THE NEW REALITY

Stephanie Maury, a process improvement specialist in the area of environmental, safety, and health, and Trent Legendre, a traffic and logistics specialist, both with Bechtel, helped to test the virtual reality system in Houston at the firm's innovation center.

BECHTEL

Virtual reality, augmented reality, design automation, and robotic construction are poised to revolutionize the way that engineers go about designing, constructing, and monitoring infrastructure projects. •••• **By Catherine A. Cardno, Ph.D.**

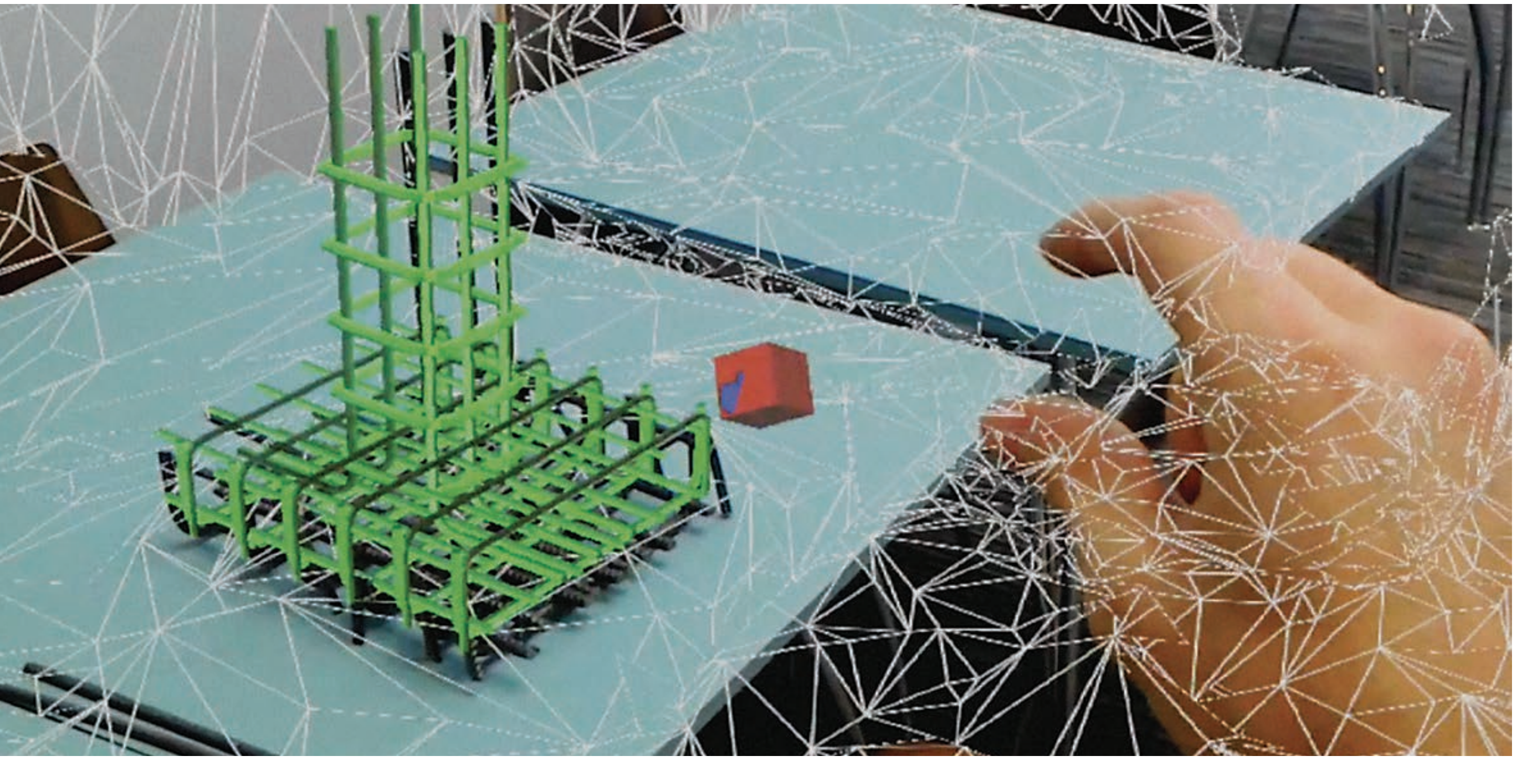
As data collection becomes ever easier with such technologies as drones, autonomous robots, digital imaging, and lidar, the manner in which engineers aggregate, analyze, visualize, and communicate that information to one another and to others will be crucial to the success of the civil engineering profession. Just as slide rules, hand calculations, T squares, and pencils were overtaken by computer-aided design and this type of design was further supplemented by computer analysis and building information modeling (BIM), the digital visualization revolution is poised to transform the infrastructure engineering field. This transformation will include the integration of virtual and augmented reality at every stage of design, construction, and operation, as well as the automation of routine design procedures. These changes will free engineers to focus on problem solving and on designs that are more creative, more resilient, and more in keeping with the principles of sustainable development.

