Memo

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From: C. Brooks, K.A. Endsley, M. Forster

CC: D. Evans, R. Oats, K. Vaghefi, R. Hoensheid, de Melo e Silva

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Re: DSS update - integration of bridge health indicators and development of the bridge condition signature

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The first and second primary goals of our project, as stated in the proposal's Technical Approach, are as follows:

1. Establish remotely sensed bridge health indicators.
2. Develop a baseline bridge performance metric, the "signature," for benchmarking overall bridge condition.

The first goal is an ongoing effort to validate remote sensing technologies for bridge health applications which involves all members of the project team and includes activities such as laboratory testing of remote sensing technologies. These efforts have milestones such as the Commercial Sensor Evaluation Report (as posted to http://www.mtri.org/bridgecondition/Tasks_and_Deliverables.html) and the numerous experiment plans, collection procedures, and data processing workflows generated along the way. The next step towards achieving this goal involves integrating what remotely sensed bridge health indicators we have established so far into the decision support system (DSS) and linking them to traditional metrics of bridge condition.

The second goal, to develop a comprehensive metric of bridge condition, is a desired outcome of the DSS design and development. The Bridge Condition Decision Support System, currently under development and recently displayed at the Technical Advisory Committee meeting, will include the ability to apply algorithms used to extract and combine relevant condition information from sensor data, compare current sensor data to historical data in order to establish trends, and make recommendations to ensure optimal bridge health using cost-effective maintenance and repair protocols. Central to its utility will be the ability to synthesize measures of bridge condition from the disparate remote sensing, historical and inventory datasets. This effort will require insightful modeling and display of the data and careful design of the underlying DSS database.

A Survey of the Datasets and their Parameters

The following datasets are currently planned for integration with the DSS, depending on the level of development and practicality they reach through lab studies and the field demonstration:

1. Existing bridge inventory data (e.g. MDOT's bridge inspection data)
2. Radar imagery and analysis outputs
3. 3D optics models and analysis outputs
4. "StreetView-style" photography
5. Thermal infrared analysis results
6. Digital image correlation analysis results
7. Satellite imagery and aerial photography analysis results
8. Representative LiDAR data

Of these technologies, currently the 3D optics, StreetView-style photography, thermal infrared and radar imagery analyses are the furthest along towards a summer 2011 field demonstration. In late March 2011 we received a “snapshot” of the full bridge condition database used in MDOT’s bridge management system (BMS).

The remote sensing datasets will initially be comprised of specially-processed data, each with their own representation of bridge health indicators. It is the interpretation that arises from analysis of these outputs that must be represented in the database in a consistent and meaningful way. Meaningful indicators such as width of cracks, depth of spalls and area of delamination must be extracted from these outputs.

Starting with the existing bridge inventory data (in this case, from MDOT), the following parameters are those which are likely to be informed or updated by other datasets:

- Deck rating
- Substructure rating
- Superstructure rating
- Culvert rating (if any)
- Sufficiency rating
- Bridge length
- Deck width
- Clearance

The other fields in the existing bridge inventory data represent parameters that are not likely to be captured or updated by any other type of investigation. These bridge *metadata* signify that the table(s) of existing bridge inventory data will also serve as *lookup tables* for contextual information. This context includes bridge data that never change during the life of the bridge (e.g. year built, location) or bridge metrics that change only with human intervention (construction and maintenance) such as the number of lanes and spans and the dates of maintenance activities. In addition, the existing bridge inventory of a state DOT contains the ratings (e.g. superstructure, substructure, culvert) given to the structure, and an approximately 10 to 12-year record of those ratings, according to a description of the database from MDOT. We are currently investigating the bridge condition database to gain a fuller understanding of all the details and time periods contained within it, and will be meeting with our DSS focus group to continue this process in April 2011. Included below is an overview of the technologies investigated during this project and the bridge condition indicators it is anticipated they can collect information about. The metrics of bridge condition to be extracted from these indicators are detailed as well.

