Framework and implementation of a continuous network-wide health monitoring system for roadways

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Abstract

According to the 2013 ASCE report card America's infrastructure scores only a D+. There are more than four million miles of roads (grade D) in the U.S. requiring a broad range of maintenance activities. The nation faces a monumental problem of infrastructure management in the scheduling and implementation of maintenance and repair operations, and in the prioritization of expenditures within budgetary constraints. The efficient and effective performance of these operations however is crucial to ensuring roadway safety, preventing catastrophic failures, and promoting economic growth. There is a critical need for technology that can cost-effectively monitor the condition of a network-wide road system and provide accurate, up-to-date information for maintenance activity prioritization.

The Versatile Onboard Traffic Embedded Roaming Sensors (VOTERS) project provides a framework and the sensing capability to complement periodical localized inspections to continuous network-wide health monitoring. Research focused on the development of a cost-effective, lightweight package of multi-modal sensor systems compatible with this framework. An innovative software infrastructure is created that collects, processes, and evaluates these large time-lapse multi-modal data streams. A GIS-based control center manages multiple inspection vehicles and the data for further analysis, visualization, and decision making. VOTERS' technology can monitor road conditions at both the surface and sub-surface levels while the vehicle is navigating through daily traffic going about its normal business, thereby allowing for network-wide frequent assessment of roadways. This deterioration process monitoring at unprecedented time and spatial scales provides unique experimental data that can be used to improve life-cycle cost analysis models.

Keywords: Infrastructural health monitoring, Sensor Systems, Pavement Management, Data Fusion, Big Data Handling

1. INTRODUCTION

According to Federal Highway Administration (FHWA) statistics in 2011, there are 4,094,447 miles of public roads in the US. Considering the lanes, this number goes up to 8,602,666 miles [1]. Besides constant load and traffic, roads are also exposed to a variety of climate and weather conditions. Thus road pavements deteriorate, and distresses such as potholes and cracks appear on them. These defects need to be repaired to restore the serviceability of roads. Statistics suggest that Federal Government spends about 50 billion dollars each year on roadways, a considerable portion of which goes to road rehabilitation and maintenance. [2] This number would drop significantly if cities and states conduct preventive maintenance. Preventive repairs impede roads from reaching critical levels. This results in extending the lifecycle of the roads, ensuring roadway safety, preventing catastrophic failures, and promoting economic growth. This requires the capability of inspecting road defects in a reasonable time-span of their occurrence, hindering them from spreading out and dominating a larger area. Figure 1 shows the impact preventive repair could have on a pavement's life-cycle and cost of rehabilitation. [3-4]

City officials and States' Department of Transportation (DOT) rely on maps and databases assembled from available road distresses data to visualize road conditions and plan cost-effective road maintenance considering their budgetary constraints. Currently, the data collection methods for pavement condition maps can be categorized by two general practices, varying from simple visual inspection to complex image analysis algorithms:

1) <u>Calculating ASTM's Pavement Condition Index (PCI) values between Intersections of streets.</u> Developed in 1976 by the US Army of Corps, the PCI is the main measure used in the United States to assess road conditions [5]. To calculate the PCI, either experts visually inspect and assess the severity of 19 pavement distresses, or while riding in a car, experts see through the windshield and try to record these distresses, requiring the vehicle to move slowly. These methods are time consuming, cause traffic interruptions, trained experts are required, and results are low resolution (i.e. only a single PCI per street), making them periodic, subjective and non-comprehensive [6].

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2) Outputs from mobile condition survey systems with sensors installed on vans or cars. Generally these systems utilize optical sensors such as cameras, 3D cameras or Laser Profilometers. This method usually cannot calculate PCI but other pavement parameters such as International Roughness Index (IRI), Mean Texture Depth (MTD) or Pavement Serviceability Index (PSI). Typically, this method assesses road conditions by extracting the transversal and longitudinal profiles. While this practice reduces survey time in the field significantly and produces high resolution results, some limitations of the former methods remain unresolved, such as the heavy amounts of time and human resources for manual or semi-automatic data processing. Moreover, these systems are rather expensive to purchase or deploy [7].

These methods are both time-consuming in processing the data and expensive to be carried out on a frequent basis. Consequently, decision makers lack modern comprehensive infrastructure inspection and assessment information to allocate maintenance funds in a cost-effective way. A network-wide health assessment of the roadway infrastructure is necessary to replace or at least complement them. A system that allows for more frequent pavement health monitoring would go a long way of providing more insights into the road deterioration process and would allow for measures to stop road defects from spreading out, which would be a large societal benefit. Service fleet vehicles, such as postal vans and taxis could be equipped with vehicle-friendly affordable sensors to collect pavement related features while roaming through daily traffic and going about their business. This would eliminate hazardous, congestion-prone work zones that are typically set up to gather these critical inspection data sets. Based on this framework, the VOTERS project has been defined.

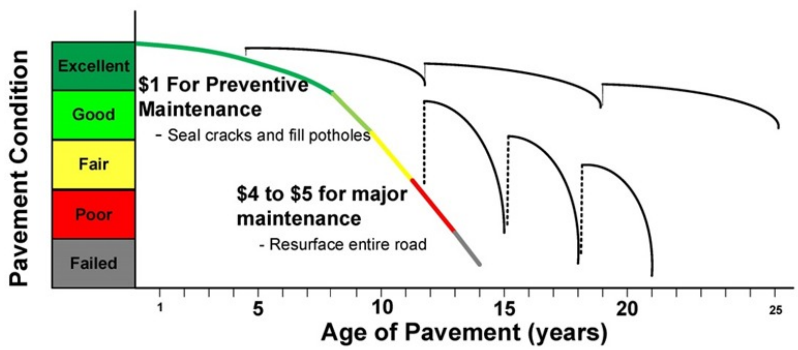

Figure 1. Maintenance activities effect on lifecycle of pavements and money spent

2. VOTERS PROJECT

Versatile Onboard Traffic Embedded Roaming Sensors (VOTERS) has developed a multi-modal mobile sensor system to complement periodical localized inspections of roadways and bridge decks with continuous network-wide health monitoring. This system includes four new cost-effective lightweight prototype sensing systems, compatible with the framework that

1) collects data containing surface and subsurface condition information of roadways and bridge decks,
2) locates and maps road defects at traffic speed, and
3) requires minimum human interaction for data acquisition, processing, analysis and visualization.