Virtual reality and augmented reality, concepts originally popularized by video gaming systems, create immersive digital environments that viewers can explore. Often the images are viewed through specially designed goggles or on large screens in custom-built rooms. Virtual reality gives viewers a realistic and often three-dimensional image of elements that have been designed but not yet built; augmented reality combines those virtual images with images from the real world, showing elements that exist overlaid with images of elements to come.

Using virtual and augmented visualizations on civil engineering projects "is a total paradigm shift," says Carl Haas, Ph.D., P.Eng., F.ASCE, a professor and the holder of a Canada research chair in the construction and management of sustainable infrastructure at the University of Waterloo, in Canada. The project visualization that virtual and augmented reality offer prior to the start of construction makes communicating with the public, owners, and the construction and asset management teams far easier. "Before, you had 2-D drawings, and it took skill and experience to interpret and visualize from a combination of plan and elevation drawings what it was that you were trying to build. It was really hard," he notes. But with these new visualization techniques, it is no longer an uphill battle to help those who are not engineers understand exactly what a design calls for.

Burcu Akinci, Ph.D., M.ASCE, the Paul P. Christiano Professor of Civil and Environmental Engineering and the associate dean for research in Carnegie Mellon University's College of Engineering, agrees, noting that good visualization makes it possible for design teams to effectively conceptualize and manage large, complex projects. "You need to know where you are and what's going on so that you can make the most effective decisions," she notes. "It's a critical step for engineers to have good visualization of what is going to be built. [They need to see not only] the design intent and the construction process but also the existing condition."

While academics are focusing on research that promises to push the boundaries of what is possible in the visualization field, the effect of the digital revolution on practicing engineering firms is already tangible. From immersive BIM rooms to the use of virtual and augmented reality in complex designs, engineers are already embracing these innovations. (Read "Virtual and Augmented Reality Resolve Remote Collaboration Issues," *Civil Engineering,* September 2016, pages 40–43.)

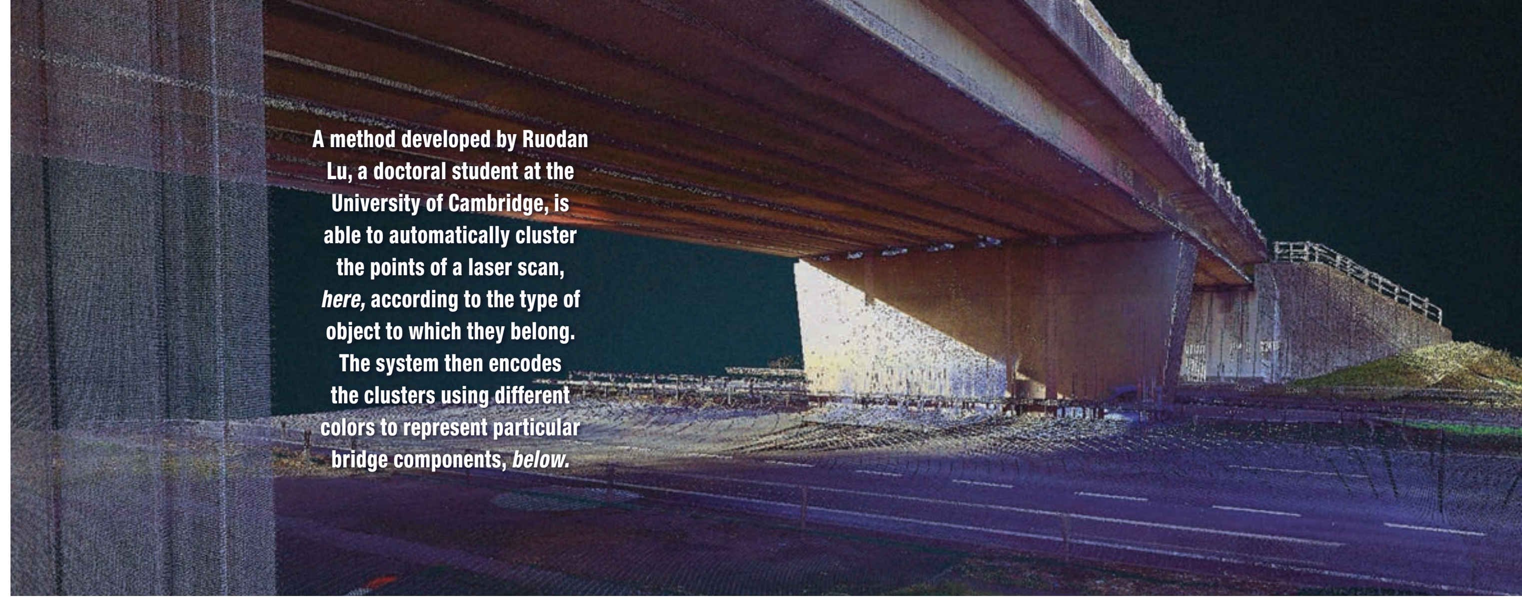


Microsoft HoloLens goggles can be used to view digital models overlaid on real-world views. By using a 'Holotap,' a person can click on a digital cube that denotes the corner of a model, in this case one showing a rebar cage, and align it with the actual item. The triangulation marks denote geometric points in the room detected by the goggles.

