from an engineering firm in support of a road construction project

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Unmanned Aircraft Systems for Transportation Decision Support

University of Vermont

Executive Summary

Our nation relies on accurate geospatial information to map, measure, and monitor transportation infrastructure and the surrounding landscapes. This project focused on the application of Unmanned Aircraft Systems (UAS) as a novel tool for improving efficiency and efficacy of geospatial data acquisition to provide decision support in five areas: 1) construction management, 2) stream geomorphic assessment, 3) resource allocation, 4) cost decision support, and 5) bridge inspections.

Findings & Outputs

UAS provide considerable cost-savings compared to more traditional approaches of geospatial data collection to aid in transportation decision support. In many instances the data collected by UAS are more detailed and can be turned into meaningful information faster than other alternative approaches. These benefits enable managers to make rapid decisions with greater confidence all while reducing the cost of data acquisition. Nevertheless, UAS (Figure 1) should not be seen as a complete replacement for other methods, such as surveying and inspections, but rather a technology that is best employed in concert with these approaches.

Figure 1: The senseFly eBee, a fixed-wing UAS, comes in for landing following a transportation corridor mapping project

Products & Outcomes

Our stream geomorphic assessment decision support system consisted of a web-based portal that allows users to browse UAS imagery, view the locations of woody debris mapped at various times from the UAS data, and see woody debris fluxes by stream segment. This marked the first time a comprehensive woody debris inventory (Figure 2) had been carried out for the Great Brook. The decision support system provided consulting engineers involved in a bridge redesign project along the Great Brook in Plainfield, VT with crucial information they needed for their hydrologic models and design alternatives.

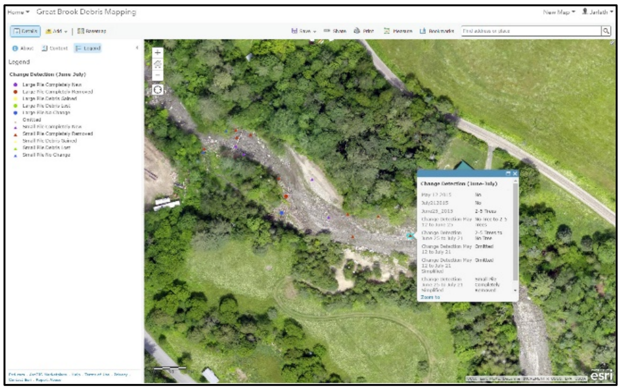

Figure 2: A web-based decision support tool for woody debris mapping

Transportation managers are now able to more efficiently and exhaustively inspect bridges thanks to our UAS-based bridge inspection workflow. This process removes the need for costly, heavy machinery whose availability is limited. The process also yielded 3D models of unprecedented detail that document the condition and configuration of historic structures (Figure 3).

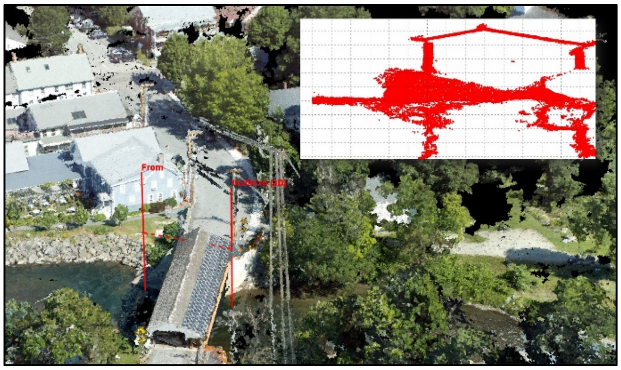

Figure 3: UAS-derived 3D model of a historic covered bridge slated for renovation

Emergency response and recovery efforts can now allocate resources using accurate, detailed geospatial information using the UAS-procedures we developed for natural disasters. During the winter floods that affected Vermont in February of 2015, 2D and 3D geospatial products derived from UAS data enable managers to determine the risk rising waters posed to critical pieces of the transportation network and document flood conditions (Figure 4). These products were generated for areas that were not readily accessible and under conditions that traditional remotely sensed assets could not acquire data for. In two major disaster response exercises UAS data collected as part of this project were integrated with Federal Emergency Management Agency's (FEMA) online imagery decision support systems, marking the first time UAS data had been used to drive operations in a disaster response scenario in FEMA

Region 1. The rapid acquisition and processing of the UAS imagery set a new standard for the timely delivery of remotely sensed products.