These sensor systems are:

- Acoustic technology that uses tire-induced vibrations and sound waves to determine surface texture and subsurface defects like debonded asphalt layers. The waves are recorded with directional microphones [8] and a newly developed Dynamic Tire Pressure Sensor (DTPS) [9-10].
- Improved air-coupled Ground Penetrating Radar (GPR) array technology that will map subsurface defects such as corroded rebar, trapped moisture, voids, and the pavement layers (thicknesses and electromagnetic properties) [11-13].

- Millimeter-wave radar technology (24 GHz) for the near-surface inspection of roadways and bridge decks focusing on pavement condition change detection and surface features covering the roadway such as ice, water, or oil [14].
- Video technology used to capture surface defects and automatically analyze any increase in defects over time for verification of results from other sensors [15].

The integrated sensing system has been deployed on the VOTERS prototype vehicle and an on-board controller manages the positioning and the above listed sensor systems as shown in Figure 2. The on-board controller manages the individual sensor systems, synchronizes data streams with sub-ms accuracy, registers all data streams in time and space, and an access point to the control center [16-18].

VOTERS' sensor-cyber-system is committed to provide simple, affordable solution for maintenance inspection of urban roadways. Through the acoustic sensors (microphone and Dynamic Tire Pressure Sensor) and an Axle-Accelerometer, prominent pavement condition indicators such as Mean Texture Depth (MTD), International Roughness Index (IRI) and Pavement Condition Index (PCI) has been computed, all correlated highly with the existing reference values of these parameters [19-21]. Additionally, VOTERS sensor-system is capable of collecting subsurface information with the GPR array. Along with other sensors, subsurface measurements contribute to deterioration modeling of roads to predict their future conditions and plan cost-effective maintenance activities accordingly.

To handle all these information gathered from these sensors, evolve them into meaningful knowledge, and be able to make decisions from what they entail, VOTERS has also designed a new GIS web-based Pavement Monitoring System. This hierarchically constructed application provides a unified solution for control, management, operation and processing of the large-scale sensor data collected by the VOTERS prototype [22]. Since multiple such systems might collect data simultaneously VOTERS has automated the data flow through the system from the data acquisition to where it is automatically processed and placed into the database and on the map. In the following sections we will briefly discuss these achievements of VOTERS project in addition to concisely demonstrating the VOTERS datasets, PAVEMON application and some of the latest results.

Figure 2. VOTERS prototype Van, Sensors and Data Acquisition System

3. SENSORS AND TECHNOLOGIES

3.1 Tire Excited Acoustic Sensor Systems

Tire excited acoustic sensors measure acoustic waves generated by tires during normal driving to extract the condition of asphalt pavement on the road and the condition of the concrete deck beneath it (Figure 3).

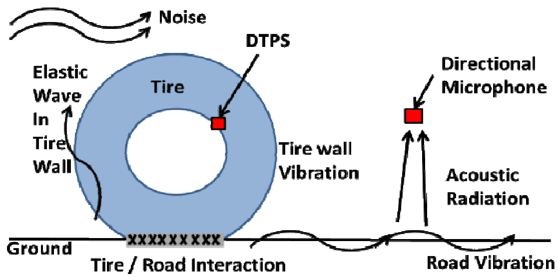

Figure 3. Mechanism of tire/road interaction and different acoustic sources

Dynamic Tire Pressure Sensor: Dynamic Tire Pressure Sensor (DTPS) was developed and patented by VOTERS project [9-10]. DTPS connects directly to the rear tire's valve stem and differs from conventional vehicle tire pressure sensors as it measures only changes in tire pressure -not static pressure. Another difference is in the frequency of DTPS compared to the conventional sensors which sample at very low frequency (for example, one measurement every ten minutes). This sensor has the ability of calculating road profile, and "International Roughness Index (IRI)". ASTM defines IRI as "a quantitative estimate of a pavement property defined as roughness using longitudinal profile measures."[23] In simple words, IRI is a measure of pavement ride quality and smoothness. From the road profile calculations described above, IRI values are extracted. An axle accelerometer is also used for eliminating pressure caused by axle movement. Because of the compatibility with different wheels and the low cost of this sensor, this method has an advantage over the conventional methods of measuring road profile and roughness values. Figure 4 shows roughness of the road reflected in DTPS measurements and how Weibull distribution makes it more observable. Details are discussed in [20].

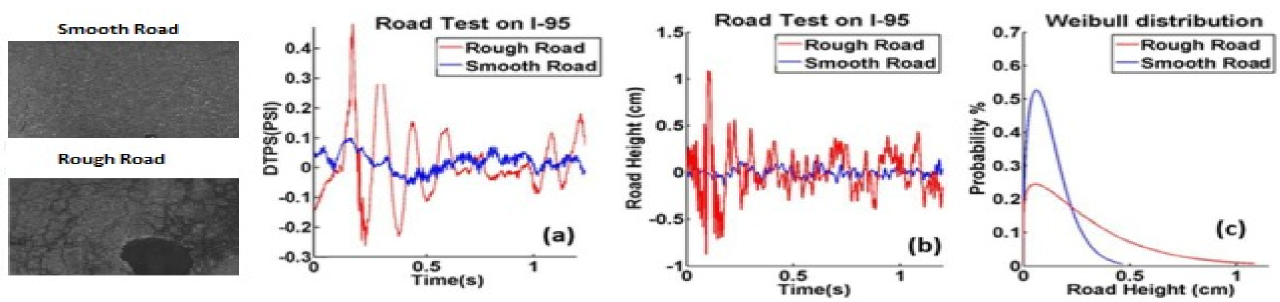

Figure 4. Comparison of rough and smooth road sections presented as (a) raw DTPS data; (b) expressed here as road height, a macro-texture proxy; and (c) as seen by a Weibull distribution.

