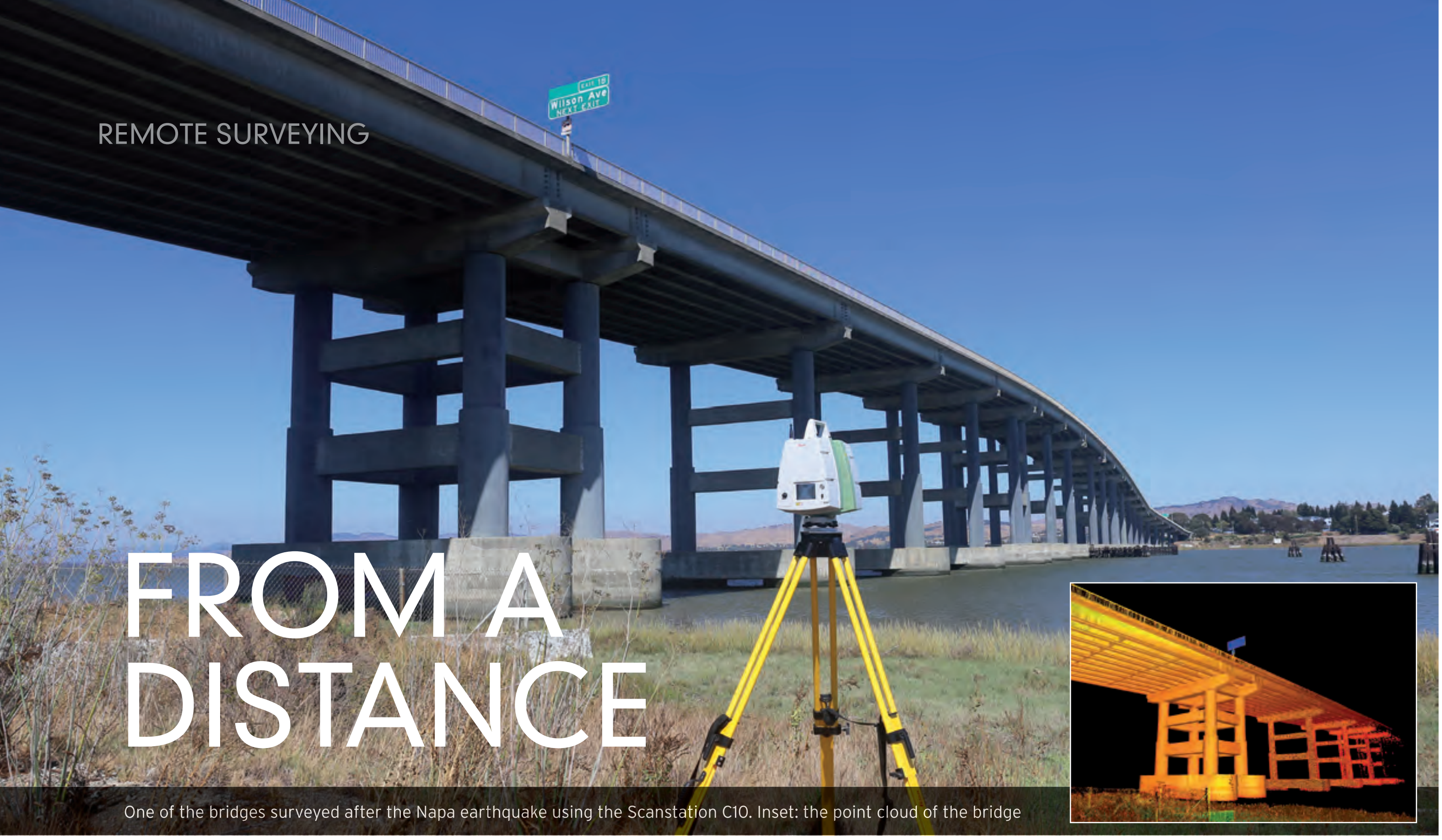
FROM A DISTANCE



One of the bridges surveyed after the Napa earthquake using the Scanstation C10. Inset: the point cloud of the bridge

Inspection of bridges in the aftermath of seismic events is vital, but it can be hazardous and difficult. Now the opportunities offered by new technologies are being explored in this field. **Mark Yashinsky**, **Shakhzod Takhirov**, **Khalid Mosalam**, **Tara Hutchinson** and **Falko Kuester** explain

In the aftermath of the South Napa Earthquake which struck California in August this year, new technologies for post-earthquake bridge inspections were highlighted and a wide range of traditional and non-traditional inspection methods was used. While robots are often cited as a potential solution for carrying out dangerous duties such as inspecting bridge decks next to traffic, and they have often been piloted, especially in Japan, US bridge engineers are sceptical about the concept.