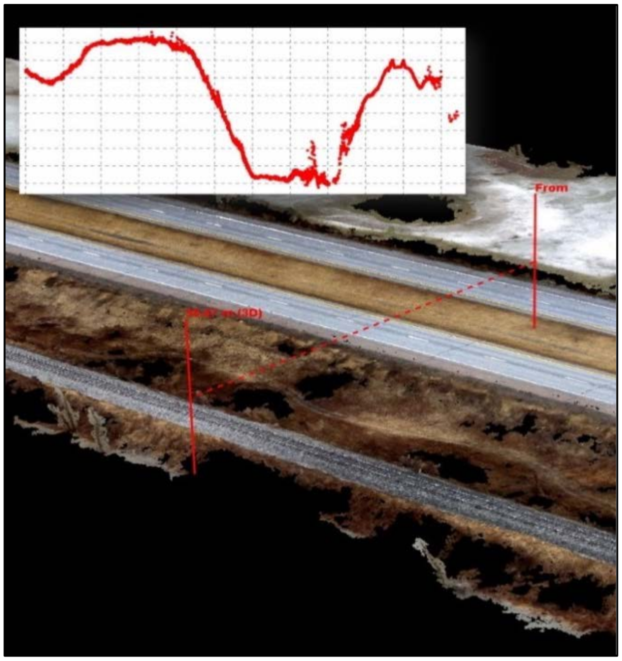

Figure 4: 3D model derived from UAS data used to assess the threat of flood waters to adjacent transportation infrastructure

The first ever 3D model of an approach surface for a state airport in New England was developed as part of this project for analysis to ensure that the approach surface met FAA requirements for clearance from trees in the surrounding landscape (Figure 5). UAS data collected as part of construction phasing mapping were used to build an exact 3D model of the vegetation. This effort resulted in thousands of dollars of savings compared to traditional field survey methods while providing greater detail and fidelity for the risk assessment.

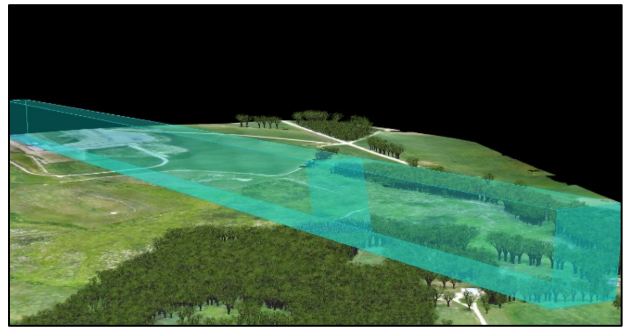

Figure 5: Modeled approach surface for a state-run airport. Tree heights were extracted from UAS data to determine compliance with FAA regulations

Post Project Initiatives

The University of Vermont's UAS Team continues to work with government and private sector partners to expand the use of UAS technology in the transportation sector. The UAS Team has also expanded its activities to include K-12 - Science, Technology, Engineering and Management education outreach. A partnership with a local school district and an engineering consulting company involved over 100 middle school students in a UAS mission that centered on mapping a portion of their town's transportation network to support a redesign initiative (Figure 6).