The outputs from radar data collection (i.e. coherent radar images) initially cannot be represented as table(s) in a database. Feature/information extraction will deliver metrics of bridge condition that can be incorporated into the database and compared to other measures of bridge condition. Based on our laboratory testing and the Commercial Sensor Evaluation Report, radar is capable of resolving the following bridge condition indicators: deck cracking, delaminations, and corrosion of rebar. While the processed radar images will be made available separately within the DSS, parameters such as width of deck cracks, measured area, depth and extent (percentage of total area) of delamination, and crack density are expected to be derived from the analysis.

The outputs from 3D optics will include digital surface models and original high-resolution photographs. Final results and interpretations of 3D optics will be available through the DSS within the current constraints of web browsers. The major limitation to analyzing these data is that the digital surface models cannot be viewed within the web browser in 3D. Instead, 2D projections of these surface models might be made available for viewing. Analysis of the 3D models, through feature extraction algorithms not exposed in the DSS, should provide parameters of bridge condition assessment which will be incorporated into the DSS including depth, area, extent (percentage of total area), and volume of spalls, section loss and potholes.

Outputs from the "Street-View Style" photography will be a series of photographs or photographic panoramas. These will be made available in the DSS through a GIS, where the data are tied to their geospatial context. While feature extraction is not planned to be a part of the analysis of these data, they might have important metadata associated with them such as date/time of collection, collection rate, and vehicle speed in addition to the foreign key (NBI bridge identification) which ties the data to the established (inventory) metadata. These high-resolution "photolog"-type inventories allow state DOTs to efficiently monitor how a bridge has changed visually over time.

Thermal infrared imaging outputs are in the form of a series of photographs reflecting the changes in thermal radiation of the target over time. As with radar and other remote sensing modalities, the post-processed images will be available in the DSS for the power-user’s interpretation and analysis. In addition, the following parameters of bridge condition will be extracted and tabulated for comparison and visualization in the DSS: the depth, area, and extent (percentage of total area) of spalls, section loss, and potholes as well as the extent of deck cracks and map cracking. Since these metrics would also be extracted from the radar dataset(s), the DSS would offer multiple, equally-valid (presumably) measurements of bridge condition indicators which could be substituted for one another or used to complete a time series history of bridge condition.

The application of digital image correlation (DIC) to bridge condition assessment will produce numerous plots of the strain field over time as well as maps of rigid displacements. These outputs, generated by special processing algorithms, will also be available in the DSS (again, for power-users). The tabular metrics to be extracted from the post-processed data include the offset of bridge settlement or transverse bridge movement, and the amplitude, frequency, and modes of vibration.

Processed aerial and satellite electro-optical (EO) images, as with the images collected and processed through other remote sensing techniques, will be available for viewing within the DSS. The metrics to be extracted (through algorithms not exposed in the DSS) include measurements of bridge length, surface roughness, width of deck cracks, area and extent (percentage of total area) of map cracking and surface depressions as well as length of seal/expansion joint damage.

Based on what LiDAR data will be available for use in the demonstration DSS, the anticipated outputs, like those from 3D optics, will not be directly included in the DSS. Rather, the metrics extracted from these indicators will be included for analysis and comparison with other datasets within the DSS; these metrics include: width and depth of deck cracks, area and extent of map cracking and surface depressions as well as depth of depressions, volume of section loss and, possibly, the global metrics transverse bridge movement and bridge settlement offsets.

Integrating Multiple Indicators through Identifying Commonalities in Data Models

All of the datasets have some characteristics in common. As regards the database, they are each dynamic in that their respective tables within the database will be continuously updated with new records in the future. This is especially true for the existing inventory data which are based on routine bridge inspections. How are these metrics to be represented as a time series in the database? Are they best represented as a series of successive tables or as individual records in one table?

In the demonstration DSS, time series are likely to be represented by individual records that encapsulate an observation in time. The date/time stamp and the metrics obtained from a remote sensing data collection will be fields included with every record. Unless multiple observations are stitched together and a single, representative metric is produced, the granularity of records will be based on how many individual observations were obtained during a survey (e.g. multiple snapshots of bridge deck captured by 3D optics camera system, thermal infrared camera, or scanning radar). This means that one bridge may have multiple observations (records) on the same day over the duration of a single survey of that bridge. To obtain the average deck crack width of a single bridge at a single point in time, say, extracted from multiple 3D surface models, aggregation of these records for the given time period would be performed. This "average deck crack width at the given time" could then be plotted in a series of similar measurements for the same bridge or multiple different bridges to extrapolate desired decision criteria of any kind (e.g. average crack width changes over time or distribution of crack widths in an inventory at a given time).

