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An Information Theory-Based 'Thermometer' to Uncover Bridge Defects

By Lakshmi Chandrasekaran (https://sinews.siam.org/About-the-Author/lakshmi-chandrasekaran)

Aging roadway infrastructure generates the threat of sudden bridge collapses, along with the possibility of catastrophic human mortality rates. Unlike with a faulty mobile phone, one cannot simply pick apart a bridge, identify the defect, repair it, and put everything back together.

"When an inspector detects a sign of distress—say, cracking—it is not always straightforward to figure out the cause of the problem without an in-depth analysis," Pinar Okumus (https://engineering.buffalo.edu/civil-structural-environmental/people/faculty_directory/pinar-okumus.html), assistant professor of civil, structural, and environmental engineering at the University of Buffalo, New York, said. "This makes it hard, and sometimes subjective, to evaluate the seriousness of the condition. So, the decision-making to mark a bridge safe or not after detection of a problem is one of the hardest parts of the job." Okumus was not associated with this study.

Is it then possible to perform preemptive, hands-free checks on the mechanical 'health' of bridges? The answer is yes, according to a study (http://aip.scitation.org/doi/full/10.1063/1.4967920) by an interdisciplinary team of applied mathematicians—Amila Sudu Ambegedara, Jie Sun, and Erik Bollt—and civil engineer Kerop Janoyan, all of Clarkson University. The work was published in *Chaos*.

How does math help prevent bridge-collapse disasters? The research team, led by Bollt and Sun, uses techniques from 'information theory,' a branch at the intersection of mathematics and electrical engineering that can help monitor the structural health of bridges.

In 1948, a mathematician and electrical engineer named Claude Shannon (https://en.wikipedia.org/wiki/Claude_Shannon) developed this seminal field to study how information can be quantified, stored, and transmitted through abstract “wires” in terms of bits 0 and 1, igniting modern telecommunication. Incidentally, we celebrated Shannon’s 100th birthday in 2016.

Information theory, is currently comprised of a combination of physics, mathematics, computer science, and engineering methods. This field has spawned the rise of the internet and the World Wide Web, cell phones, cryptography, and many cutting-edge applications.

However, information needs a medium for transmission. Imagine a communication channel via fiber optic cables – one of the fastest media. A nick or tear in the cable would impair communication, as it would be noisy and travel slower. Similarly, a mechanical or structural defect in the bridge would affect mechanical waves travelling through it.

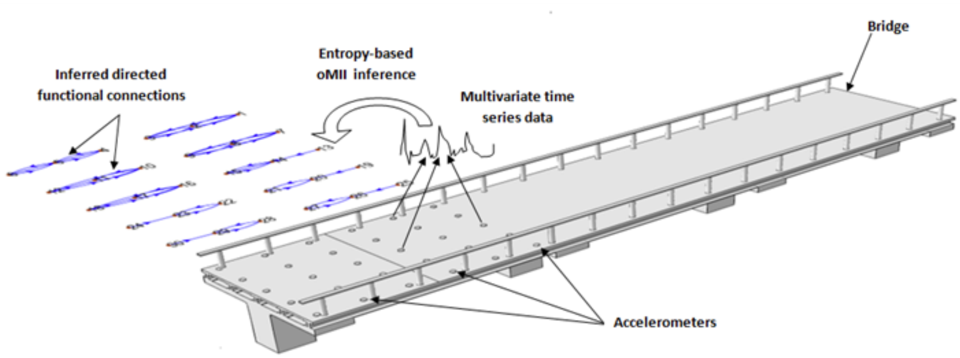
“I have always been fascinated with the concept that the way a given disturbance, an acceleration, a distortion travels through media is clear, but the details of how tightly built that structure is will moderate the details of how the signal travels through the structure,” Bollt said, explaining his motivation for this research. “So a good way of ‘listening’” to the structure could do the job. This work is essentially about an information-theoretic way of listening to the signals travelling through the structure.”

The scientists primarily used various forms of “Shannon entropy” to detect and analyze damages in bridges. “The entropy of a system measures how ‘disordered’ or ‘unpredictable’ the system is,” Sun explained. “This quantity can be extended to study the flow of information among subcomponents of a complex system, and that is exactly what we did in this study; we used what we called ‘causation entropy’ and optimal mutual information interaction (oMII) to detect structural patterns and damages in bridges.”

One attractive aspect of this method is its purely noninvasive nature; this is in contrast to conventional manual inspection, which is invasive and can be cost-prohibitive. Additionally, it may not be possible to detect problems with bridges by visual inspection alone. “For example, corrosion of steel bars on concrete cannot be detected by visual inspection. Special instrumentation might be required, but these instruments have varying levels of reliability,” Okumus said.

In order to conduct their experiments, Janoyan led an engineering squad to place thirty accelerometers (wireless sensors) at various locations on the

Waddington Bridge in Waddington, NY, which measured how each small part of the bridge was disturbed as a truck passed through. The team compared these results with the bridge's response under "damaged" conditions by removing a few bolts, thereby artificially inducing damage and collecting time series sensor data from various locations. They found that the sensor signals obtained from different sites were more likely to be coincidental under "healthy" conditions than damaged ones.