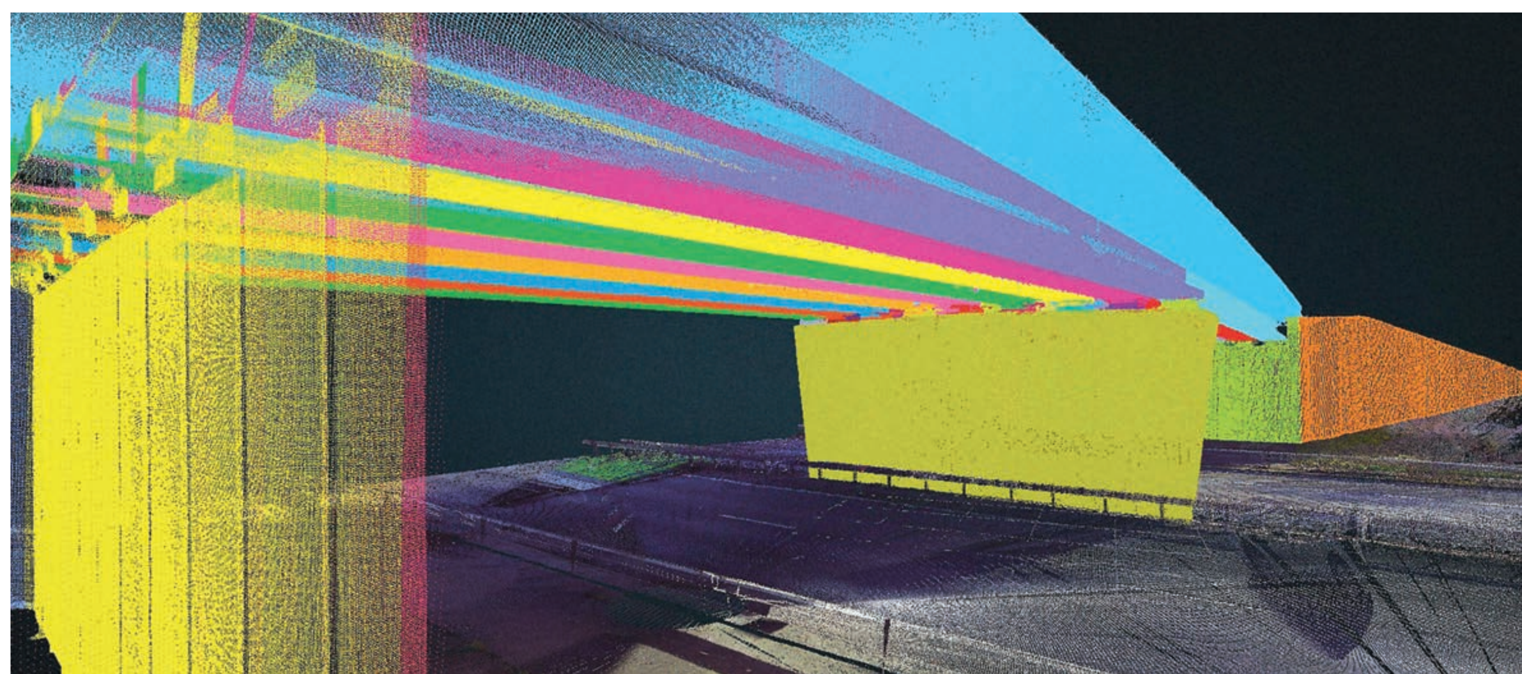
"Immersive visualization technology can be used in any engineering field and is particularly effective in the design of infrastructure since models are so large and complex," said David J. Odeh, P.E., S.E., F.SEI, F.ASCE, a principal with Odeh Engineers, Inc., of North Providence, Rhode Island, and a former president of ASCE's Structural Engineering Institute. Odeh sees virtual and augmented reality as an opportunity to take the 3-D BIM modeling that structural engineers are already using for design and apply it to other parts of the design and construction process. "The trend toward using virtual and augmented reality will require civil and structural engineering companies to introduce 3-D modeling into their work flow at the earliest stages of design," Odeh explained in written responses to questions posed by *Civil Engineering.* "Firms that are adept at 3-D modeling for virtual and augmented reality may have the opportunity to perform new services for clients and expand their role in the design and construction process."

GOOD VISUALIZATION MAKES IT POSSIBLE FOR DESIGN TEAMS TO EFFECTIVELY CONCEPTUALIZE AND MANAGE LARGE, COMPLEX PROJECTS.

Odeh Engineers has constructed what it calls an immersive BIM room at its headquarters. Because of the size of the screen, which is 32 ft wide and 10 ft high, the room creates an environment similar to virtual reality, and here a team can view digital models of a project. The room is 32 ft wide and 30 ft long and has a long conference table facing the screen, essentially creating a multiperson virtual reality environment for viewing designs without the need for individual headsets. "Meeting in the room allows the team to visualize the work of multiple disciplines and use the experience of each participant to brainstorm big-picture design concepts, coordinate the integrated design, and resolve clashes between systems before construction takes place," Odeh explained. "By exposing the design in such an accessible



A method developed by Ruodan Lu, a doctoral student at the University of Cambridge, is able to automatically cluster the points of a laser scan, *here,* according to the type of object to which they belong. The system then encodes the clusters using different colors to represent particular bridge components, *below.*



CIT LAB, UNIVERSITY OF CAMBRIDGE, *ALL THREE*

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manner, less is left to the imagination, and teams can communicate their ideas better," he noted. "Clients especially can see the project come together [so] that they can truly grasp the finished product before it is constructed, when they still have a chance to make changes to improve the design."

