Video camera being used to observe displacement of rails and deck end on a swing bridge *(Photo: Imetrum)*

Spoiled for choice

Owners and engineers have more choices than ever when it comes to carrying out detailed examinations of bridges, taking measurements, looking inside the structure and monitoring its health. Lisa Russell reports on some of the latest developments

The growth in plans for long-term instrumentation of bridges is leading to close examination of how structural health monitoring works in practice, ranging from the choice of systems and their ongoing calibration to how to manage the information they produce.

At the same time, engineers can draw on an ever-wider selection of non-destructive techniques to investigate the current status of bridges. There are also more options for how to access difficult parts of the structure – which is fortunate, as modern designs and features such as noise barriers can make it difficult to use conventional means.

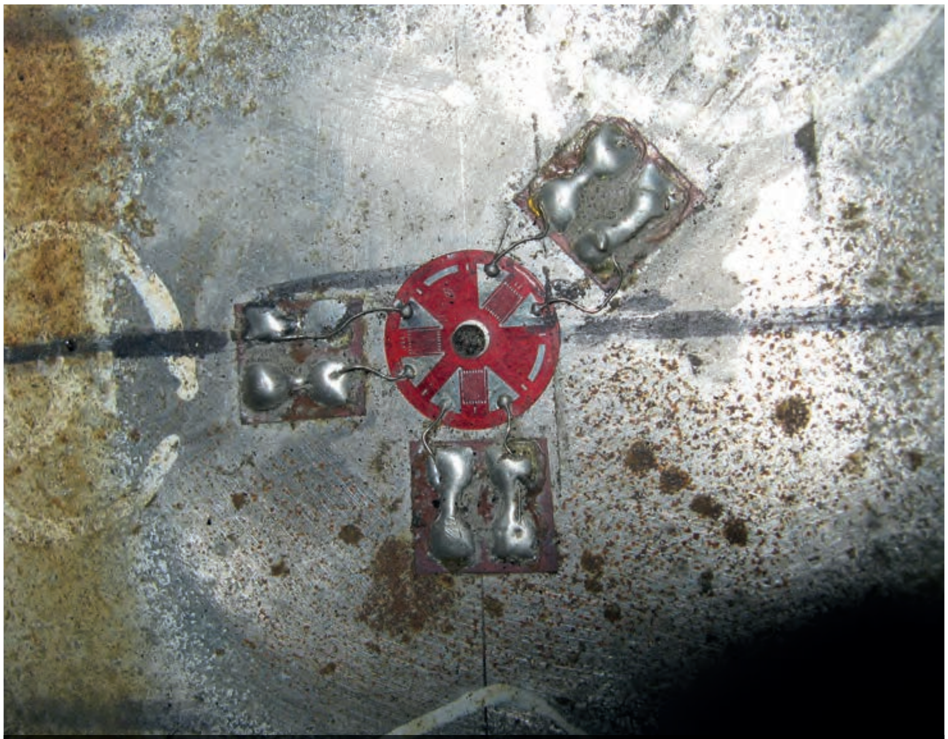
When it comes to specifying structural health monitoring systems, opinions are split, as Strainstall Monitoring technical director Matthew Anderson explains. "There are most definitely two schools of thought with regard to the specifications for structural health monitoring," he says. Some seek to measure everything that might potentially be required, whereas others are only interested in gathering data when something major happens – an earthquake or hurricane for instance. "They are far more focused on real-time aspects, and less so on data for a future design," Anderson says.

Huge increases in computing power mean that the collected data can now be processed far more quickly and to a far greater degree. In addition, better visualisations can be achieved. Communication improvements enable relatively large volumes of data to be obtained from most sites in real time.

"Everybody likes and wants cutting-edge technology – but it tends to be more expensive," says Anderson.

"In our experience, the main methods that are used to instrument and collect data are generally based on tried-and-tested techniques. What actually changes is what you do with the information, rather than how you gather it."

The big future prospect is the use of fibre optic technology for collecting data which could include strain, displacement and temperature, says Anderson. The technology already exists, but is more expensive than conventional strain gauges. "One of the key advantages is that you can have many sensor elements on a single fibre," he says. A special laser is used to etch a grating on the cable at specific points. "If you distort that shape, the wavelength changes and that is what is being detected," he says.



In situ stress measurement on a major steel viaduct at a vulnerable detail *(Photo: Imetrum)*

Anderson also questions the process of designing monitoring systems. "There possibly isn't as much engagement by the designers of structural health monitoring systems with the practitioners as there could be," says Anderson. "That might result in more pragmatic solutions."

It would be better if they didn't choose the actual sensors and heavily specify aspects of the data acquisition system, he says. They may not have access to the latest state-of-the-art instruments; or they may not have sufficient information to make a pragmatic choice. For instance, pricing can increase dramatically – a 5% increase in accuracy might cost 100% more.

Visual impact

Video and still images are playing an increasingly important role, both as a means of recording the details of actual events, and as monitoring tools in their own right.

Strainstall has been working with Imetrum to develop a method of using videos and analysing them. "The video images from successive frames are analysed and a group of pixels is selected as being the virtual target that is monitored," says Anderson. "The way that target moves or changes shape or size is calculated in the algorithm." Strain changes can be detected on a microscopic scale when close to the subject. Similarly it can be used on a bigger scale to look at a section of a bridge, perhaps detecting movements of a fraction of a millimetre. "The algorithms don't care what they are looking at," he says. All they check is how the virtual target is moving within the frame. Field tests have been carried out to compare the results with more conventional techniques and it has performed favourably.

