How Digital Twins Can Be Applied to Help Engineers Understand the Unexpected

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Introduced in 2002, the concept of digital twins is still relatively new (see Perspective articles in the Summer and Fall 2021 issues of *ASPIRE*® for an introduction to this topic). This article—which is based on a detailed explanation of a proposed digital twin architecture for a bridge that was presented at the 2020 American Society for Nondestructive Testing Annual Conference[1]—presents an example of how a digital twin could be used to better understand the in-service behavior of a structure and to possibly identify problems before they become severe.

In a recent webinar, Dan Isaacs, chief technical officer of the recently formed Digital Twin Consortium, said that if you asked 10 people to define a digital twin, you would get 10 different answers. However, one thing that is universal to all digital twin concepts is the requirement for sensor data to measure the physical structure.

Given the geometric complexity, high stiffness, and environmental conditions that affect the behavior of concrete bridges, what to measure, and how, are not simple matters.[2] Such issues fall under the metrology domain, which has been a primary interest of mine for over 40 years, and, in recent years, has led me to an interest in bridge applications. Some engineers will suggest that one useful measurement parameter for bridges is deflections, primarily because they are something that engineers intuitively understand and use as design criteria, and because anomalies are readily recognized. For example, anomalies such as disparities between the physical bridge and the digital twin, asymmetries between sides and similar spans of a bridge, unexpected deformations caused by frozen bearings, and disparities between similar bridges, as well as nonlinearities, hystereses, and historical changes, can provide valuable information.

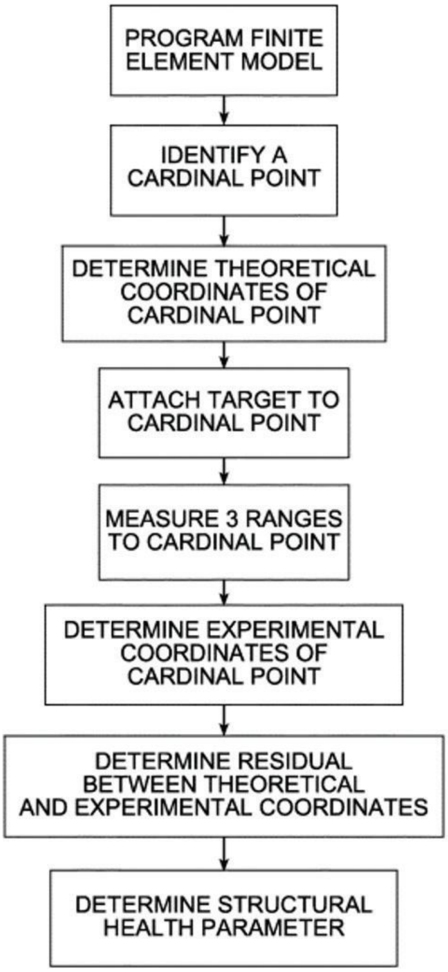
The literature on digital twins is rich with bridge proposals employing many sensors with high-speed wireless data acquisition systems. In many papers, questions about what the sensors measure, where they are located and why, and how the reams of acquired data are used, are glossed over or hand-waved to artificial intelligence or machine learning. Such an approach is anathema to experienced metrologists.

Before any measurements are taken, the uncertainties of the measurement instruments must be understood. For example, machinists sometimes work with a tape measure; however, in other cases, they may need to use a caliper or micrometer, and, in the most accurate applications, a laser interferometer may be required. Using manufacturers' specifications, statistical analysis techniques, and experience, a metrologist will know the expected uncertainty of a measurement before purchasing instruments or conducting an experiment.[3] This same rigor must be applied to digital twin instrument architectures, if they are to be useful.