David Wilson, P.E., the chief innovation officer for Bechtel Corporation, which is headquartered in San Francisco, and a principal vice president in the company's Houston office, wrote in an email to *Civil Engineering* that the effect that virtual and augmented reality will have on project work flow and communication will indeed be significant. "Bechtel has a history of working with virtual and augmented reality technologies, from the drawing board to desktop screen, to mobile tablet devices, and now headset technology," he explained. "Virtual and augmented reality will impact how we deliver projects throughout their life cycle by optimizing information delivery and decision making."

Wilson also noted that one of the primary benefits of these technologies is that they enable a team to see potential clashes and issues in advance so that smarter design decisions can be made early, avoiding costly delays and the need for later reworking. During construction, he said, the benefits extend to offering real-time models and schedule reviews that offer comprehensive records for tracking a project's progress on-site.

> "BY EXPOSING THE DESIGN IN SUCH AN ACCESSIBLE MANNER, LESS IS LEFT TO THE IMAGINATION, AND TEAMS CAN COMMUNICATE THEIR IDEAS BETTER."

Tom Loader, the head of digital transformation at the London office of the international firm Balfour Beatty, envisions a future in which such visualization processes will be able to help solve the key problems facing the construction industry. "It is a known fact that the infrastructure industry is facing many challenges, such as resource scarcity, urbanization, population growth, ecological decline, and climate change," Loader wrote in response to questions posed by *Civil Engineering*. "As digital technology becomes more a part of our working day and…reinvigorates our standard working practices, we become more aware of the things we can do as an industry to stay ahead of the curve. We must seek a future where technology can increase efficiency, solve the issues of skills shortages faced by countries around the world, and take the danger out of building, making zero harm a reality and [putting] a human-free construction site within our grasp."

Construction without humans may sound farfetched and even somewhat unsettling. But the leaders of Balfour Beatty envision that by 2050 infrastructure construction sites will be almost completely devoid of humans as robots work in teams to build complex structures using dynamic new materials, according to a recent report prepared by the firm entitled *Innovation 2050.* Site managers and design professionals will simultaneously operate multiple projects remotely using 3- and 4-D visualizations and data, according to this report. Drones will fly over sites continually to collect data on progress and resolve problems by automatically updating instructions to robotic builders and cranes. The few humans who will be on-site will wear robotically enhanced exoskeletons and will use neurologically controlled technology to move machinery and robots, the report explains.

Apart from the technological developments needed to realize the future envisioned in *Innovation 2050*, the company is calling upon infrastructure customers, companies, and regulatory bodies to embrace such changes and support innovation, agility, and digital transformation within the industry; to protect infrastructure from cyberrisks; to ensure that increasing volumes of digital data can be aggregated and managed in a way that protects the privacy of individuals; to "future-proof" infrastructure so that it can be integrated with multiple generations of digital technology over its life span; and to ensure that the energy supplies and regulatory frameworks needed by new infrastructure developments are in place.