The key benefit is that there is no need for a physical target on the element being observed. It has already proved ideal on a railway bridge where there was no opportunity to set up normal displacement monitoring equipment. The limitation is that, as it is an optical system, the patterns may be affected in bright sun or rain for instance. This system has been in development for about four years and within the last year has been benchmarked and validated by UK's National Physical Laboratory.

Cameras also offer owners the opportunity of an immediate assessment of the situation at a structure after a bridge strike or similar incident, and may allow the traffic to continue using the bridge while an engineer is sent out to site.

Bridge strikes by overheight vehicles can be a major issue for rail operators; trains have to be kept waiting until the bridge has been inspected and cleared for use. But Itmsoil's Bridge Strike monitoring system is designed to reduce the delays. "We are trying to get asset owners to recognise the benefits of retrofitting instrumentation to their assets to help manage them better," says Itmsoil business development manager Nick Slater.

A new system rolled out last year to 20 Network Rail bridges in the UK uses cameras for remote inspection once an incident has been reported. "The intention is to get trains moving as quickly as possible," says Slater. Reference images are available online and the operator can call up fresh images once a report comes in that a bridge has been hit. These can then be compared to the reference images using a checklist. If the structure appears sound, trains can be given permission to cross at a cautious speed. In parallel, the existing inspection process is still followed, with an approved inspector going to site to check the bridge and give the all-clear. The advantage being that traffic hasn't been brought to a standstill in the interim.

Itmsoil originally developed a reactive system using accelerometers to measure movement, together with a camera to view the bridge approach. Both record on a loop; if the accelerometers register an event they can commit to memory the period immediately before and afterwards. An email is also sent with the data and the image. "That allows us to verify that it is a genuine strike as there is a picture of the vehicle," says Slater. The technology has been tested and works, he adds. "Our view is that the two systems would work very well together." The company is in talks with rail operators in other countries about its Bridge Strike technology, both for road traffic and on waterways.

"Something we are seeing more and more now is systems combining data from a sensor with an image," he says. Using a sensor to tell you to look at a picture is a powerful way of making decisions remotely."

Laser treatment

Capturing accurate dimensional data about a bridge is now becoming a much simpler process with the increasing use of laser scanning. "We think that perhaps in future technology will move away from the surveying companies towards consulting engineers or architects," says Faro Europe senior technical product manager Oliver Bürkler.

When Faro introduced its Focus 3D scanner

Laser scanning is increasingly being used for capturing dimensional data *(Photo: Faro)*

the price was less than half that of other laser scanners and this has opened up new customer areas, Bürkler says. Its light 5kg weight and ease of operation mean that engineers and architects may not need to turn to an external surveying company for some measurement applications. "You could scan the bridge at different points in time and use the software to compare the scans and show changes," he adds.

Faro has also recently signed an agreement with Trimble which will give it greater reach into the civil engineering and surveying markets, from its background in industrial applications. The same Focus 3D scanner will be made in a different colour and sold as the TX5.

"The beauty of the scanner is that it captures everything around – it measures all visible objects," Bürkler says. The accuracy is roughly ± 2mm. The scanner spins a fan of beams around in space, capturing almost a million points a second. Every point is converted to x, y and z coordinates.

Processing now tends to happen back in the office, explains Bürkler. "Our experience is that when you are on site you are under time pressure," he says.

The range is up to 120m but in practice the number of set-ups tends to be determined by the shape of the bridge. "It sees only what your eye can see," he says. It typically takes about five minutes to carry out all the scanning from one set-up point. As there is no need for access to the points being measured, it is ideal for measuring inaccessible elements such as bridge piers in a river.

The scanner creates huge numbers of single points in space. In the software, they are displayed like a panoramic photograph, except that measurements can be taken because they are points and can be viewed in 3D. Various deliverables are possible. For instance, the results can be exported into software such as Revit, Autocad or Microstation so that the point cloud can be overlaid with the Cad model. Specialist software such as Geomagic, Polyworks or Rapidform can be used for analysing the differences between models and point clouds. But it is not necessary to have a Cad model to look for differences, says Bürkler.

Lasers are also transforming the way in which portfolios of bridges are mapped and measured. Omaha-based survey technology company Terrametrix has used mobile mapping system Streetmapper to survey more than 7,000 bridges in California at highway speeds.

Streetmapper was specifically designed for rapid 3D mapping using vehicle-mounted lasers. Consulting to Caltrans, Terrametrix used the system to meet revised federal bridge inspection standards that require the longitude and latitude of each bridge as well as measuring minimum clearance, both horizontally and vertically.

Terrametrix was able to capture as-built data of existing infrastructure at a fraction of the time and cost of traditional survey methods. "We developed an automated process to extract the data," says Terrametrix president Michael Frecks. This identified the bridges and created the output, including spreadsheets giving information such as clearances.

Terrametrix has recently measured another 250 bridges on the east coast of the USA. "We are looking at applying it in other states, because it brings such a cost-saving to the DOTs, and it is far safer too," says Frecks.

Asked how the company would have tackled these projects without Streetmapper, the answer is simple: "We wouldn't have," says Frecks.

Sensors working overtime

Reliability of some technologies and the difficulties of calibrating sensors in practice are still posing challenges for this sector. A recent NPL project which was completed in 2012 involved investigations over a three year period on a redundant reinforced concrete footbridge built in the 1960s. A monitoring campaign was carried out over various cycles of damage and repair to the bridge, mimicking the processes experienced by a deteriorating bridge.

The experimental part of the project is complete and data analysis is now in progress but work has already identified that new methods will be required to address issues arising, such as deriving reliable information from distributed sensor networks. The issues relate to uncertainty evaluation and the need for traceable calibration.

"The most important conclusion is that the data and results are very variable," says Elena Barton, NPL's science lead for structural asset monitoring. "Our challenge was to understand the physical, scientific and technical reasons for that variability." It doesn't mean that the sensors work poorly, she stresses. "What it means is that the calibration procedures are not quite relevant when it is working in the real environment."