In recent years, spaceborne technology has proved extremely useful in assessing the extent of large- and moderate-scale disasters. Satellite and high-resolution airborne imagery has been used to quantify post-earthquake damage in earthquakes since 2010, including the recent quake in Napa. One major development that has helped promote the use of this technology has been its accessibility. Some type of high-resolution imagery – whether space or airborne – is usually available within a day either from government or commercial platforms, and the resolution of images has improved significantly.

The application of satellite and aerial imagery for post-earthquake damage assessment of bridges and highway networks has been studied by a number of researchers. Under a federal grant from the US Department of Transportation, Imagecat worked with the University of California at Irvine and the University of Nevada at Reno to assess the feasibility of using not only satellite imagery at moderate to high resolution, but also active sensor technologies such as Lidar to identify post-earthquake damage to large bridge structures. The general conclusion was that these technologies were extremely useful for bridges that had suffered partial or full collapse, but were limited in quantifying non-collapse damage states. The primary reason was that the resolution required to distinguish the level of on this scale were not available; also the majority of this type of damage can only be seen from the side of a bridge, images of which are not generally available from these sources.

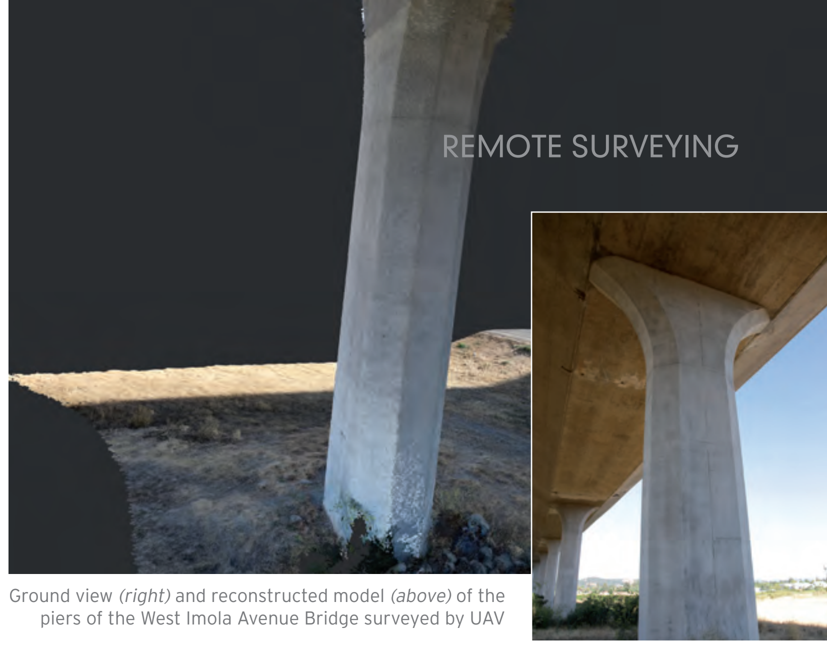
However, the main benefits of using remote sensing information after a large earthquake are that it can provide visual evidence of damage without having to deploy in the field, thus overcoming any access issues that may impede field teams, and wide coverage of an affected area can usually be obtained quickly, providing a rapid overview of the impact of a large earthquake. Hence deployment of remote sensing technologies and sensors should be a critical part of any post-event investigation toolbox.

The use of drones for bridge inspections has become a hot topic, but Caltrans first studied their potential in 1999, investigating the feasibility of building twin-motor, single duct, electric-powered Aerobots to carry video cameras up to 60m in elevation to enable inspection of bridges and other elevated highway structures. The technology of the time was very different, with the Aerobot being an 18kg machine with two electric motors with power, control commands, and sensor images transmitted through a thin-wire and fibre-optic 60m cable. It was capable of vertical take-off, translation to horizontal movement as commanded by the pilot, able to hover at a point in space as commanded, rotate about its vertical axis (yaw control), and perform controlled descent to a vertical landing.