Directional Microphone: A microphone has been installed behind the driver side rear tire and directed towards the tire to characterize structural and surface properties by recording of acoustic wave signals and necessary signal processing.

Studies has confirmed the assumption that pavement macrotexture contributes a lot to the noise from tire/road interactions. The physical parameters extracted from this microphone: Wet pavement friction and "Macrotexture depth" of pavement (macrotexture MTD). International Organization for Standardization (ISO) describes pavement texture as "the deviation of a pavement surface from a true planar surface" [24]. "Macrotexture" is the pavement texture with spatial wavelengths from 0.5 mm to 50 mm. Macrotexture is highly related to tire/road friction in wet weather, hence related to the severity of the sound generated by tire-pavement- interaction. It's also partially related to dry weather friction. [25-27] Figure 5 shows how differences between pavement macrotextures are observed by microphone measurement. A significant advantage that this method has is that the microphone can be used in regular traffic speeds, making it possible to use in the urban areas. For a more detailed description refer to [19].

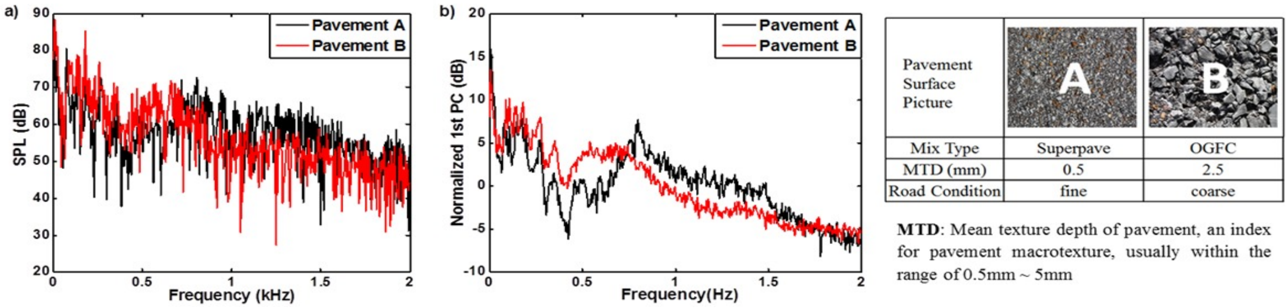

Figure 5. Comparison of two pavement types with different Mean Texture Depth (MTD) as seen by (a) the Sound Pressure Level (SPL) collected by a microphone and (b) its normalized 1st Principal Component (PC).

3.2 Electromagnetic Methods

VOTERS project has developed two new electromagnetic sensing systems for pavement inspection. First a millimeter-wave radar system that is mounted underneath the mobile data collection platform, collecting unique information on the surface roughness and quality. Second a GPR system that is based on micro-power impulse radar technology, faster than any other comparable system available right now, and capable of collecting data sets diverse in frequency, geometry, and polarization.

<u>Millimeter-Wave Radar:</u> The millimeter-wave radar operates at 24 GHz. Such systems are typically used in stationary applications, e.g. to measure the distance to an objects or in airport body scanners. In VOTERS system, it is mounted underneath the mobile sensing platform and points at the road. The measurements of the in-phase I and out-of-phase Q components contain unique information on the roughness and quality of the ground surface. Currently a 5 channel array is mounted underneath the VOTERS survey van. All channels are collected simultaneously providing 5 parallel profiles, distributed over the width of the van. This data set contains road surface condition information complementary to the acoustic measurements [14].

<u>Ground Penetrating Radar:</u> GPR array system that is geared towards mapping subsurface defects such as corroded rebar, trapped moisture, voids, and the pavement layers (thicknesses and electromagnetic properties) [11-13]. The main requirement for this system was that it would be fast, i.e. capable of collecting GPR traces at cm intervals at traffic speeds. The resulting GPR system is able to collect 1000 traces per second. In addition it is low-profile, low-cost, low-power, array-capable, and can operate at a low or high frequency range. Its design allows for the collection of diverse data sets in frequency, geometry, and polarization. The VOTERS project has also developed custom antennas that are compatible with this GPR system for air-coupled or ground-coupled deployment [28].

One complementary VOTERS research study was to explore the sole use of GPR to assess the corrosion state of bridge decks. A thresholding model was developed to distinguish corroded from healthy area [29-30]. This has been carried out by analyzing the radar signals of a large library of bridge decks with descriptive statistics. These statistics were compared to the amount each bridge deck was corroded, computed using the HCP measurements. The analysis indicated that a combination of statistics provided a significant correlation (93%) with the percentage each deck was corroded. Using this model, future decks can be assessed by simply scanning the deck with GPR, computing the statistics about the radar signals, and using the model to determine how much the deck is corroded. Since the decks assessed thus far have been bare concrete with black steel, further analysis is required to investigate bridge decks outside of this category. Rebar reflection amplitudes of corroded areas are much fainter than in healthy areas, thus GPR can distinguish between healthy and corroded areas by comparing them. These amplitude differences can be plotted as contour maps showing the GPR derived corrosion state of bridge decks, as shown in Figure 6.

Table 1 summarizes the VOTERS technologies, their measurements and specifications.