Considering there are now so many sensors and systems available, a robust framework needs to be developed," she says.

Similar issues were identified with the various types of technology tested for two fundamental reasons, she says. One of the challenges is that all the materials are much more sensitive to temperature than anything else. "The second is that we live in a constantly varying three-dimensional space."

There is a big difference between a

A mobile mapping system is being used in the USA to survey bridges at highway driving speeds

measurement instrument that is taken out to site and can be regularly recalibrated and one that is permanently embedded in the structure.

The concepts of calibration and traceability of measurements might need to be reassessed and re-examined, particularly for medium to long-term performance. "It is important to ensure that when people look at the data they know what it actually means and how much they can trust it," says Barton. "We are embarking on a three-year project to develop this type of framework," she says. "In order to make this work useful, very close collaboration with the sensor manufacturers and people using the sensors in the field is required. We need to reach a consensus."

Managing data

"When you are managing a large asset, you also need to manage a lot of information," says Advitam product owner and commercial manager Alexandre Chaperon, who manages the on-going development of the company's new Scanprint IMS system. A structure such as a major bridge could have more than a million items of information associated with it – even a single highway sign has 38, he says.

Some owners need a system for a specific asset such as a single bridge, but there is growing demand for systems that incorporate other assets such as roads. "You cannot optimise your global budget forecasts if you don't bring all assets together," Chaperon says.

Another trend in the last few years has been for people to look towards GIS systems with the aim of mapping all assets. "This approach has its own limits," says Chaperon. A map needs to have additional functionality to incorporate information such as inspection reports. "If you want everything to be included on the map, then the map becomes overloaded. This is true as soon as you process or perform daily updates of large amounts of information with a traditional GIS approach," he says.

In parallel there is a trend for growing use of building information modelling, or BIM, though the 'b' could of course also stand for bridge. "The idea is to have a single platform into which you can input all the information from design and construction. But this all has to work together," says Chaperon.

Advitam's latest development is Scanprint IMS, which was due to be launched in February 2013 and is a major update of its Scanprint technology. The new system is the result of two years of research to identify the information needed to manage and make decisions about all types of asset, from road signs to major structures. "It can manage everything from design onwards," Chaperon says; it integrates the database and the engineering information into a single platform and is web-based so can be accessed either in the office or on mobile devices such as tablets. "We have built BIM compliancy into our system and it can also communicate with other systems," he adds.

In the USA, the Federal Highway Administration has chosen Scanprint IMS as its system to manage information about all 600,000 bridges on US highways, using a web portal that will be available to all US transportation departments. "We are developing bridge engineering components to integrate into the system," says Chaperon. "All this information will be provided to the state DOTs to help them manage their bridges."

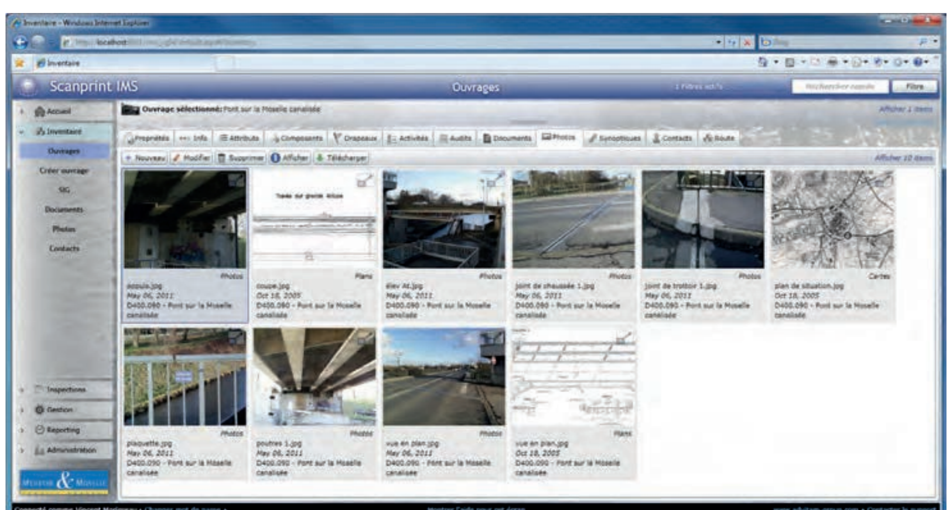
However data storage in structural health monitoring still remains an issue despite growing hard drive capacity, as the volume of data continues to grow, says senior technical executive Timo Laurila of structural health monitoring company Savcor. It is not unusual for 300 or so sensors to be required where once fewer than 100 would have been specified, he says.

One role of SHM can be to inform designers about the structure's actual behaviour. "Designers use very sophisticated 3D modelling tools and they want to confirm that the models they have created reflect reality," says Savcor senior technical executive Timo Laurila. But the bridge owner may not see any direct benefits in paying for sensors purely to further the designer's understanding. "We have a strategic goal to focus more on the needs of the end user who is paying for the system," he says.