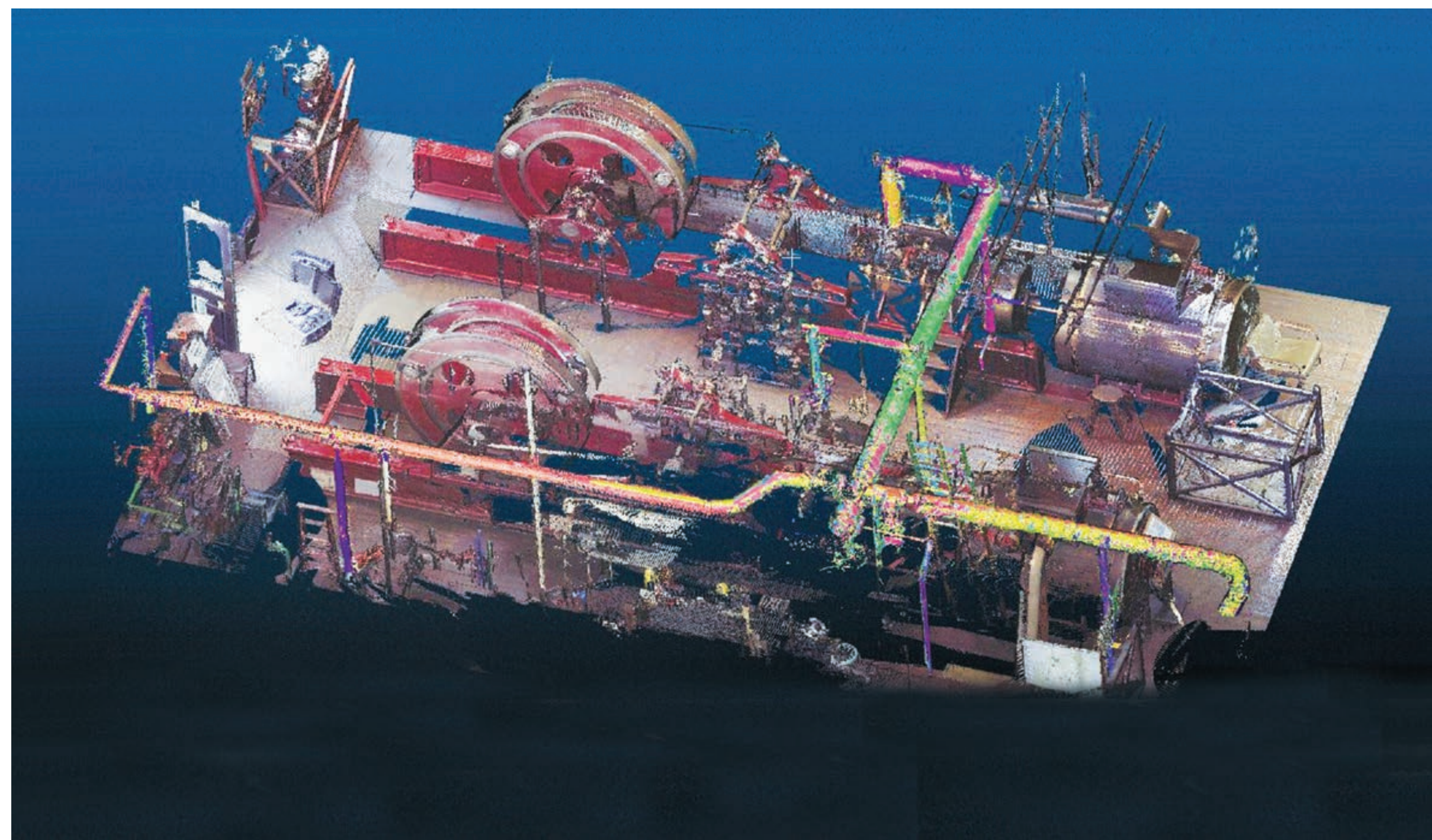
While Balfour Beatty's vision may seem like science fiction, researchers are already developing the kinds of technologies that could make that future a reality. Ioannis Brilakis, Ph.D., M.ASCE, the Laing O'Rourke Lecturer of Construction Engineering at the University of Cambridge, in the United Kingdom, is overseeing a group developing information technology for construction. The group is focused on generating information-rich virtual models of existing structures and exploiting those models through virtual and augmented reality, and it is exploring how various methods of construction automation could improve on-site productivity, quality, safety, and sustainability. The work includes research in virtual and augmented reality, haptic technology, and robotics, and the researchers are even using the electrical activity of the brain to interact with digital replicas of infrastructure.

"We went down this path because of a pull and a push: On the one hand, the construction industry lags behind all other industries in data generation and exploitation and consequently in productivity, safety, and quality," Brilakis says. "On the other hand, computer science, as a field of science, has grown by leaps and bounds in the last few decades and now provides us with new tool sets that can change the way we see and experience construction products and processes."

The work that Brilakis's group is doing could fundamentally change the way in which construction is carried out, and while some may argue that the concept of robotic construction jeopardizes the job prospects of construction workers, Brilakis says that his group is "trying to move the workers out of the site and into the office." This includes work on a robotic construction worker that would be linked wirelessly to a remote human worker who would be fitted with motion-capture sensors, a virtual reality headset, and haptic feedback gloves. The human would control the robot working on a project site; as he or she moves, so too would the robot. The first prototype was completed last year, with the second due this year and a targeted commercial deployment anticipated in five to seven years, according to Brilakis.

Other areas of research include integrating time-dependent BIM models with actual images of projects in progress so that inspectors could immediately see any construction delays or problems. (Read "On-Site Virtual Mapping Could Aid Inspection," *Civil Engineering,* May 2017, pages 36–37.) The team is also working to outfit hard hats with electroencephalography sensors that would enable an inspector to "tick

Industrial facilities often have myriad objects within a tight space that need to be modeled. To do this, the technology must be able to differentiate, for example, walls, *above*, from machinery, *below*.



CIT LAB, UNIVERSITY OF CAMBRIDGE, *BOTH* off" checklist items and "click on" objects shown in the augmented reality system using just his or her mind, a useful option if the inspector is located high on a ladder with both hands fully occupied, Brilakis notes. While this technology might seem implausible, Brilakis anticipates that it will be on the market within three years.

David Mascarenas, Ph.D., a research and development engineer at the Engineering Institute, a collaborative program within Los Alamos National Laboratory's National Security Education Center, also is working on developing virtual and augmented reality systems that could help in monitoring and inspecting infrastructure. "Most of the time when I see people [use] augmented reality, they're just focused on visualization, but I'm much more interested in using it as a real-time tool to augment the human," Mascarenas says. "It's really about combining human intelligence with machine intelligence in very seamless, intuitive ways that can be used on the fly during active tasks."

For example, construction workers fitted with augmented reality glasses could automatically assess the thickness of a layer of asphalt, he explains. The system could also be programmed to monitor construction workers to, for example, ensure that they are using the type and quantity of rebar for the concrete specified by the engineer or verify that the concrete is placed to the correct thickness, he notes.