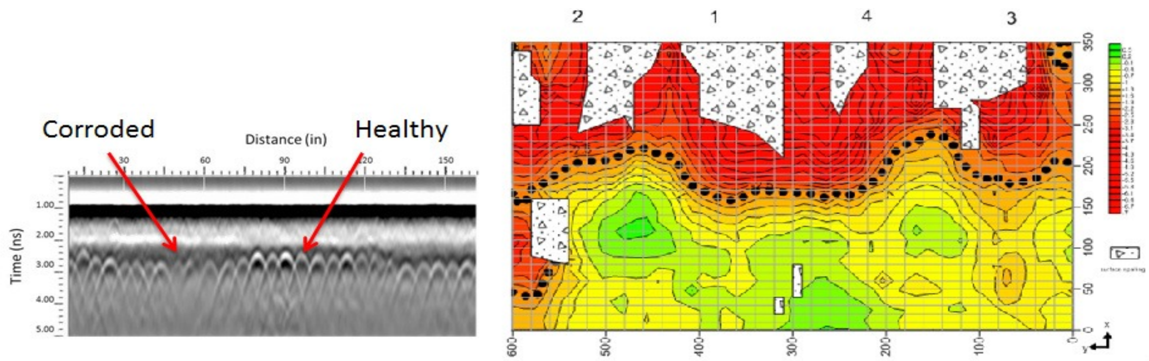

Figure 6. GPR sensor to derive corrosion state of bridge decks

Table 1. Summary of VOTERS technologies, their measurements and specifications.

Technology	Measurements	Specifications	Picture
VOTERS Microphone Acoustic measurement of the tire noise	• Friction • Raveling • Bleeding • Mean Texture Depth (MTD) • Polished Aggregate	• Sensor height: ½ - 3 inch • Sampling Rate: 2 - 200 KHz • Sensitivity: 44 - 52 mv/Pa	
Dynamic Tire Pressure Sensor (DTPS) Acoustic measurement of the dynamic pressure from the tire/road interaction	• Roughness • Road Profile • Road Height Variations • International Roughness Index (IRI)	• Frequency: 0.5 Hz - 20 KHz • Sampling Rate: 2 - 200 KHz • Dynamic Pressure: 0 - 1 psi	
VOTERS Camera Color Video acquisition and automated analysis system	• Crack Density • Patch Density • Potholes • Shoving • Rutting • Feature Identification	• Resolution: 2.82 Megapixel • Speed: Gigabit Ethernet	
Millimeter-Wave Radar Measurement of road surface condition	• Rutting depth • Bleeding • Moisture • Ice • Wetness • Feature identification	• Operation: 24 GHz • Arrays: 5 channels	
Ground Penetrating Radar Measurement of road subsurface characteristics	• Rebar Corrosion • Layer Depth • Vertical Profile • Subsurface Feature Identification (delamination, potholes, etc.) • Subsurface Moisture	• Frequency: 0.8 - 5 GHz • Data rate: 1000 trace/sec • Low cost • Low power • Small	

3.3 System Integration

VOTERS framework requires a system capable of managing mobile sensor fusion and bulk data handling in addition to integration of interactions between various components of this design. Using system-level integration methods, VOTERS has created expandable flexible distributed multi-OS system architecture suitable for many mobile heterogeneous (multi-modal) sensing systems. This modular system architecture contains all necessary functionality for such a system to be autonomous from the vehicle operator. The automation includes start and stop of the coordinated data acquisition through monitoring of a GPS-based home zone and partitioning of data sets into hierarchical, expandable definition of data streams containing the data files. Once the mobile sensor system returns back home and after detecting the presence of the home network the automatic bulk data upload to the data server starts. Automatic processing of individual or multiple data streams and in what sequence is controlled by a configurable Plugin Executor which we will discuss in section 3.3.2. Significance of automation lies in the nature of the project: VOTERS system would need to collect hundred Gbytes of data a day. Here, we will briefly discuss VOTERS system integration design and achievements, more details can be found in [16-18].

Each subsystem within VOTERS contains one or more sensors. The raw data of the sensor as well as processed data from one or more sensors are recorded as streams. One stream can be the raw unprocessed stream, such as video images of the road surface; another could be processed from the raw stream and show an image of detected cracks. For each sensor, there is a stream called "log file". Geo-relations are defined by time-stamps which are the one column present in all the log files. VOTERS data diversity and volume is summarized in Table 3.

Parts that come together to store, process, analyze and represent VOTERS data are File Server, Plugin Executor and GIS Server, as shown in Figure 7.

3.3.1 File Server

After each survey is completed, raw data are uploaded to the file server. The "Plugin executor" responsible for processing data also places streams into the file server.

3.3.2 Plugin Executor

For displaying streams and for processing raw data inside the streams, "plugins" are defined. Plugins are scripts that transform one stream type (e.g. unprocessed data) to another stream type (e.g. feature extracted data). A plugin executor tracks the survey data available on the file server. Plugins operate on one or more streams and produce one or more new output streams that are added to the datasets on the file server.

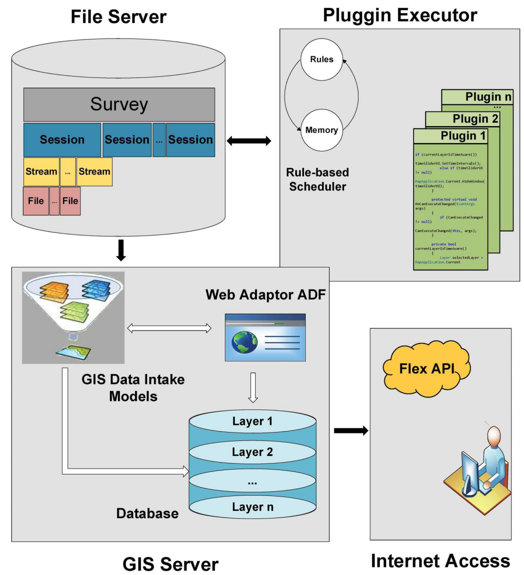

Figure 7. Data Flow in VOTERS System.