Another thing these datasets have in common, necessarily so, is their primary key. Identifying the primary key for a bridge database requires a consideration of the problem domain context. At a national level, every bridge in the U.S. has unique bridge identification (ID). In some state DOT's Bridge Management Systems, every bridge may also be identified by a structure number which is unique to every bridge in that state but is not necessarily unique outside of that state. For scalability, we have decided to use the national bridge ID as the primary key identifying unique bridges in our database. Each observation of a bridge condition indicator through any remote sensor is then tied to a specific bridge at a specific time. It is the temporal and spatial queries executed on these observations that derive the decision criteria of interest and allow for integration of multiple bridge condition indicators into a user-defined, comprehensive bridge signature.

Representing Bridge Condition Indicators through Established Ratings of Bridge Condition

In order to convey bridge condition in a meaningful way to bridge inspectors and manager, it is important to represent metrics of bridge condition through established rating systems (e.g. NBI). To this end, we will be using the current references and standards materials prepared for and by state DOTs, national transportation agencies and our representative DOT partner (Michigan). These are likely to include, but will not be limited to:

- AASHTO Guide Manual for Bridge Element Inspection - 2011, First Edition. https://bookstore.transportation.org/collection_detail.aspx?ID=97
- MDOT Project Scoping Manual - October 2009. http://www.michigan.gov/mdot/0,1607,7-151-9622_11044_11367-243045--,00.html
- MDOT Prestressed Concrete Box-Beam Superstructure Evaluation Handbook. April 2011. Available from the Michigan Tech Transportation Institute Tech and the MDOT Bridge Operations Unit.
- Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridge. 1995. USDOT FHWA Report No. FHWA-PD-96-001.

- Reports and updates posted to the National Bridge Inventory web page (http://www.fhwa.dot.gov/bridge/nbi.htm).
- MDOT's Asset Management program information, especially as it relates to bridge condition information, such as the Bridge Management System of the Transportation Management System (BMS, http://www.michigan.gov/mdot/0,1607,7-151-9621_15757---,00.html).
- MDOT's Michigan Structure Inventory and Appraisal Guide (http://www.michigan.gov/documents/MDOT-Bridge-SIAMANUAL-2_87989_7.pdf)

To the extent that condition indicators for a bridge overall and bridge structural elements described in these and other relevant publications can be linked to remote sensing, this project will be able to demonstrate how remote sensing can be used to assess bridge condition and an overall bridge signature. The effort to synthesize a comprehensive bridge signature from the different bridge condition indicators is currently underway and will continue through the next quarter in both the bridge characterization task and the DSS development task. Our spreadsheet entitled "Performance Rating of Commercial Remote Sensing Technologies", as shown in Table 3 of the Commercial Sensor Evaluation report, was the start of that process. That spreadsheet and also an example of measurable bridge indicators tied to established ratings based on the Michigan Structure Inventory and Appraisal Guide, are attached to this memorandum.