However the device did not perform as expected within either the initial or extended schedule of events, due to a number of implementation issues, and was never deployed. This year Caltrans Geotechnical Services carried out a preliminary investigation into the feasibility of using unmanned aerial vehicles for steep terrain investigation work. Several state DOTs are actively carrying out research using UAVs, including Florida, Washington, North Carolina, Ohio and Utah. However in order to use such equipment, public agencies must obtain FAA approval through a Certificate of Waiver or Authorization.

One particular project in process, sponsored by US DOT and expected to conclude this month *(November)*, is examining how such systems can be used for disaster response and recovery. Caltrans' Office of Structures Maintenance & Investigations, which is responsible for closing and repairing bridges, prefers to have a licensed engineer at the location of any bridge damage. By contrast Caltrans' Office of Earthquake Engineering, which is responsible for evaluating the performance of their seismic criteria, is eager to explore this technology since it lacks the equipment or training to get to many of the bridge elements. The regulatory environment is the main barrier to procuring and routinely operating this equipment, but some public entities are already operating UAVs without approval and it may be possible to seek exemption for emergency situations. The technology is relatively mature, prices are low, and there are already many applications.

During the South Napa Earthquake, Pacific Earthquake Engineering Research Center researchers from the University of California, San Diego tested manual and semi-



Ground view *(right)* and reconstructed model *(above)* of the piers of the West Imola Avenue Bridge surveyed by UAV

automatic survey techniques using unmanned aerial vehicles to support immediate post-earthquake perishable data collection at a bridge in downtown Napa.

The West Imola Avenue bridge crosses a small river, hence its main structural components are difficult to access. A semi-automated and fully-automated survey strategy was tested, using a GPS and altitude-guided mode, allowing the UAV to fly parallel to the bridge, maintaining constant altitude and distance while capturing imagery at regular intervals. Two flights were completed: one from the north and one from the south, with each pass conducted at two different altitudes. To explore rapid integrity assessment strategies for bridge columns, multiple close-up imaging runs were conducted using flight paths with horizontal and vertical sweeps respectively. A high-resolution 3D model was reconstructed from the image data while on site, supporting rapid, data-driven visual inspection.

Laser scanning technology is rapidly becoming an essential tool for accurate non-destructive three-dimensional measurements of structures. It enables users to capture millions of points from the subject structure with accuracy of a few millimetres. In particular, high-definition laser scanning technology provides both qualitative and quantitative information which is discretised as a cloud of millions of points in space.

Laser scanners provide a non-contact means of capturing all three coordinates of the points on a surface. As such, a large number of exposed points can be digitised and recorded making out-of-plane deformations and curvatures accurately quantifiable. Another advantage of the laser scanner is that it captures the entire exposed surface of a specimen, allowing the point cloud to be used in the calibration of a finite element model of the structure by recording residual deformations and/or failures.

In post-earthquake field survey, there are many difficulties in assessing structural damage, caused by inaccessibility and reliance on visual inspections which can introduce uncertainty and subjectivity into the assessment. But accurate assessment of post-earthquake damage is a key step to the subsequent loss estimation, decision-making and resources allocation, and this can be improved by the use of laser scanners. Another advantage of HDS is its long range capability that allows failure modes of a structure containing hazardous materials to be documented from a distance.

After the South Napa earthquake, Pacific Earthquake Engineering Research Center researchers from the University of California, Berkeley, scanned two bridges close to the epicentre in order to assess residual structural capacity. On one of the bridges, a number of scans were carried out and the results combined, with the pier groups being extracted from the main point cloud so engineers could investigate any residual tilt in the pier columns. The Scanstation C10 used in the study supports a dual-axis compensator, which automatically corrects scanner data for 'tilt' from the levelled position. The compensator was turned on, hence the point clouds had a reference vertical axis coinciding with the direction of gravity at the location of the scan. For the pier group consisting of two columns it was shown that one of the columns had a slight tilt in the transverse direction of the bridge. The team is planning to publish a detailed report on all the columns and deck alignments of this 1.2km-long bridge.

The laser scanner used in this study delivers individual point accuracy of 4mm and this accuracy can be further increased by best-fitting sections of the point cloud to lines or surfaces. An internal study at the University of California, Berkeley showed that the error of surface acquisition can be reduced to 1mm by means of averaging point cloud. In case of inclination measurements, the error on the angle estimate can be as low as 0.02 radians. For most purposes, this accuracy is comparable to conventional instruments such as displacement transducers and inclinometers. The quantitative damage assessments from the scans of the bridges show good correlation with the qualitative visual damage assessment and conventional quantitative approaches

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