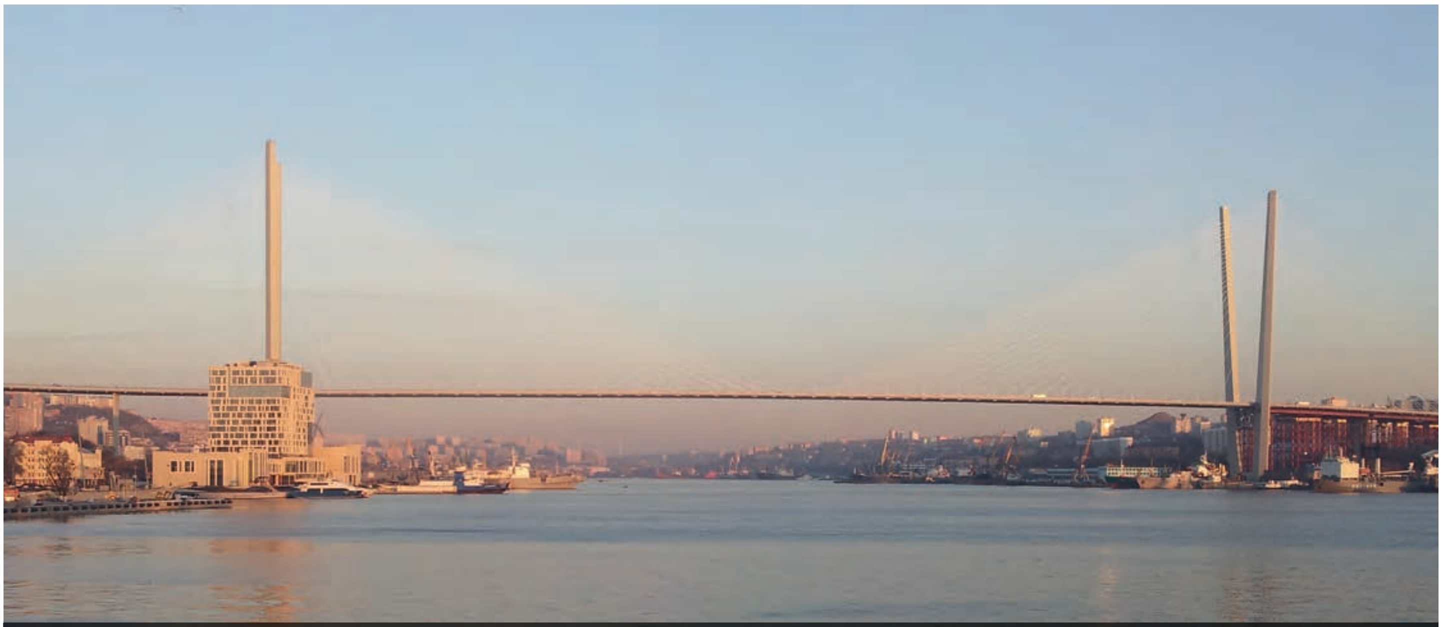
"Functional integration with other systems is a growing trend," adds Laurila. At the end of last year, Savcor launched a new system, known as the intelligent structure concept. It enables the combination of systems that would traditionally have been kept separate, such as structural health, traffic control, safety systems, corrosion and weather. "From an asset manager's point of view it is easier to have just one global system."

Developments over the last decade mean that the reliability of sensors and data acquisition systems is no longer an issue, claims Savcor structural health monitoring division manager Pekka Toivola. Previously, the data acquisition nodes used for transmission were quite fragile

Carbon fibre repair panels on the footbridge that has been under test at NPL



Screenshot of the Scanprint IMS system



A structural health monitoring system is being installed on the Golden Horn Bridge in Vladivostok, Russia, which opened last year *(Photo: Savcor)*

and susceptible to damp. Today's sensors are much tougher; some would keep working even if submerged in boiling water, he says.

As regards the amount of data, the company has developed a proprietary data compression method that saves on storage. This approach enables all the data to be saved, instead of just data from 'events'. The problem with relying on triggers, says Laurila, is that someone has to determine what the trigger level is. "If you methodically save all the data, you don't have this problem and can see what happened prior to the incident."

Installation of structural health monitoring equipment in a steel box girder *(Photo: Mistras)*

It is essential to avoid overwhelming the user. "Our experience is that if you give out too much information the user steps away and stops using it completely," says Laurila.

When there is an incident such as a ship impact, for example the owner's immediate question is whether the structure is still safe to use and, if not, what must be done. "We try to get inside the head of the end user and focus on what they want to see," he says.

"One thing today's clients are asking is how we can synchronise camera data with other data from the monitoring system," says Toivola. Cameras provide a very straightforward way of answering questions about an incident. "We pride ourselves on synchronising the whole system down to sub-millisecond levels," adds Laurila.

One area that has seen continued development and is increasingly being adopted is global satellite systems. Their use is increasingly being specified, particularly as prices have fallen. Movements as small as 10mm can be detected, marking a considerable improvement from previous accuracies of perhaps 500mm.

Use of fibre optics is also growing. "They have their advantages as they are immune to electro-magnetic interference, but on the other hand the instrumentation and fragility of these fibres create different kinds of problems," says Laurila.

Integrated approach

"Thankfully most of bridge monitoring is benign and not a lot happens," says Mistras Group structural monitoring specialist Jon Watson. However one notable exception was the 50-year-old Hammersmith Flyover, a key transport artery in London. Ongoing acoustic monitoring of the internal cables by Mistras alerted Transport for London engineers to the locations and rate of ongoing deterioration and the decision was taken to close the structure in December 2011 due to the condition of post-tensioning cables. The flyover was reopened to light traffic in January 2012 and an urgent strengthening programme was carried out, enabling it to reopen fully in May, well before the Olympic Games began.

Watson says that the monitoring of the Hammersmith Flyover illustrates a key trend in structural monitoring – the integration of different technologies into a single system rather than just using a single technique. "It enables you to get a complete view of how a structure is behaving," he says.

Acoustic monitoring for wire breaks directed the engineers to the key problem areas with the post-tensioning. This acoustic monitoring was combined with other methods such as checking the segmental box girder for any separation of precast units and a bearing monitoring system covering displacement, longitudinal movement and any pier rotation. "It is all integrated, enabling cross-correlation," he says.