Table 3: Performance Rating of Commercial Remote Sensing Technologies

Location	Challenges	Indicator	Desired Measurement Sensitivity	Rating Based, in Part, on Theoretical Sensitivity for Measurement Technologies											
				GPR	Spectra	3D Photo-grammetry	EO Airborne/ Satellite Imagery	Optical Inter-ferometry	LiDAR	Thermal IR	Acoustics	DIC	Radar (Backscatter/ Speckle)	InSAR	Streetview-Style Photography
Deck Surface	Expansion Joint	**Torn/Missing Seal**		0	8	14	12	11	13	11	0	0	9	0	13
		Armored Plated Damage		0	0	14	12	11	13	11	0	0	0	0	13
		Cracks within 2 Feet	0.8 mm to 4.8 mm (1/32" to 3/16") width	0	8	14	0	12	12	11	0	0	9	0	13
		Spalls within 2 Feet	6.0 mm to 25.0 mm (1/4" to 1") depth	0	8	14	12	12	12	11	0	0	9	0	13
		Chemical Leaching on Bottom		0	11	0	0	0	0	0	0	0	0	0	0
	Map Cracking	Surface Cracks	0.8 mm to 4.8 mm (1/32" to 3/16") width	0	8	14	12	12	12	11	8	0	9	0	13
	Scaling	Depression in Surface	6.0 mm to 25.0 mm (1/4" to 1") depth	0	8	14	12	12	12	11	0	0	9	0	13
	Spalling	Depression with Parallel Fracture	6.0 mm to 25.0 mm (1/4" to 1") depth	0	8	14	12	12	12	11	0	0	9	0	13
	Delamination	**Surface Cracks**	0.8 mm to 4.8 mm (1/32" to 3/16") width	0	8	14	0	12	12	11	8	0	0	0	13
Deck Subsurface	**Expansion Joint**	**Material in Joint**		0	0	0	0	11	0	0	0	0	0	0	0
	Delamination	**Moisture in Cracks**	Change in moisture content	11	0	0	0	0	0	11	0	0	0	0	0
		Internal Horizontal Crack	Approximately 0.1 mm (0.004") level	0	0	0	0	0	0	11	8	0	0	0	0
		Hollow Sound		0	0	0	0	0	0	0	8	0	0	0	0
		Fracture Planes / Open Spaces	Change in signal from integrated volume	12	0	0	0	0	0	0	8	0	12	0	0
	Scaling	Depression in Surface	6.0 mm to 25.0 mm (1/4" to 1") depth	12	0	0	0	0	0	11	0	0	0	0	0
	Spalling	Depression with Parallel Fracture	6.0 mm to 25.0 mm (1/4" to 1") depth	12	0	0	0	0	0	11	0	0	0	0	0
	Corrosion	Corrosion Rate (Resistivity)	5 to 20 kΩ-cm	0	0	0	0	0	0	0	0	0	0	0	0
		Change in Cross-Sectional Area	Amplitude of signal from rebar	13	0	0	0	0	0	0	8	0	13	0	0
	Choride Ingress	Choride Content through the Depth	0.4 to 1.0 % chloride by mass of cement	12	0	0	0	0	0	0	0	0	12	0	0
Girder Surface	**Steel Structural Cracking**	Surface Cracks	< 0.1 mm (.004"), hairline	0	8	11	0	12	0	11	0	0	0	0	0
	Concr. Structural Cracking	Surface Cracks	.1 mm (.004")	0	8	11	0	12	0	11	8	0	0	0	0
	Steel Section Loss	Change in Cross-Sectional Area	Percent thickness of web or flange	0	0	11	12	0	13	11	0	0	11	0	0
	Paint	**Paint Condition**	Amount of missing paint (X %)	0	9	0	0	0	0	11	0	0	0	0	0
	Concrete Section Loss	Change in Cross-Sectional Area	Percent volume per foot	0	0	11	12	0	13	11	7	0	11	0	0
Girder Subsurface	**Concr. Structural Cracking**	Internal Cracks (e.g. Box Beam)	Approx 0.8 mm (1/32")	0	0	0	0	0	0	11	8	0	0	0	0
	Concrete Section Loss	Change in Cross-Sectional Area	Percent volume per foot	0	0	0	0	0	0	0	7	0	11	0	0
	Prestress Strand Breakage	Change in Cross-Sectional Area	Wire 2 mm or strand 9.5 mm diameter	9	0	0	0	0	0	0	8	0	9	0	0
	Corrosion	Corrosion Rate (Resistivity)	5 to 20 kΩ-cm	0	0	0	0	0	0	0	0	0	0	0	0
		Change in Cross-Sectional Area	Amplitude of signal from rebar	8	0	0	0	0	0	0	8	0	13	0	0
	Choride Ingress	Choride Content through the Depth	0.4 to 1.0 % Chloride by mass of cement	10	0	0	0	0	0	0	0	0	11	0	0
Global Metrics	Bridge Length	**Change in Bridge Length**	Accuracy to 30 mm (0.1ft) (smaller)	0	0	15	13	0	0	0	0	9	0	12	0
	Bridge Settlement	Vertical Movement of Bridge	Approximately 6 mm to 12 mm	0	0	12	0	0	12	0	0	9	0	12	0
	Bridge Movement	**Transverse Directions**	Approximately 6 mm to 12 mm	0	0	12	0	0	12	0	0	9	0	12	0
	Surface Roughness	Surface Roughness	Change over time	0	9	14	13	12	12	0	0	0	11	13	13
	Vibration	Vibration	.5 -20 Hz, amplitude?	0	0	0	0	12	0	0	0	10	12	12	0