One of the biggest hurdles that the industry needs to overcome before digital visualization and communication capabilities find widespread use is risk aversion, according to Balfour Beatty's report *Innovation 2050.* Bechtel's Wilson agrees. "The fear of failure—rightly so in construction—limits our experimentation and testing of technology," he said. This results in slow adoption and even slower modification of technology to industry standards, and this reluctance in turn slows the process of developing and tailoring these technologies for architectural, engineering, and construction industry needs, he noted. The result is another excuse for delays in adoption. As Wilson put it, it's a "vicious cycle of self-fulfilling skepticism."

This is one of the reasons that Bechtel set up a $60-million investment program in 2016 that it calls the Future Fund. "Bechtel established the Future Fund to further stimulate our internal culture of innovation," Wilson explained. The fund is "specifically tasked with seeking out new, disruptive ideas from our colleagues, suppliers, and customers," he said, and its resources are distributed for the "exploration, prototyping, and piloting of ideas with the potential to dramatically improve our quality, safety, effectiveness, and efficiency." More than 2,000 ideas have been submitted by the company's employees, and half of the fund has been allocated to more than 360 ideas that are already in the prototype stage. These ideas include wearable devices aimed at improving employee efficiency; drones for accurate and low-cost data collection; using virtual reality to train those who will work in high-risk environments; drill head collision detection; and data-rich design modeling, Wilson said. Other ideas, he noted, include automated mooring systems, "smart" wheelbarrows, and inflatable scaffolding.

Using digital visualization after the construction phase for long-term monitoring has the potential to fundamentally alter how infrastructure is designed in the first place. David A. Lattanzi, Ph.D., P.E., M.ASCE, an assistant professor in the civil engineering department at George Mason University, sees digital visualization as a way of maintaining a comprehensive record of how infrastructure decays or persists over time, providing engineers with a vast amount of data that can be mined to determine the life-cycle costs of infrastructure and improve construction methods and materials. Such visualizations could take the form of lidar or digital camera images of infrastructure obtained with the aid of drones, robots, standard vehicles, or tripods. (Read "Autonomous Flying Robots Designed to Aid Bridge Inspectors," *Civil Engineering,* October 2016, pages 36–37.)

Los Alamos National Laboratory's Mascarenas also is working on monitoring structural health. He envisions a world in which infrastructure is designed and built to last hundreds of years, in contrast to the standard 50 or 75. "If you have a piece of infrastructure that's lasting 200 years or [more], even language changes over 200 years, so what you want to have is unambiguous high-resolution measurements of what the structure really looked like and how it has changed," Mascarenas says. "Once you have all this data, you could start combining it with modeling and statistical classifiers [for example] to find other useful information about how the structure is damaged, and that could be fed into finite-element models. There's a lot of things that you could enable with this kind of technology that weren't doable in the past."

The main issue with digital data collection for structural health monitoring, however, is making sense of the vast amount of data and images that are collected. "We are in a moment in which things are changing, and visualization is just a small part of this," says Lucio Soibelman, Ph.D., F.ASCE, a professor and the chair of the civil engineering department at the University of Southern California. "You have a lot of capability of acquiring data that you hadn't before, with cheaper laser scanners, flying drones, and very different ways of acquiring the data. But the main issue is not just acquiring the data; it's the analysis. What do we do with this data?"

In monitoring the health of a structure or a facet of infrastructure, being able to determine which data need to be analyzed by humans and which can be analyzed by computer programs is of cardinal importance, according to Soibelman. "For instance, RedZone Robotics [of Pittsburgh] has developed a small autonomous robot that can rove sewer pipes and return with 10 hours' [worth] of data in a day," he notes. "So a city the size of Los Angeles might have 20 of the robots that

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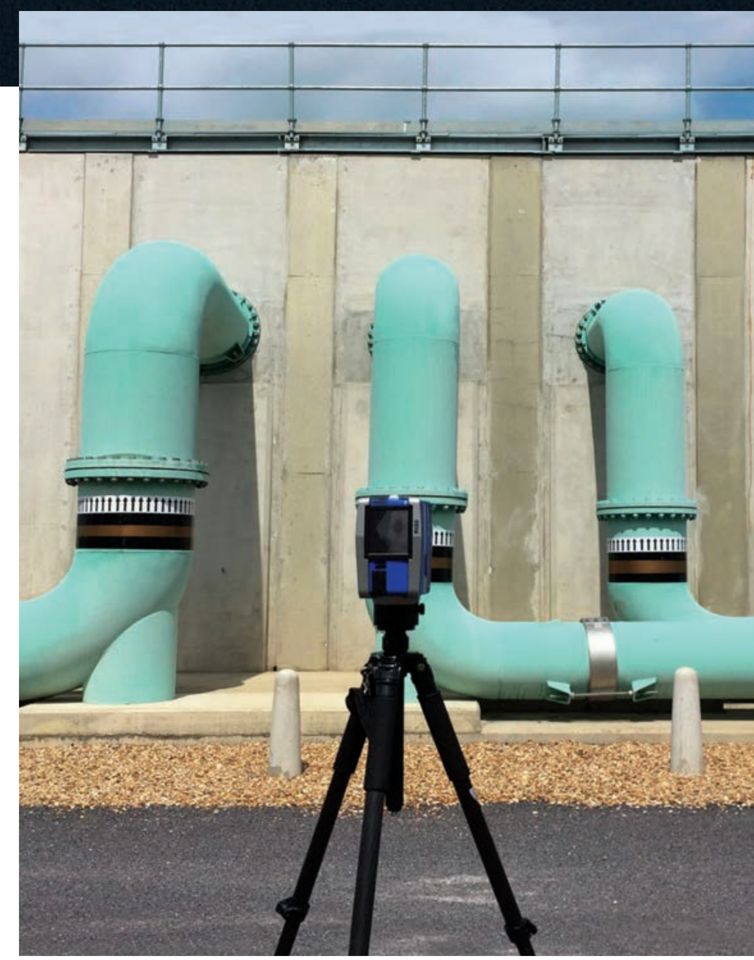