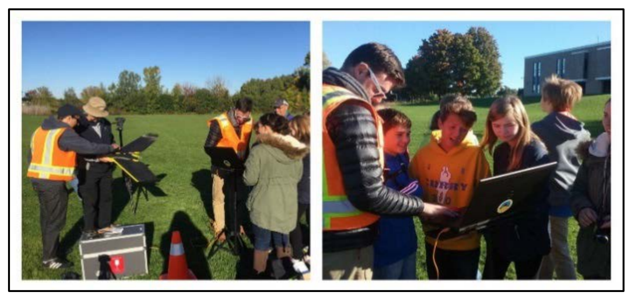

Figure 6: Middle school students participate in a UAS mission to develop improved maps ahead of a transportation redesign project in their town

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InSAR Remote Sensing for Performance Monitoring of Transportation Infrastructure at the Network Level

University of Virginia

Executive Summary

The goal of the project was to develop usable tools based on interferometric synthetic aperture radar (InSAR) data that permitted network-level inspection of a predefined transportation corridor, as well as outreach, education and financial planning material designed to facilitate the introduction of such technique and tools within the decision-making framework of interested agencies. The datasets represented two 40x40km^2 areas of interest. These provided an ideal analysis ground including high sinkhole and karst hazard together with some of the highest traffic volume routes in Virginia facilitating the evaluation of road response to high traffic load. The project developed a set of tools (both standalone and as ArcGIS-based), providing detection and analysis capabilities for events such as subsidence, bridge settlement, landslides (linear trend detection), and road smoothness. The project also developed a web-based decision support system (live demo). Education material on InSAR and its application is collected within the project portal. A workshop was held during TRB 2016 to showcase the results. All workshop materials to evaluate the cost-benefit of InSAR technology are available for download through the project portal.

Findings & Outputs

In addition to the development of tools and outreach material, a possible correlation between the International Roughness Index (IRI) and the amplitude response of the SAR images over roads was discovered. Exploiting this correlation might lead to the development of an InSAR-based approach for network level discrimination between good and bad pavement with potential. The cost-benefit analysis at Virginia Department of Transportation (VDOT) has shown that early identification of culverts failure would provide substantial savings for the agency. This lead to the development of an additional toolbox that focuses on early detection of such events. The flexible financial analysis tool is available for download from the project portal and can be used to identify areas where implementation of InSAR techniques would provide substantial savings. Two active areas were identified within Northern Virginia (Figure 1).

The first, located in the area of Hill East and Capitol Hill near the RFK Stadium and along the Anacostia river, showed a strong subsiding behavior that was correlated with an ongoing tunnel project.

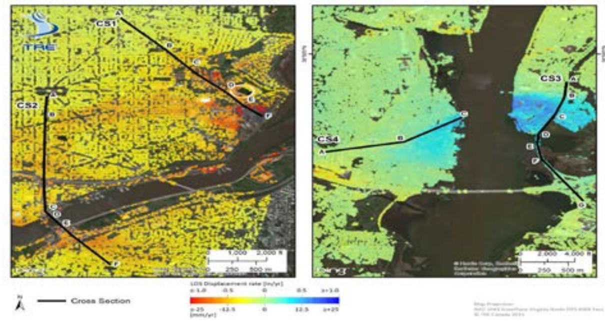

Figure 1: Subsidence (left) and eastward motion (right)

The other, near Alexandria, VA, initially believed to be indicating strong uplift, was later identified as a strong eastward movement (correlated with local GPS measurement) of still unknown origin. Both detections showcase the capability of the developed analysis techniques to quickly identify potentially hazardous regions within large monitored areas.

Products & Outcomes

A standalone *subsidence analysis* executable (both for mac and windows) allows users to achieve early identification and analysis of developing subsidence hallmark of potentially dangerous events for the transportation infrastructure. The output is a set of geo-referenced raster files, providing the location and evolution characteristics of the detected subsidence that can be easily imported within GIS environments. An example of network-level analysis on roads is shown in Figure 2 where warmer colors indicate sections undergoing subsidence. A set of three toolboxes, fully integrated within the ArcGIS software environment, was developed.