3.3.3 GIS Server

In GIS Server, large volumes of data are given spatial references and evolve into meaningful knowledge. "Data intake plugins" feed available streams into a commercial grade work station hosting GIS software, an Oracle database, a web adopter and a Flex API. GIS software is responsible for geo-referencing streams and spatial analysis while the Oracle database stores the streams that GIS software refines. The web adopter pushes data to the web and the Flex API consumes services on the GIS server (Figure 7). This web-based front end application is introduced as PAVEMON.

Table 2. VOTERS data diversity and volumes

Sensor	Max Sensor	Min Trigger Interval	Points/ Sensor/ Trigger	Size/ point [byte]	Data rate [GB/h]
Positioning Data	1	0.2 s	4	4	0.0003
Acoustic Microphones	4	25 us	1	4	2.1
Dynamic Tire Pressure	2	25 us	1	4	1.1
Millimeter-wave radar	10	25 us	1	4	5.4
Video Systems	1	1 m	5018400	1	467.4
GPR array	16	0.0.1 m	1024	2	305.2

To illustrate the value of this design, we compared the time effort for data collection, transfer and processing in three scenarios: using the VOTERS system integration framework, traditional manual methods and van-based systems with expensive optical sensors installed. This is reflected in Table 3.

Table 3. VOTERS system integration compared to other road inspection methods

	Data Collection[h]	Data Transfer[h]	Data Processing[h]	Total [h]
Traditional Methods	800	0	320	**1120**
Van-based systems	32	16	320	**248**
VOTERS	24	16	14	**54**

4. SENSOR FUSION AND CORRELATION

VOTERS system collects data and extract features from multiple sensors: GPR array, acoustic microphones, dynamic tire pressure, millimeter-wave radar, video images and positioning information. Information from one sensor could contribute in increasing the confidence intervals inferred from another sensor's measurements. As an example, mm-wave radars could detect metal hence presence of manholes on the road. While driving over a manhole, signals from acoustic sensors are agitated similar to variations in signals caused by patches, potholes or other road distresses which are crucial in assessing road conditions. Mm-wave radar could help in differentiating between these two scenarios, making acoustic data more reliable, as shown in figure 8.

Each sensor in VOTERS system contains information about a particular aspect of road quality. To predict the overall pavement condition and deal with heterogeneous and redundant observations one must fuse them for jointly-derived higher-confidence results for a better decision making. A naive way of combining this information is by concatenating the features as a single input vector to a standard classifier for predicting the PCI score. This is suboptimal because feature types may be incompatible and information structure can be lost [31-32]. Instead, VOTERS has designed specialized predictive models / classifiers for each sensor. VOTERS then developed a fusion scheme for combining the predictions of all these sources and choosing the predictors with the best performance. In the final model (Figure 9) through data fusion of a subset of parameters extracted from Tire Excited Acoustic Sensor Systems, PCI has been successfully predicted. Table 2 is a comparison between our predicted PCI values and a reference PCI value collected manually by a local engineering firm (CDM Smith) for 7 streets in city of Brockton, MA, USA.

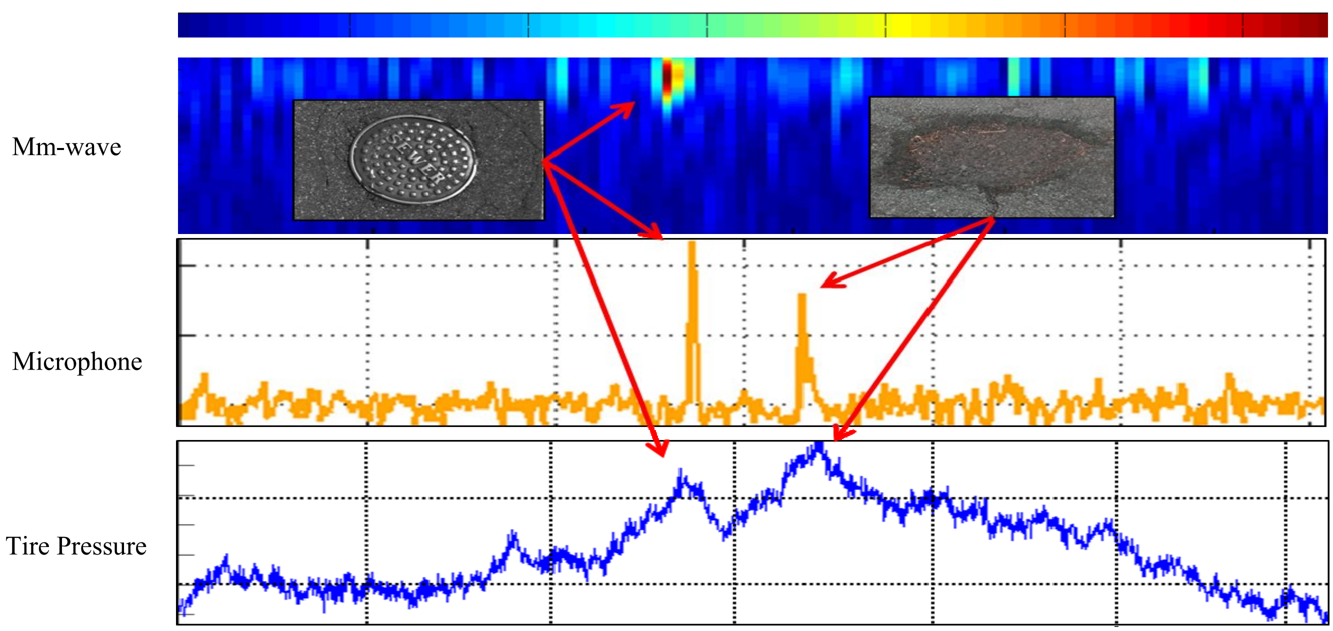

Figure 8. Temporal Sensor Fusion differentiation between manholes and distresses.