No matter what type of data is produced, it will be of no value if there is insufficient space to store it or resources to assess the output. "I'd rather provide one sensor and the data be used and evaluated to its full capacity than to provide information from 100 or 1,000 sensors that never sees the light of day," says Watson.

"Our system differs from most others in that data is collected at a high rate in a buffer. If nothing happens we select one out of ten or 100 values to record," says Watson. This ensures that very detailed information is available for a period of perhaps ten seconds or a minute for situations such as an unauthorised heavy load crossing the structure. Saved readings then revert to the routine slower rate, which might be one a minute or one an hour. That enables the response of the structure to be recorded when something significant happens, but also keeps results showing the overall picture with a less frequent pulse of data. Mistras has found this approach very effective; data quantities can be optimised even when carrying out multiple types of monitoring on a structure.

Mistras tends to focus on damage and end-of-life monitoring and Watson – perhaps surprisingly given his business – is not always an advocate of the routine incorporation of sophisticated sensor networks into new bridges. The problem is that nothing should really happen to a structure for at least ten to 20 years, he says. "Monitoring systems should easily last five years – which is a typically requested guarantee period – and would probably get to 10 years or more. But realistically the whole system would need completely refitting within the first 20 years," he says. "It's a generalisation, but I don't see a massive value unless you have a specific problem. And if a bridge engineer has a specific problem, then they should be designing it out."

Identifying priorities

Using structural health monitoring to identify priorities for maintenance spending can be cost-effective in the long run, believes David Cook of SHM system provider Straen. There might be 12,000 bridges in a state, with perhaps 7,000 rated structurally deficient or functionally obsolete and a certain proportion at high risk. Of the 300 or so at high risk, the owners won't know which face the biggest problems. "They know they need to be repaired or refurbished, but they don't know if they have another five, ten or 20 years," says Cook.

Managing a portfolio of bridges as individual assets tends to change the decision-making process, he says, and the primary approach is to try and identify the degree of damage and work out the residual life in theory.

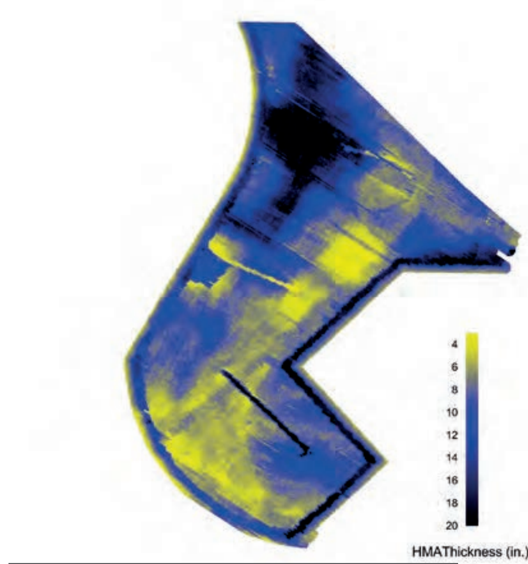
"Some people prefer not go through the whole process of trying to identify and estimate damage," Cook says. "Instead they would rather try to assess the health directly – we now have the ability to do that."

Inspecting the hanger cables on the Silver Jubilee Bridge in the UK *(Photo: Vertical Access)*

Sensors can be deployed at a very reasonable cost and the health of the bridge can then be assessed on its performance. "If you wired up the entire portfolio with these sensors, you would learn which of those, say, 300 bridges were safe, which needed repair and which needed refurbishment or replacement."

Even the most detailed visual inspection cannot pick up every piece of damage, Cook says. He sums it up as the difference between knowing how many cracks there are and of what length, versus knowing whether the neutral axis has changed.

For example if seven bridges in a city are of high concern, the chances are that at least one is going to be much healthier than was thought, and might not need major work for a decade or two.



Asphalt thickness contours revealed by the Infrasense system

The Hi-Bright system developed by IDS uses georadar to establish concrete slab thickness and rebar positions

This could save some US$20 million, which would not only pay for the wiring of the other six but also for wiring anything up to one hundred more, he suggests.

Moving towards the long-term

As the health of an increasing number of structures is assessed using instrumentation, there is likely to be a continuing trend towards longer term monitoring, believes Fugro Aperio's division head for structural investigation Simon Brightwell. Much of his work involves non-destructive testing of existing structures, assessing the condition of the bridge at the time of the test, but this can cross over into longer term monitoring.

"I think that we will see a lot more integration between collecting data in the 'here and now' sense and leaving instrumentation in place over time," says Brightwell, and in the next five years he believes this will become the norm. Historically – and to some extent currently – people distinguish between the two but Brightwell makes a compelling case for change, especially when the costs of instrumentation are considered in terms of asset management costs overall.

Comparing results between inspections that take place years apart is not as useful as leaving instruments in situ, he feels. "Once you go to the cost of mobilising to get on a structure, the marginal cost of leaving instruments there and monitoring them over time may be a very good investment compared to the alternatives of maintenance and repair – or in the worst case a loss of service," he says.

Local authorities in Europe are financially under huge pressure, he points out. "There is terrible pressure to avoid anything that is not required on a statutory basis. On the other hand, you can also argue that it is exactly the time when you need some clever thinking," he says. Being able to do things such as gathering more comprehensive data that will save money over a period of a few years is in the public interest.

Events such as the sudden closure of London's Hammersmith Flyover drew attention to problems that can afflict post-tensioned structures. "People are beginning to see the value of a non-destructive approach in looking at the condition of the tendons using a combination of methods," Brightwell says.

The classic approach Fugro Aperio takes begins by testing to see if there are voids. The company uses high-resolution radar to map the tendon precisely, then one or both of two different acoustic techniques. One is a low-frequency ultrasound flaw detection system. "It is a relatively quick, perfectly benign passive test," says Brightwell. The other, its 'cousin', is the impact echo test.

