Memo

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From: K. Arthur Endsley

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Re: Progress report on Commercial Sensor Evaluations

Commercial Sensor Evaluation Report

In the course of this study thus far, we have evaluated several remote sensing technologies for their suitability in the structural health monitoring of bridges. These technologies not only reflect the domain expertise of the Michigan Tech Research Institute staff but are also most promising for broad, practical implementation in a bridge condition assessment strategy. Other technologies have been evaluated and other will continue to be evaluated, but the techniques specified here represent those that best fit the objectives of the project.

Digital Image Correlation and Tracking

Digital image correlation and tracking is a straightforward approach to measuring structural condition and dynamic character using recognizable features on a target surface. The most reliable implementation involves the use of several fiducial marks of variable sizes. These marks are either projected from a light source or painted directly on the target surface. Once marked, high-resolution photographs of the target surface and the superimposed pattern of markings. A reference photograph can be used for comparison with subsequent still images or a series of photographs can be taken at regular intervals to characterize structural dynamics. Displacement of the target is calculated at the pixel scale based on the displacement of individual marks.

The technique is attractive as it requires no expensive, sophisticated equipment—high-resolution digital SLR cameras are available commercially for less than $1000. The data collected and the processing required to derive measurements of interest are easy to understand and have real-world meaning. Though the fiducial marks can be applied rather easily to the target object, it can be time-consuming as the scale and number of structures to be evaluated increases. Other drawbacks to this technique include its inability to sense changes in a bridge or other structure that do not manifest as deflection and that it is hindered by poor weather, aberration of the optics (such as dirt), and cannot be performed in darkness.

Our implementation of this technique consisted of painting a pattern of dots with a wide size distribution directly on concrete or steel structural elements. A wide size distribution is required in order to prevent aliasing; to ensure that a wide range of rigid displacements can be detected. It is capable of measuring both in-plane and out-of-plane displacement for an effectively 3D measurement of displacement and/or vibration. Most bridge dynamics can be optically sensed and this technique, in particular, allows for very fine accuracy. The resolution is dependent on the distance to the target, but dynamics such as displacement and strain can be measured at sub-pixel accuracy. In laboratory testing of this technique on a steel I-beam, we were able to measure displacement as small as 1/10 of an inch, however, it is possible to measure displacement down to 1/1000 of an inch by controlling spot size, optics selection, and distance to the target. With the appropriate optics, long standoff distances are possible, and these may be more practical for implementation. We expect to rigorously explore the relationship between sensor-target geometry and effective resolution and to demonstrate the technique's flexibility in this respect during field deployments.

Synthetic Aperture Radar (SAR)

Radio detection and ranging (radar) is a familiar but complex remote sensing technique that can measure a target's displacement, speed, frequency of oscillation, modes of vibration, size, distance, and even its material properties. The emission and reflection of electromagnetic (EM) waves is the basis of radar measurement.

In the previous phase of this study, several applications of radar for bridge condition assessment were identified including measuring gross displacement of bridge structure, vibration of the bridge structure, penetrative imaging for the detection of defects, inclusions, or material changes, and the characterization of surface roughness. We have already identified what aspect of the radar signal these measurements will be based upon. Displacement can be measured directly using conductive markers attached to the bridge—these strongly reflect EM energy and their position can be easily calculated from radar returns. Material changes will manifest as changes in the dielectric constant. Surface roughness can be quantified from coherent speckle (sometimes considered to be noise in radar images) as it is proportional to the contrast.

Synthetic aperture radar (SAR) is a technique that combines radar returns from multiple tiny apertures for the purpose of simulating one measurement from a very large aperture. The term aperture here refers to the radar antenna's beam width and, as a rule; larger antennas have narrower beam widths. Consequently, to increase the resolution with which a target surface is imaged a larger antenna is needed. This is obviously inefficient and even impractical for applications with high-resolution requirements. Instead, the effect of using a large aperture can be achieved by post-processing the returns from multiple radar measurements at different positions along a transect line over the target. One tremendous advantage of SAR over GPR in this arena is that the radar returns have real dimensions unlike the singular peaks associated with GPR data. This enables us to measure the dimensions of subsurface features such as rebar—when looking for corrosion—or defects such as delamination when we're interested in specifying the condition of a bridge deck.

We have conducted an investigation into the application of range-compressed radar measurements for detecting and characterizing concrete-embedded features and defects. In a laboratory test, concrete slabs with improvised reinforcing bar inserted in between were imaged using a new radar system featuring range gating, a low-noise amplifier, and position encoder. The slabs were illuminated by EM energy from 500 to 2,000 MHz and we were able to achieve a resolution of 10 cm. The resulting image enabled us to locate the position of the rebar and even distinguish the discontinuities between separate concrete slabs.