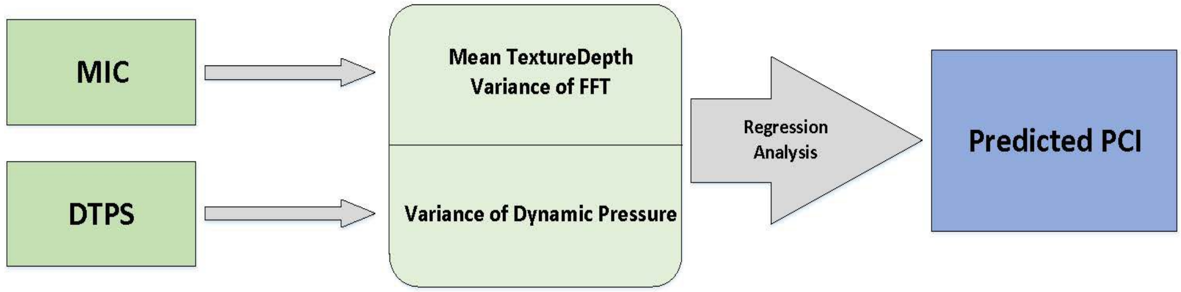

Figure 9. Fusing outputs from acoustic measurements to predict PCI.

Table 4. Comparison of seven roads from VOTERS predicted PCI versus manual surveyed PCI

Streets	Manually-surveyed PCI	VOTERS Predicted PCI
Tina Ave	0	12.73
Brookville Ave	7	7.77
Gary Rd	12	9.13
Field St	41	43.90
Lisa Drive	64	62.84
North Montello St	84	94.20
North Quincy St	90	90.26

5. PAVEMON APPLICATION

PAVEMON (PAVEment MONitoring) is VOTERS geospatial data repository and analysis tool. It is designed to visualize and perform spatial analysis on large amounts of VOTERS data that contain surface and subsurface information of pavements. As described in section 5.3, PAVEMON, built on the ArcGIS platform and published to a customized Flex interface, writes huge amounts of data (raw, processed, fused) to an Oracle database, and makes them accessible across the web for visualization and spatial analysis.

For every 10 m of road, different parameters are calculated and geo-referenced on the map. These parameters include pavement related features of roughness, friction and road profile in sections 4 and 5. As there no intentions to visualize or analyze all the data of all locations at the same time, data are stored in layers. Having a layer-based design gives a significant boost to this application as users will be querying only a fraction of the Terabytes of data managed by PAVEMON. After these layers are published to the web by the web adopter, the Flex API consumes them to grant access, enable queries, and spatial analysis capabilities to front-end users. Prompted by the user, PAVEMON references each layer out of the database.

From correlating sensor data with the corresponding images, collected by a camera installed on back of the vehicle, data mining algorithms can be developed and validated. Captured every 1.2 meters, these images have been geo-tagged and mosaicked together in the pyramid scheme to provide a resolution far beyond the aerial photography without caching lot of memory. Google Street-view images have also been integrated into PAVEMON as a third party API to further verify sensors' data. Accessing all these layers through PAVEMON has greatly enhanced pavement management capabilities. Figure 10 shows an overview of PAVEMON's features and different parts. More details can be found in [22].

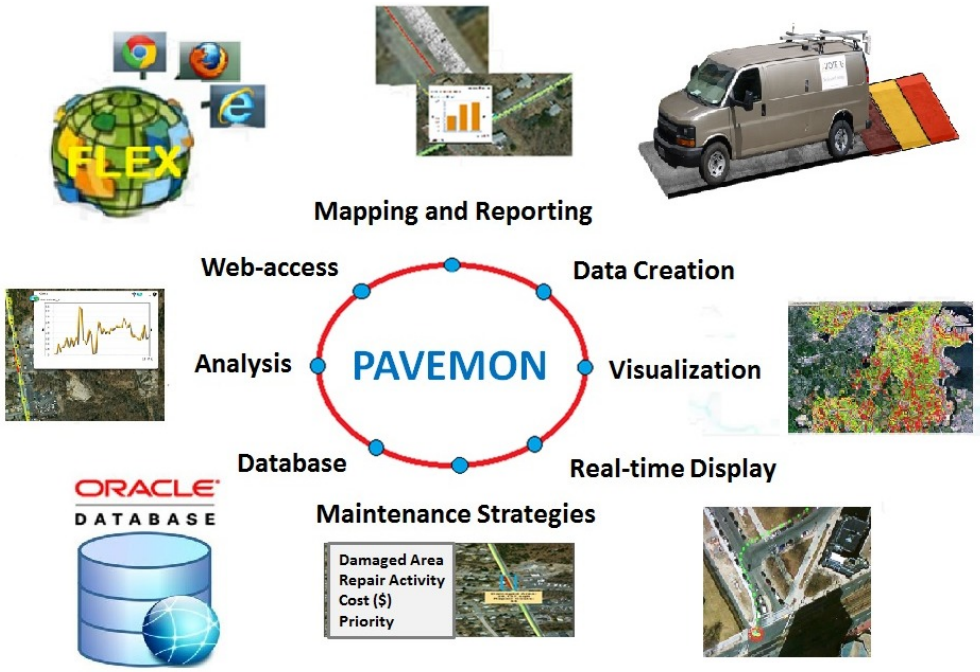

Figure 10. PAVEMON features and different parts

On right side of figure 11, the developed GIS visualization portal is shown with multiple data layers covering a given roadway. Multiple data visualizations are available such as crack density or the pavement image. In the query interface at the bottom, user can fine tune the refined survey results such as the examination of single data point or a geographical area. In addition, a zoomed-in image embedded in the figure shows the detailed roadway performance validated by the images collected by the camera sensor. Google street-view image is also available as shown in top right. The entire VOTERS system and PAVEMON architecture has been evaluated in assessing infrastructure performance of the entire city of Brockton, Massachusetts, USA. Taken as a screen shot from the GIS visualization portal, the left side of Figure 11 shows the city pavement condition for entire road network of the Brockton city, MA.