Ultrasonics involves sending a sound wave into the structure and examining the level and velocity of the energy that comes back. Not much will come back from a solid surface, while the voids will give reflections.

The impact echo technique looks at whole-body vibration and effectively involves the surface being tapped with a tiny hammer. "You can scarcely imagine that it will have enough impact to set up a signal," says Brightwell. A solid, uniform structure gives a uniform reading while a discontinuity gives a higher or lower response.

"The beauty of both these methods is that they are effectively blind to metal," he adds. "While radar may be the most attractive technique in terms of being really quick, it won't see through the metal duct – you are really limited to acoustic techniques there." Once anomalous locations have been highlighted, some can be opened up. "The amount of direct testing you need to do is a fraction of that needed otherwise and it is placed intelligently where you suspect there may be an issue."

Long-range research

As would be expected in this rapidly-developing sector, there is plenty of work going into new research. Two EU-funded research projects being coordinated by TWI involve development of guided wave ultrasonic technology for example. The Wi-Health project, which is a collaboration between European SMEs, research organisations and the Humber Bridge Board, seeks to create an active wireless network with autonomously-powered long-range acoustic nodes for total structural health monitoring of bridges. The object is to create a way to assess long-span bridges using fewer sensors and with less disruption to traffic.

The project has a number of elements: wireless communications development, acoustic emission and guided waves, renewable energy through power harvesting and software development. Whereas acoustic emission is a passive technology that waits for an event to happen before issuing an alert, long-range ultrasonics can monitor the existing status against baseline information.

The technique could identify if something is starting to happen, even if it is not yet apparent to the acoustic emission sensors.

"The size of defect that we can detect depends on the wavelength," says TWI's Kamer Tuncbilek, who is managing both projects. It is not easy to detect a defect if it is smaller than the wavelength sent through, so the wavelength is increased or decreased to try and detect different sizes of defects.

The Cross IT project also focuses on bridges, in this case concrete ones. "We are trying to reduce unnecessary maintenance costs as well as providing information about areas that cannot be accessed," says Tuncbilek. The aim is to use guided waves, along with ground penetrating radar to assess tendons buried in concrete. TWI is working with Atkins, NTUA in Greece and three SMEs.

Ground-penetrating radar is used to detect tendons and reinforcement. Guided waves are sent through the concrete and the returning signals are then assessed. "We are trying to assess corrosion issues and breakages or loss of material," says Tuncbilek.

"What we are trying to do is show what cannot be seen by the naked eye and highlight problems if there are any. So far in our experimental set-up we have recorded really promising results."

Infrared thermography

Another non-destructive technique is infrared thermography, which has been used by Infrasense, whose recent projects include the completion of subsurface investigations for 17 bridge decks in the Greater Chicago area. These detailed condition evaluations enabled maps of delaminated areas to be built up for each deck, while minimising disruption to traffic flow.

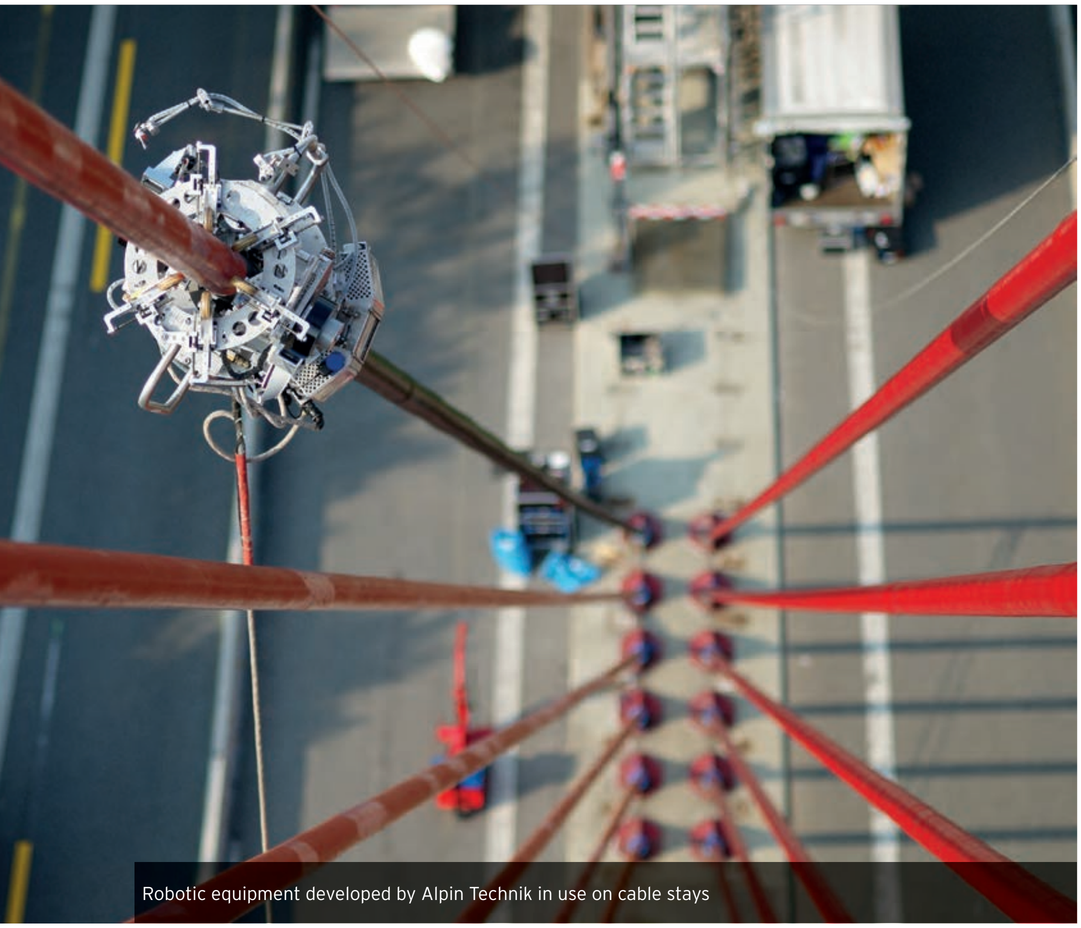
The company regards the prioritisation of bridge deck maintenance and rehabilitation efforts as an ideal market for non-destructive testing techniques, says Infrasense staff engineer Evan Guarino. Most states in the US have tight budgets, and more bridges that are rated as structurally deficient or functionally obsolete than they can handle, he says. "We want to help states determine which decks need most work, and which can be bumped down the priority list."