By scanning an industrial facility, *left,* using lidar, a data-filled digital building information model of the facility, *above,* can be generated automatically.

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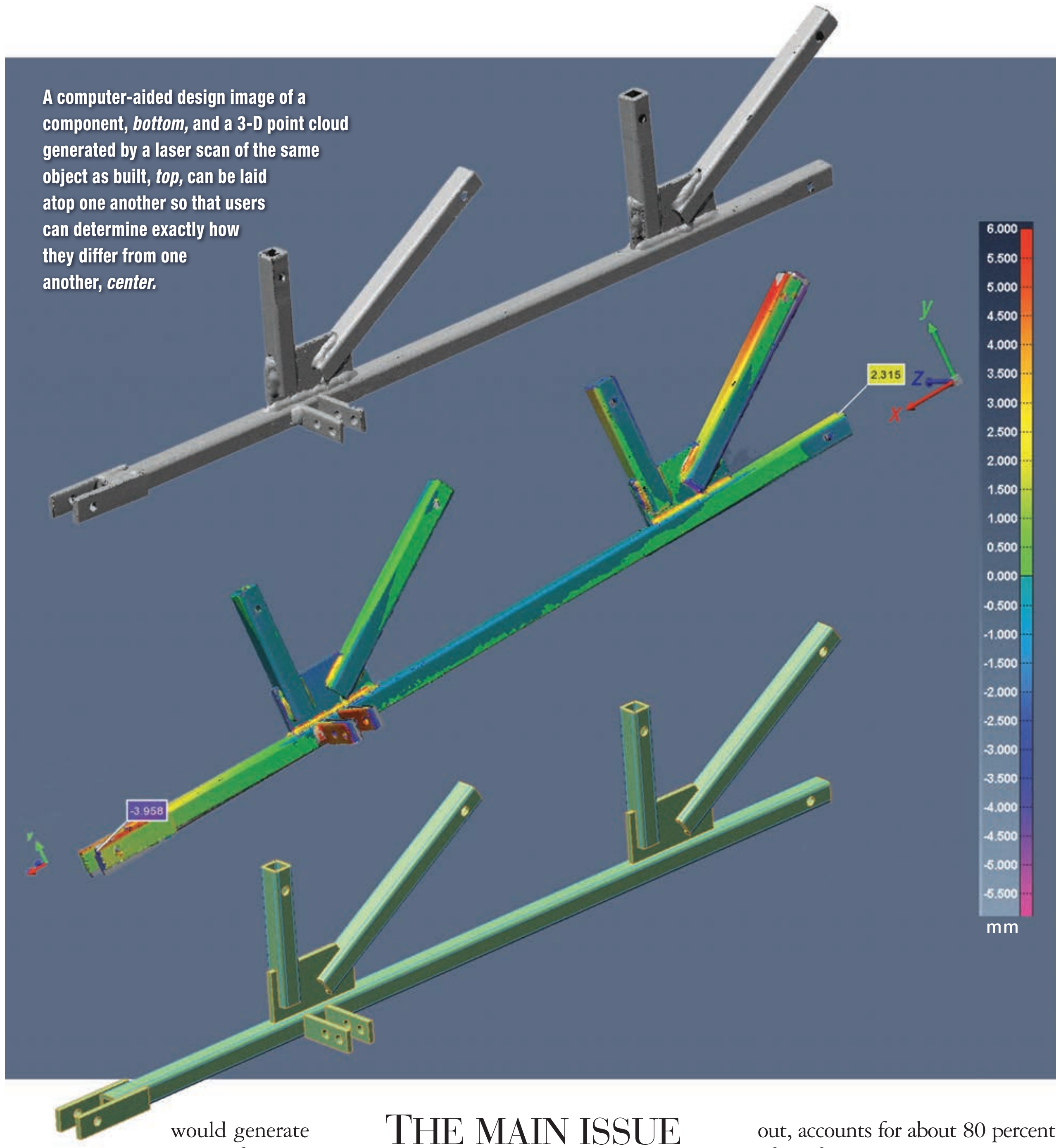

A computer-aided design image of a component, *bottom,* and a 3-D point cloud generated by a laser scan of the same object as built, *top,* can be laid atop one another so that users can determine exactly how they differ from one another, *center.*

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would generate 200 hours' of images daily." But having enough experts trained in properly classifying sewer pipe defects to review every inch of pipe captured in the 200 hours would be far too costly. "So now you are drowning in data…and [that] is where we have a bottleneck today," Soibelman notes. A research group led by Soibelman and James Garrett, Ph.D., P.E., F.ASCE, a civil and environmental engineering professor at Carnegie Mellon and the dean of its College of Engineering, developed algorithms capable of recognizing the healthy parts of the pipes captured on the images, which, it turns out, accounts for about 80 percent of the footage. In this way human experts can focus their time on the 20 percent that actually needs to be addressed. But developing these algorithms is only the first step, Soibelman notes. "The next step is to develop the algorithms to do the classification themselves," he says.