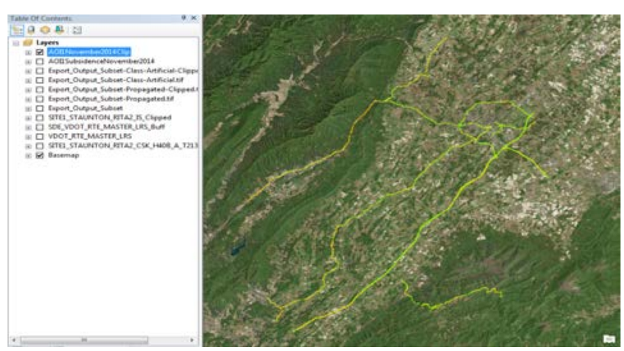

Figure 2:- Subsidence analysis on the central Virginia road network dataset

A bridge settlement analysis toolbox that allows users to identify those structures showing excessive displacement. A linear trend analysis toolbox allowing identification of regions undergoing linear displacement with respect to the satellite line-of-sight. This analysis is useful in detecting linear motion associated with creeping in slope-like geohazard as illustrated in Figure 3.

Figure 3: Bridge settlement (left) and linear trend analysis (right) toolboxes

A road smoothness analysis toolbox. This last tool was designed using an approach based on graph signal processing and it evaluates a smoothness coefficient, based on the measured distortion, giving higher weight to large pavement distortion occurring over short distances (Figure 4). The integration of this with the framework offered by ArcGIS Online, facilitate the output of the developed toolboxes to be seamlessly delivered over a mobile environment allowing network managers to redirect crews and obtain immediate inspection and real-time feedback about detected hazards (Figure 4).

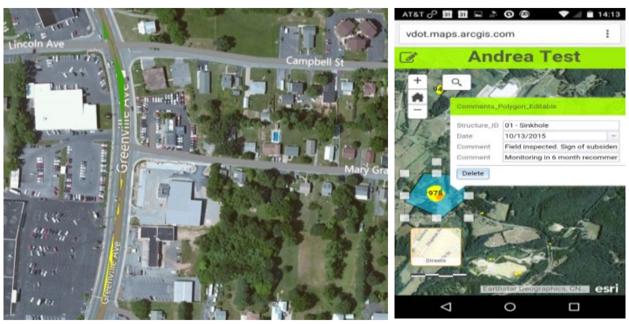

Figure 4: Road smoothness analysis toolbox (left) and ArcGIS Online mobile interface (right)

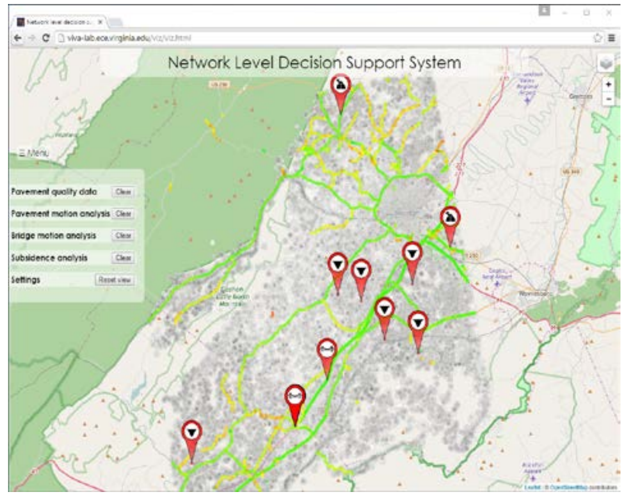

Figure 5: Web-based Decision Support System

A web-based decision support system (Figure 5) was developed to allow for a quick overview of the results obtained from the various analysis tools and their direct comparison with existing databases, such as pavement quality information.

Post Project Initiatives

There is significant potential in InSAR data that could dramatically transform the way inspections are conducted and bring on an efficient and streamlined maintenance approach to the transportation infrastructure. Thus the Team recommended the adoption of the developed tools with the VDOT decision process while TRE Canada, the commercial partner, is supporting the outreach effort to identify new interested stakeholders.

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