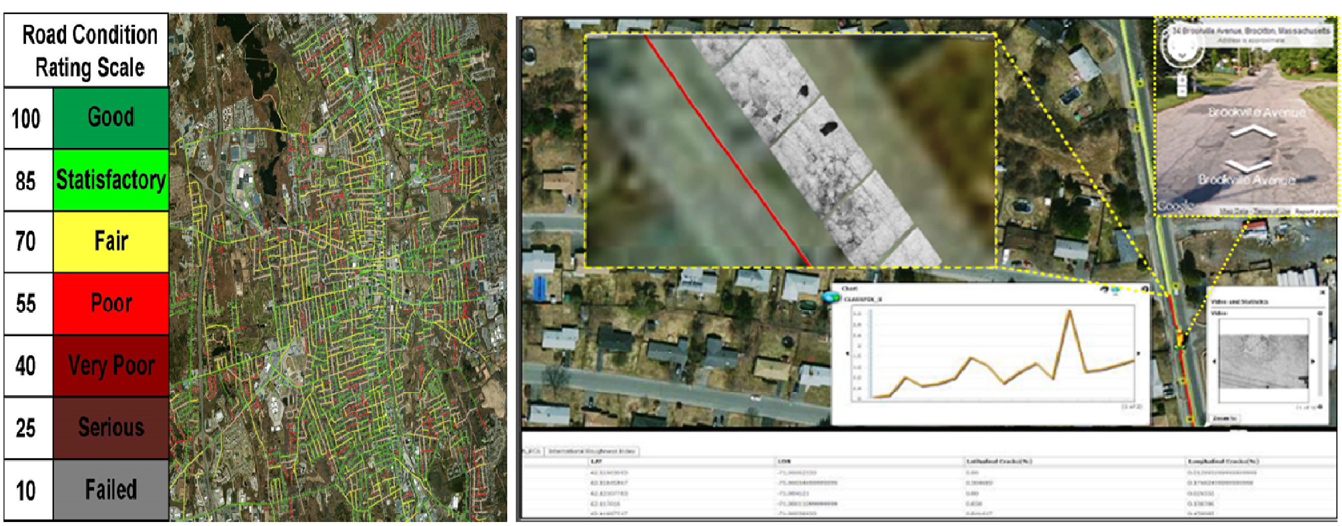

Figure 11. Brockton, MA, Roadway Assessment (Left), visualization, analysis and query portal (Right)

7. CONCLUSION

Performance monitoring of civil infrastructure has always been an arduous undertaking. While substantial endeavors have been made to find alternatives for manual inspecting each street of a road-network, an affordable framework that could offer a continuous network-health monitoring of roadways is yet to be defined. Within these paradigms, the VOTERS project has developed a multi-modal mobile sensor system and mounted it on a prototype vehicle. In its' fifth year of development phase, VOTERS system is able to automatically collect, store, and process Gbytes of data coming out of light-weighted affordable acoustic, optical and electromagnetic sensors. Along with providing information on surface conditions and road distresses, VOTERS processed data streams entail subsurface information. Through time and frequency domain analysis along with sensor fusion techniques and statistical analysis, prominent pavement parameters that infrastructural managers rely on are extracted from acoustic sensors. These include measures of roughness (IRI), skidness (MTD) and overall road conditions (PCI). A web-based GIS application ensures accessibility to this valuable data set through a thin client application. Pouring in after each survey are Terabytes of data which are visualized, accessed, and analyzed within a day after of data collection through VOTERS Pavement Monitoring System, PAVEMON.

Major advantages of VOTERS system over similar vehicle-mounted sensor systems are:

1. Fully automated data acquisition and processing, no human interaction required (except driving)
2. Affordable light-weighted sensor suite
3. Vehicle-friendly system, potentially any typical vehicle can be equipped with this system
4. Subsurface features considered
5. Includes outputs on all aspects of pavement for every 10 m of roads

Utilizing VOTERS framework is not only a large societal investment, but creates unique windows of opportunities by providing time series datasets previously unattainable for researchers and infrastructural managers. The ability to quickly implement a large scale survey especially comes in handy after an extreme event such as snow storms or hurricanes which will change the pace of deterioration.

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REFERENCES

[1] Federal Highway Administration, 2011, www.fhwa.dot.gov/policyinformation/statistics/2011/.
[2] Federal Highway Administration, U.S. Department of Transportation, 1999, Pavement Preservation: A Strategic Plan for the Future, FHWA-SA-99-015.
[3] Purdue University, 2012, Introduction to Transportation Engineering, https://engineering.purdue.edu/~ce361/LECTURE/Lrigid_pms.html.
[4] Spalding DeDecker Associates, Inc., Pavement Management, http://www.sda-eng.net/?page_id=420.
[5] American Society for Testing and Materials (ASTM), 2009, Standard Practice for Roads and Parking Lots Pavement Condition Index Surveys.
[6] Vines-Cavanaugh D., Wang M., McDaniel G., 2013, Real-world application and validation of vehicle-mounted pavement inspection system, Proceedings of SPIE on Smart Structures and Materials and Nondestructive Evaluation and Health Monitoring, San Diego, CA .
[7] Tsai, Y., Li, F., 2012, Detecting Asphalt Pavement Cracks under Different Lighting and Low Intensity Contrast Conditions Using Emerging 3D Laser Technology, ASCE Journal of Transportation Engineering, 138(5), 649–656.
[8] Zhang, Y., McDaniel, J. G., Birken, R., & Wang, M. L., 2013b , Quantification of Pavement Condition by Tire/Road Noise Measurement, Proc. of IWSHM 2013, September, Stanford, California.
[9] Wang, Q., McDaniel, J. G., Wang, M. L., 2012, Feasibility Investigation of Dynamic Tire Pressure Sensor in Pavement Assessment, Journal of Sound and Vibration.