THE MAIN ISSUE WITH DIGITAL DATA COLLECTION FOR STRUCTURAL HEALTH MONITORING, HOWEVER, IS MAKING SENSE OF THE VAST AMOUNT OF DATA AND IMAGES THAT ARE COLLECTED.

With the automation of routine tasks, engineers and inspectors will be able to focus their attention on solving increasingly complex problems. "We're really good at design—and that's not to say that we can't be better—but there is so much effort about how do we do more with less and how do we create buildings that last longer and serve our purposes for longer," Lattanzi says. "And that's the goal for almost all of this. How do we take all this data and use it? How do we leverage it to make better decisions? How do we leverage it to better understand and communicate with the infrastructure that we've built?" he asks. "That's the whole purpose of thinking about human and computer interaction for civil engineering. It's about making better use of all the data and information streams that we gather to make better decisions about the life cycle, maintenance, and management of our systems."

"IF [WE] WANT TO ATTRACT A NEW GENERATION OF ENGINEERS TO OUR FIELD, WE HAVE TO ADOPT NEW TECHNOLOGY BECAUSE THEY DO SEE THE VALUE OF IT."

To this end, Lattanzi is working to create a method that would permit a BIM model to be overlaid with lidar images of the same structure over the course of its life cycle. With such a method, the as-built model could be compared in minute detail with the BIM benchmark, and the aging process could be tracked. Brilakis's group at the University of Cambridge also is working to develop a way of superimposing high-resolution bridge images on a bridge model to automatically detect and measure visible damage. The group also wants the bridge model to be automatically enriched with data on its current condition so that any damage from aging, extreme weather, or impact could be assessed. By comparing highly detailed past and present images of the same structure, bridge inspectors would be able to track in detail how structures age and change over time.

"The gold standard is, if you ask me, to have the physical infrastructure we build and a completely digital copy of that infrastructure that is a living model of the structure, that evolves over time and allows us to visualize the history and evolution of our infrastructure systems," Lattanzi says. "Being able to capture and interact with that digital representation in a variety of ways becomes powerful because we're looking at that model, we're understanding how it changes and how it's evolving, and it helps us make predictions."

To realize this future, undergraduate and graduate training and research in civil engineering will need to expand to encompass digital and visualization technology. And once they do, the capabilities of digital software will be more finely attuned to the needs of the industry.

See Virtual Reality in Action

THE VIRTUAL and augmented reality efforts of both Odeh Engineers, Inc., of North Providence, Rhode Island, and Bechtel Corporation, of San Francisco, are featured in 2 of the 10 educational videos developed in conjunction with *Dream Big: Engineering Our World,* the giant-screen film produced by ASCE in partnership with MacGillivray Freeman Films and Bechtel to give the public a better understanding of the work that engineers do, to heighten interest in the profession, and, perhaps, to change certain perceptions that people have of engineering and engineers. The videos are part of a collection of materials that engineers can share with students to inspire them and encourage them to consider careers in engineering. To see all of the educational videos, as well as trailers and behind-the-scenes clips from the film, go to www.dreambig-film.com/videos/. Odeh Engineers' initiative is featured in the video *Virtual Modeling,* and Bechtel's can be seen in *Innovative Engineers.*

"The problem that you have today is that a lot of [virtual and augmented reality systems] have been developed by computer scientists, but they don't understand the behavior of the infrastructure. They are not engineers [and do not] understand exactly how to interpret things or what we do with the data," Soibelman explains. "At the same time, the civil engineers understand about the structure, but they are not at the level that its needed to be able to develop the tools that we will need."

The solution, he says, would be provided by engineers trained in computer science, data management, and programming so that they could speak the language of computer scientists and thoroughly understand that field as they work on increasingly complex projects.

The University of Waterloo's Haas agrees. "I think that we're going to have to start teaching computer vision, computational geometry, modeling, as well [as] augmented reality, because it uses all the same tools, just in different combinations," he says. "Young people are learning about them in high school anyway, and we've just got to learn how to use them properly because they're really useful for civil engineers."

Carnegie Mellon's Akinci also sees this technology as a way to attract today's best students to the civil engineering profession. "If [we] want to attract a new generation of engineers to our field, we have to adopt new technology because they do see the value of it," she says. "I don't think any of the new engineers want to spend hours looking for information in a drawer, when [in other areas of their lives] they can know with the click of a button what's going on with their friends on the other side of the world. They won't tolerate that. So one way or another, [change] is coming." CE


Cardno

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