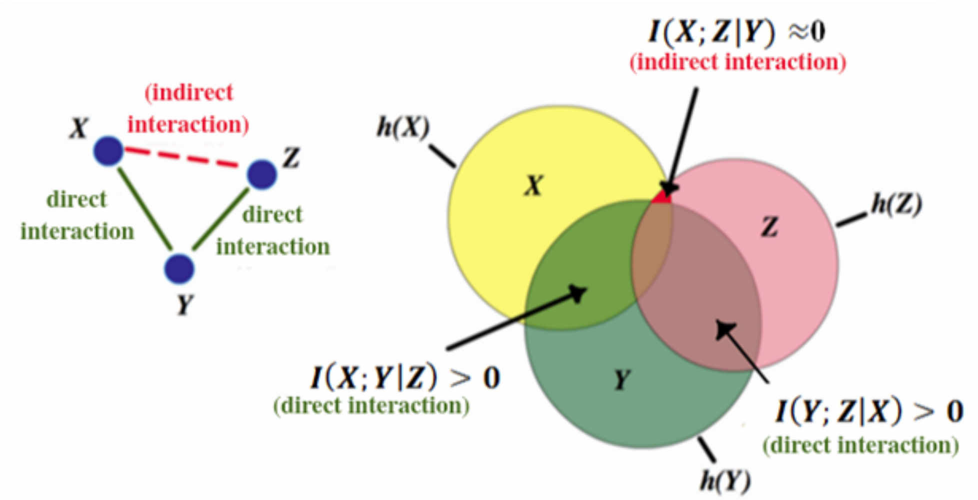


This figure shows a top view of the Waddington Bridge in NY. The research team placed a total of 30 dual-axis accelerometers (wireless sensors) near one end of the bridge, uniformly covering roughly one-third of the surface area. They collected the accelerations measured at each accelerometer as a multivariate time series dataset and recorded them into a digital computer. Using the recorded data, the team then inferred directed functional influences as connections between the accelerometer sites using an entropy-based optimal mutual information interaction (oMII) algorithm. Figure credit: Amila Sudu Ambegedara, Jie Sun and Erik Bollt.

Ambegedara applied oMII, an entropy-based optimization algorithm developed by Sun and Bollt, which compared the structural monitoring of the bridge's health to the measurement of our body temperature, which detects abnormalities in our health. "I have always been amazed by how much information a tiny bit of change in body temperature can tell us about our health," Sun said. "Thus, I always liked the idea of having a simple thermometer-like device to monitor the internal status of very complex systems."

Bollt noted that the work merges two unique aspects to use real-time data when detecting the presence of structural change in the bridge. "One is the noninvasive and automated nature of the data collection process, which has become popular in structural health monitoring but is not yet common," he said. "The other is the specifics of the unique data analytics tool that we developed, which is able to infer direct information flow and significant interactions."

"On the analytical/computational side, we apply an entropy-optimization algorithm—which we recently developed—to the measured data to detect effective interactions among the sensor locations," Sun said, describing the use of techniques normally used in deciphering big data. "Without such 'big data analytics,' we will be left with just large volumes of data and no clue of what's actually going on with the bridge."



X, Y, and Z are three random variables whose interdependences are represented by a three-node directed network. Solid edges indicate direct dependence, whereas the dashed edge represents indirect dependence. The Venn diagram shows direct and indirect mutual information interactions of these variables. Direct interactions (dark green area) have significant mutual information, between X and Y, given Z, and between Y and Z, given X, for example; on the other hand, proper conditioning enables one to "filter out" indirect interactions (small red area), which are those interactions characterized by having mutual information that disappears upon conditioning, between X and Z, given Y, for example. Figure credit: Amila Sudu Ambegedara, Jie Sun and Erik Bollt.

A key component of the analysis was the data processing technique oMII that can identify significant direct interactions between individual sensors in the system. According to Bollt and Sun, oMII is an excellent technique based on ideas from information and communication theory. It uses state-of-the-art statistical estimation routines. "The key idea is to search for interactions that are most relevant to the increase of predictability (reduction of uncertainty) of the bridge oscillations," Sun said. "If the bridge's structure has been altered either due to damage or deformation, the details of the sensor interaction network are expected to change, enabling one to detect the health status of the bridge," Bollt added. And such changes in interaction between sensors were indeed observed when the researchers removed key bolts and induced artificial "damages" to the

Waddington Bridge.

In the future, the team would like to expand the current study to assess the health of more bridges and other mechanical structures. “Ultimately, we would like to integrate our data analytics tool with automated data collection to develop something that detects the health status of a bridge as simply as a thermometer detects body temperature,” the team said.

Lakshmi Chandrasekaran received her Ph.D. in mathematical sciences at the New Jersey Institute of Technology. She is currently pursuing her masters in journalism with a health & science writing concentration at Northwestern's Medill School of Journalism. She is a freelance science writer whose work has appeared in *PLUS* math magazine, *HELIX - Science in Society* magazine at Northwestern University, and *The Munich Eye*, an online newspaper based in Munich, Germany.