[10] Wang Q.. McDaniel G., Nian X. Sun, and Wang M. L., 2012, Measuring Road Profile by Tire Pressure Sensing, Journal of Testing and Evaluation, ASTM.
[11] Oden C. and Birken R., 2011, Array GPR system for continuous monitoring of bridges and roadways, Proceedings of the Engineering Mechanics Institute (EMI 2011), Boston, MA.
[12] Oden C. and Birken, R., 2012, A GPR array system for traffic embedded monitoring of bridges and roadways, Proceedings of SAGEEP 2012, Tucson, AZ.
[13] Oden, C., and Birken, R., 2013, New digitizer technology enables low-cost GPR array system for traffic embedded monitoring of bridges and roadways: Proceedings of SAGEEP 2013, Denver, CO.
[14] Vines-Cavanaugh, David, Busuioc, Dan, Birken, Ralf, and Ming Wang, 2012, Millimeter-wave non-destructive evaluation of pavement conditions: Proceedings of SPIE Symposium on Smart Structures and Materials + Nondestructive Evaluation and Health Monitoring, 11-15 March 2012, San Diego, CA.
[15] Ghanta, S., Birken, R., and Dy, J., 2012, Automatic road surface defect detection from grayscale images, In Proc. of SPIE Symposium on Smart Structures and Materials + Nondestructive Evaluation and Health Monitoring.
[16] Birken, R., Schirner, G., and Wang, M., 2012, VOTERS: Design of a mobile multimodal multi-sensor system: Proceedings of the ACM SIGKDD International Conference on Knowledge Discovery and Data Mining, SensorKDD'12, Beijing, China, 8-15.
[17] Birken, R., Zhang, J., and Schirner, G., 2014, System Level Design of a Roaming Multi-Modal Multi-Sensor System: chapter 6 in Wang, Ming L., Sohn, Hoon, and Lynch, Jerome (editors), 2014, Sensor Technologies for civil infrastructures: Performance assessment & health monitoring: Woodhead Publ., in print.
[18] Zhang, J., Qiu H., Shahini Shamsabadi S., Birken, R., and Schirner, G, 2014, SIROM3 - A Scalable Intelligent Roaming Multi-Modal Multi-Sensor Framework, Proceedings of the COMPSAC on The Integration of Heterogeneous and Mobile Services in Smart Environments, Vasteras, Sweden. Under review.
[19] Zhang, Y., McDaniel, J. G., and Wang, M. L., 2013, Estimation of Pavement Macrotexture by Principal Component Analysis of Acoustic Measurements, J. Transp. Eng., 10.1061/(ASCE)TE.1943-5436.0000617, 04013004.
[20] Zhao Y., McDaniel G., and Wang M. L., 2012, "IRI Estimation Using Probabilistic Analysis of Acoustic Measurement", Journal of Materials Performance and Characterization (MPC), ASTM.
[21] Shahini Shamsabadi S., Birken R., and Wang M. L., 2014, Pavement Condition Monitoring by Fusing Data from a Mobile Multi-sensor Inspection System, Proceedings of the IACSM on Structural Control and Monitoring, Barcelona, Spain.
[22] Shahini Shamsabadi S., Wang M. L., and Birken R., 2014, PAVEMON: A GIS-based Data Management System For Pavement Monitoring Based on Large amounts of Near-Surface Geophysical Sensor Data, Proceedings of the SAGEEP on Geophysical Data Management, Boston, MA.
[23] American Society for Testing and Materials (ASTM), 2014, Standard Practice for Computing International Roughness Index of Roads from Longitudinal Profile Measurements.
[24] ISO 13473-1: 1997(E), Characterization of pavement texture by use of surface profiles – Part 1: Determination of Mean Profile Depth, first edition, American National Standards Institute (ANSI).
[25] Stroup-Gardiner, M. and Brown, E. R., 2000, Segregation in hot-mix asphalt pavements, Report No. 441, Transportation Research Board.
[26] Jones, D., Harvey, J., Al-Qadi, I. L., and Mateos, A., 2012, Advances in Pavement Design Through Full-Scale Accelerated Pavement Testing. CRC Press.
[27] Standard Test Method for Friction Coefficient Measurements Between Tire and Pavement Using a Variable Slip Technique, ASTM Standard TestMethodE1859-97 (Reapproved 2001), Annual Book of ASTM Standards, vol. 04.03, pp. 1079-1086, 2003.
[28] Li M., Busuioc D., Wu J., Birken R., Wang M. L., Sun N., A Novel Broadband Bowtie Antenna for Ground Penetrating Radar System", International Journal of RF and Microwave Computer Aided Engineering, Under Review.
[29] Martino N., Maser K., Birken R., and Wang M. L., 2014, Determine Ground Penetrating Radar Amplitude Thresholds for the Corrosion State of Reinforced Concrete Bridge Decks: Journal of Environmental and Engineering Geophysics, accepted for publication.
[30] Martino N., 2013, Quantifying Reinforced Concrete Bridge Deck Deterioration Using Ground Penetrating Radar, Dissertation, Northeastern University.
[31] Hall D., Llinas J., 1997, An Introduction to Multisensor Data Fusion, Proc. of the IEEE, VOL. 85, NO. 1
[32] Doeswijk T., Smilde A., Hageman J., Westerhuis J., Eeuwijk F., 2011, On the increase of predictive performance with high-level data fusion, Elsevier, Analytica Chimica Acta 705 (2011) 41– 47.