Acknowledging that radar images are not easy to interpret, we plan to develop algorithms that would extract features important for characterizing a bridge deck. These algorithms would be fully automated and lend themselves to implementation in a decision support system we conceived for reporting bridge condition and developing bridge "signatures" that help bridge managers make informed decisions about maintenance and safety.

Photogrammetry and 3D Modeling

Photogrammetry, broadly defined, is the science of making accurate measurements by means of photography. This technique achieves accurate 3D measurements of surfaces and terrain through the use of stereo pair imagery. Stereo pairs are comprised of two images with at least 60% overlap and are almost always collected by an aerial photography platform. Stereophotogrammetry as a means of measuring depth in addition to planar extents was first advocated and developed in the 19^{th} century. Since its inception it has matured from a recreational curiosity (i.e. the stereoscopes of the Victorian era) to a well-established remote sensing technique.

Acquisition of stereo pairs is commonly achieved by taking successive still photographs as the camera traverses a straight line over the target. In this way, multiple stereopairs are generated that cover a wide area of the target surface. Modern commercial software such as the Leica Photogrammetry Suite can rapidly generate 3D models from stereo pairs, and our team has extensive experience with this particular product. We have explored the use of stereophotogrammetry as a means of calculating the depth and extent of surficial features and defects on concrete bridge decks. Laboratory research has demonstrated the efficacy of creating 3D models of concrete slabs imaged from two angles. With our considerable experience in digital image processing and feature extraction we are capable of automating the calculation of feature extent and depth from these models.

Further development of this technique will involve the collection of photographs covering an entire road lane using a vehicle-mounted system. We have parameterized the collection of stereo pairs and calculated the necessary camera geometry in order to generate 3D models that will provide accurate and detailed measurements of concrete deck condition. We found that in order to image a road lane on a bridge the camera system must be elevated to total height of 15 feet off the ground. Though the system is limited to detecting only visible features and defects, it offers a rapid and automated method of evaluating bridge deck condition that does not interfere with traffic or require lane closures that might put bridge inspectors at risk.

Spectral Reflectance

Visible and infrared light can be used to characterize a target surface for representation and evaluation in an automated routine. That different materials reflect light differently is intuitive to us—it is the basis of our eyesight. This difference can be quantified, however, and represented in a way that enables us to make reasonable comparisons. Spectral reflectance is such a representation, as it is a measure of the amount of light reflected across the visible and infrared spectrums. Reflectance spectra are plotted as waveforms showing the continuous response of a material to illumination by visible and thermal energy.

Our hypothesis is that different conditions of bridge elements (which can be optically sensed) can be identified by their spectral reflectance. For example, as a concrete bridge deck ages and develops signs of wear its appearance—and therefore spectral reflectance—should change. Different levels of oxidation, chloride intrusion, and leachate issues should also contribute to differences in spectral reflectance. We have attempted to demonstrate the potential of this technology for fairly rapid bridge deck evaluations, conceiving of a vehicle-mounted system capable of capturing reflectance spectra and analyzing them on the fly, performing feature extraction and identification.

We tested our hypothesis in the field using a portable spectroradiometer capable of collecting reflectance spectra from 350 to 2500 nm (ultraviolet to near infrared). This device consists of a backpack unit that communicates wirelessly with a small laptop for data collection. The optical device integrates reflectance spectra from everything within its field of view. At a height of 1 m above the target surface, this amounts to a spot size (footprint) of 30 cm. Data at three bridges in southeast Michigan were collected. The bridges varied in age with concrete deck surfaces that were 47, 39, and 6 years old. Spectral reflectance was collected from the bridge deck surface, both large cracks and hairline cracks, spalls, and asphalt patches. One bridge in particular had areas with visible oxidation, leachate, and exposed rebar.

The reflectance spectra showed considerable difference between the youngest concrete bridge deck and the two far older decks. This difference was marked by a spike from 10 to 40% reflectance in the range of 1000 to 1750 nm. Spalls, oxidation, and leachate all showed appreciably distinctive reflectance curves though exposed rebar and degraded concrete spectra were not appreciably different from areas without defects. The Kolmogorov-Smirnov (KS) test was utilized to quantify the differentiation between spectra curves from different bridges. The test indicated that each bridge's spectral reflectance curve was different from one another, even in the case of the two oldest bridges where the difference between the curves could not be appreciably discerned by eye. This seems to suggest the KS test is not sensitive enough for these distributions. However, the test's D-statistic was considerably higher when comparing either of the older bridges to the younger one and was sufficiently low when they were compared to each other. This would suggest that it is the D-statistic itself and not the acceptance/rejection criteria of the test that should be used to determine if two spectra are sufficiently different.

Though this technique is limited to elements of bridge condition that can be optically sensed, it offers distinct advantages over traditional, visual inspection methods. Most importantly, the measurement processes itself and the data that are collected enable automation of the evaluation and replace subjective assessment with objective characterization.