Example of Object Bridge Metrics for Applying Established Rating

		Percent of...	Concrete Deck (Top)			Concrete Deck (Bottom)				Steel/Paint Corrosion		Bearings		Expansion Joints
			Cracking		Spalling	Map Cracking		Spalling	Rust	Joint Cracks	Paint Weather	Section Loss	Coating Failure	Water Leakage
			Width	Spacing	Depth	Width	Spacing	Depth	Extent	Width, Proximity	Extent			Adhesion/Seal Failure
9	Excellent	< 2%	NONE	NONE	NONE	NONE	NONE	NONE	NONE	NONE	NONE	NONE	NONE	
8	Very Good	< 2%	< 0.8 mm		NONE	< 0.8 mm		NONE	NONE		"minor"		"minor"	NONE
7	Good	< 2%	< 1.6 mm	> 10 ft	"shallow"	< 1.6 mm	> 10 ft	"shallow"	NONE	< 0.8 mm within 2 ft of joint	"minor"		"minor"	NONE
	Good	0 - 2%	< 1.6 mm	> 10 ft	"shallow"	< 1.6 mm	> 10 ft	"shallow"	NONE		"minor"		"minor"	NONE
6	Satisfactory	< 2%	> 1.6 mm	< 5ft	6.4 - 13 mm	> 1.6 mm	< 5 ft	6.4 - 13 mm	< 2 %	> 0.8 mm within 2 ft of joint	< 1%	"minor"	"minor"	NONE
	Satisfactory	0 - 2%	> 1.6 mm	< 5ft	6.4 - 13 mm	> 1.6 mm	< 5 ft	6.4 - 13 mm	< 2 %		< 1%	"minor"	"minor"	NONE
	Satisfactory	2 - 10%	N/A		N/A	N/A		N/A	N/A		< 1%	"minor"	"minor"	N/A
5	Fair	< 2%	N/A		N/A	N/A		N/A	N/A		1 - 5%	"minor"	"moderate"	N/A
	Fair	0 - 2%	"excessive"		13 - 26 mm	N/A		N/A	N/A		1 - 5%	"minor"	"moderate"	< 5% of length
	Fair	2 - 10%	"excessive"		13 - 26 mm	"heavily map cracked"		13 - 26 mm	2 - 10%		1 - 5%	"minor"	"moderate"	< 5% of length
	Fair	10 - 25%	N/A		N/A	N/A		N/A	N/A		1 - 5%	"minor"	"moderate"	N/A
4	Poor	0 - 2%	N/A		N/A	N/A		N/A	N/A		5 - 10%	< 10%	"considerable"	N/A
	Poor	2 - 10%	N/A		N/A	N/A		N/A	N/A		5 - 10%	< 10%	"considerable"	N/A
	Poor	10 - 25%	"excessive"			"heavily map cracked"			10 - 25%		5 - 10%	< 10%	"considerable"	> 5% of length
	Poor	25 - 50%	N/A		N/A	N/A		N/A	N/A		5 - 10%	< 10%	"considerable"	N/A
3	Serious	2 - 10%	N/A		N/A	N/A		N/A	N/A		> 15%	< 25%	"considerable"	
	Serious	10 - 25%	N/A		N/A	N/A		N/A	N/A		> 15%	< 25%	"considerable"	"most of device leaking or loose"
	Serious	25 - 50%							> 25%		> 15%	< 25%	"considerable"	
	Serious	> 50%							> 25%		> 15%	< 25%	"considerable"	
2	Critical										> 50%			
1	Imminent Failure													
0	Failed													
	Source:	FHWA		MDOT	MDOT		MDOT	MDOT	MDOT	MDOT	MDOT		MDOT	MDOT

References: Michigan Structure Inventory and Appraisal Guide (MDOT), FHWA Specifications for the National Bridge Inventory (FHWA)