Infrasense finds ground penetrating radar a useful tool for prioritisation as it is able to detect a certain amount of existing deterioration, as well as developing deterioration, which may not have manifested itself yet.

IR is a tool where 'you get what you see', says Guarino. Radiation heats up the deck and creates thermal inconsistencies at delaminations. Areas of sound concrete will show a particular thermal profile where the heat was able to transfer through the entire deck; unsound areas cannot transfer the same heat through the entire deck, and thus appear as spots in the infrared image.

Ultrasonic techniques are good for detecting voids, but to use this technology on an entire bridge deck would be tedious, says Guarino. "The impact echo test is really more of a spot test – we use it to confirm some of the hot spots we see in the infrared image that we suspect may be due to some surface staining that absorbs more heat, or in areas affected by shadows," he says.

"Ideally, these technologies would all be used to complement one another and provide the most comprehensive results," says Guarino. "However, we must work within our clients' budgets, time constraints,


Robotic equipment developed by Alpin Technik in use on cable stays

weather considerations, and disruption limitations to select the most appropriate technology for each project."

Georadar

Ground penetrating radar techniques, also known as georadar, are being increasingly used in bridge management. Ingegneria Dei Sistemi launched its Hi-Bright system in 2010 as the company recognised the worldwide demand for more information about the internal structure of bridges. An array of high-frequency antennae is used to identify aspects such as the slab thickness and the position of rebar.

The company's Hi-Bright GPR system is designed for early detection of concrete deck deterioration. The Hi-Bright system uses an array of 16 antennae and covers the deck in longitudinal passes. Usually it can 'see' up to 700mm below the surface; while changing the frequency allows deeper penetration, smaller targets cannot be seen at these lower frequencies.

Data acquisition is followed by post-processing to give a representation of results such as where moisture is present in the concrete.

IDS georadar division regional sales manager Giorgio Barsacchi estimates the Hi-Bridge system can carry out about 80% to 90% of a deck's condition assessment. For a complete bridge deck assessment, other tests will typically be needed, such as impact echo or techniques that employ other types of waves. Radar is not totally accurate at detecting the delamination of concrete says Barsacchi. "It is harder for this technique to evaluate the early stages of water penetration."

The company also produces the IBIS-FL and IBIS-FS systems, which use interferometric technology based to carry out remote static and dynamic monitoring. Waves are sent towards the bridge at a high frequency and the signals that bounce back are processed. The technology does not look at the internal condition of the bridge – it measures the vibration and displacement of the bridge from a distance. The advantage, says IDS georadar division marketing and sales manager Paolo Papeschi, is that the system is quick to use and permits displacement to be measured from a distance of say 1km without the need to install any reflectors.

Smart cables

Not all monitoring systems have to be incorporated into the structure as an additional element – some companies want to offer structural components with in-built monitoring, and fibre-optic sensors are central to this aim. Geocomp has been working with bridge component manufacturers who want to provide added value for owners; one such example of these smart components is at Shanghai Pujiang Cable Company where Fiber Bragg Grating moisture/humidity sensors are being developed that can be embedded in bridge stay cables.

"We are in the business development phase," says Geocomp Corporation practice area leader – structural monitoring, Tom Weinmann.

Weinmann has recently been to China to verify the performance of fibres installed a year ago in a bridge's cables. The fibre itself is the sensor. In the case of moisture, it has a coating that swells up with exposure to moisture, choking the fibre. Unlike with conventional sensors, distance is not a limitation – the fibre can extend the full length of a cable.

Weinmann is seeing increasing demand for sensors that are installed in bridges from the outset. Several major bridge projects now getting under way in the USA have sensor systems written in to the specification; even five years ago this would have been unheard of.

The technology is not new in itself, but adoption is increasing as people become more comfortable with it and more confident in the results. "What has really forced us to make these decisions is our economy," says Weinmann. Owners are starting to realise the benefits – especially given the new MAP-21 (Moving Ahead for Progress in the 21st Century Act) requirements, under which US states have to be more accountable for their structures.

"It's certainly being required on larger structures but can also be done on smaller ones," he says. Corrosion monitoring programmes are relatively inexpensive, he says, and can help with future decision-making such as when to renew deck waterproofing.

Load testing systems requiring minimal instrumentation can provide the best assurance, says Weinmann. "Going out to these structures and doing a quick load test with minimal instrumentation on a few key members will tell you a lot. "In any instrumentation programme I think that it is extremely important to carry out load tests to calibrate the system," he adds.

Bridge instrumentation can come into its own for immediate evaluation following an event such as a typhoon or barge impact. "The owner can immediately assess the force distribution on the bridge," says Weinmann. He likens this to being able to tell a doctor what is wrong with you, rather than waiting for the doctor to work it out. "The sensors on the structure allow you to pinpoint areas of concern and focus your maintenance efforts." Without this, considerable effort may have to be expended in testing to seek damage.