Frequently, engineers have very little quantitative diagnostic information to help them understand the development of potential problems or alarming conditions. Traditional diagnostic tools such as strain gauges, inclinometers, accelerometers, and acoustic emission devices are not particularly useful for global structural assessments associated with load paths, load-carrying capacities, and diagnostics—that is, for structural health monitoring of the global structure. Modern electronic distance-measurement instruments, however, provide long-distance, noncontact, line-of-sight distance measurements with distance accuracies in the 1 part-per-million (ppm) range, comparable to strain gauges. Such high-accuracy three-dimensional (3-D) coordinate measurements, combined with a digital twin and experienced engineering insight into the selection of cardinal points to measure, can be useful in a global structural assessment.

Like total stations, the angle measurements are much less accurate than distance measurements, so care must be exercised in the measurement architecture. Some configurations may require multiple instruments in a multilateration arrangement, which only uses distances, to achieve the required accuracies. This arrangement is similar to GPS, which only measures simultaneous distances to a constellation of satellites. Instruments with such accuracies are commercially available in the form of laser trackers, which resemble the more common surveying total stations but are designed for much higher-accuracy work, such as dimensional metrology standards laboratories, machine shops, aerospace manufacturing, shipbuilding, and particle accelerators.[4] Of course, laser trackers are also very expensive—in the $80,000 neighborhood. Manufacturers' specifications comply with standards in the American Society of Mechanical Engineers' ASME B89.4.19, *Performance Evaluation of Laser-Based Spherical Coordinate Measurement Systems*,[5] which are traceable to the National Institute of Standards and Technology and, given the sophisticated customer base, are rigidly followed.

Unfortunately, the bridge community has been slow to adopt



The flowchart presents a method for using a finite element model in conjunction with experimental (remote) electronic distance meter measurements to determine structural health parameters. The most useful monitoring systems would require a partnership of bridge owners, bridge engineers, digital twin software engineers, nondestructive testing specialists, contractors, instrument manufacturers, and metrologists. Figure: David H. Parker.

this technology. However, there are many contract measurement service providers, with certified 3-D metrologists, that can provide the instruments and expertise for the metrology aspect of a project to measure cardinal points selected by bridge engineers. Readers who are not familiar with these high-accuracy instruments are encouraged to review the specifications of instruments such as those manufactured by API, FARO, and Leica and, when in-person conferences resume, attend the Coordinate Metrology Society Conference to see demonstrations of the instruments, talk with dimensional metrologists, and find measurement service providers with Level-Two-certified 3-D metrologists.

Consider the case of a complex bridge structure. It would be reasonable to require precision 3-D coordinate measurements at various stages of construction, especially if there are nonredundant elements or unique construction techniques.

For example, in an uncertainty analysis for a simple 175-ft-span bridge, I determined that two laser trackers, one located on each side of the deck in the center of the span, would be adequate to provide useful data. Given the relatively small measurement volume, a multilateration architecture would not be required in this case. However, bridges that are curved or complex would require a structure-specific uncertainty study. Maximum instrumental uncertainties in the longitudinal, transverse, and vertical directions might be 0.001, 0.005, and 0.003 in., respectively, for a simple span. Moreover, the maximum 3-D root sum square (RSS) instrumental uncertainties between adjacent measurement points would be 0.001, 0.005, and 0.003 in. times the square root of two in the longitudinal, transverse, and vertical directions, respectively. Note that the thickness of a typical sheet of printer paper is 0.004 in. It is evident that the combined measurement uncertainties will be dominated by temperature and the thermal expansion of concrete, which is around 6 ppm/°F (for example, 0.013 in./°F over 175 ft). If during a construction procedure the change in the measured length of an element is greater than the change predicted by the digital twin, and the change is well above the thermal and instrumental uncertainties, it should be investigated.

Through accurate measurements and appropriate use of digital twin applications, engineers can improve their chances of correctly evaluating what is going on before a situation becomes irreversible or even dire. By knowing the 3-D coordinates of all measurement points on the structure and comparing the movements with finite-element-method digital twin predictions, engineers can have a much better understanding of how loads are being redistributed before an element exceeds service limits or fails.

In summary, the combined use of digital twin technology and remote, yet very precise, measurements of deformations during and after construction can be a useful tool to provide accurate data for evaluation of bridge behavior, especially for unique structures.

References

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