Remote control

Technology can help improve the efficiency of bridge inspections; savings can be made when these inspections are better focused, both in terms of the time engineers spend on site and decisions about where intrusive tests are needed.

Using robots and other new access techniques makes it possible to achieve significant savings in the costs of maintenance, says Alpin Technik general manager Eric Kuhn.

Robots now allow cables to be inspected without anyone needing to venture out onto the cables, although some hands-on inspection may still be carried out once any problems have been identified. But the inspector does not have to inspect the whole cable and might need just two days instead of two months, says Kuhn.

The average speed of the robot on site is about 1,000m of cable a day. "We are able to record the whole cable surface visually," Kuhn says; he believes that it is impossible for a person on the cable to document it fully. As well as noting any problems, good areas should also be recorded, he says, and sometimes the inspector may not be able to decide instantly whether something is a problem yet.

The robot captures perhaps hundreds of thousands or millions of images of the cable. They are processed to show the whole 360° surface as a single flat image. The software is designed to make it easy to 'inspect' the cable, mark findings for evaluation, list them and create a report. Once the image is on screen it takes only about 10 minutes to inspect 100m of cable.

Not many people are likely to print out a 100m image, but sections can be printed if required. Latest technology could in effect even allow a section of cable to be brought into the office and handed round for discussion. The robot can be fitted with a 3D laser system to check any areas of concern picked up by the visual inspection. A replica of the section could be created using a 3D printer. "This is amazing technology," says Kuhn. Clearly this is a more expensive option, at present likely to be used only for serious issues.

The robot can be fitted with many different systems in place of the camera and development of others continues. Options include a magnetic flux leakage module to inspect the inside of the cable for wire breaks and a thermographic system.

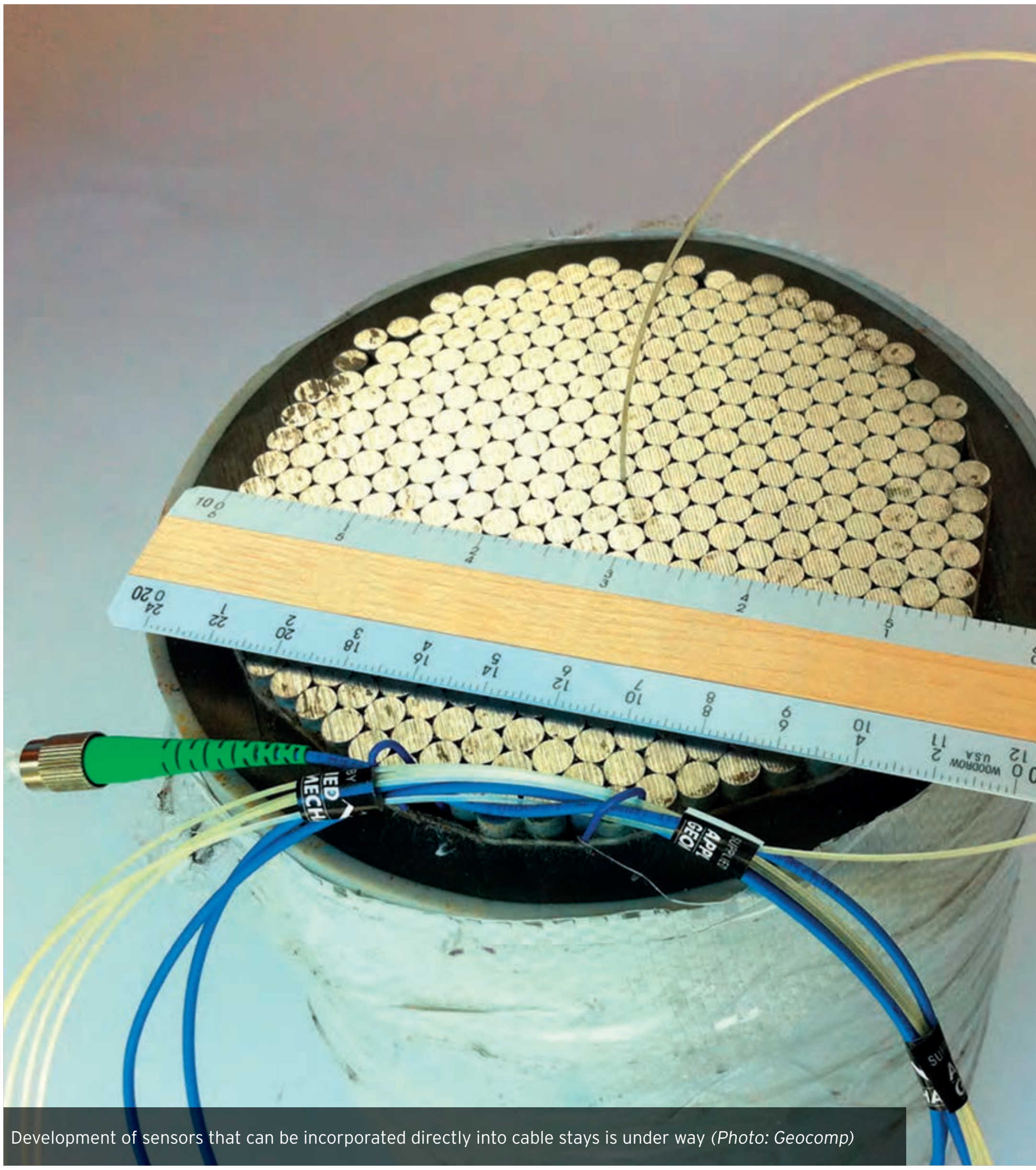
This could be particularly useful for any issues identified within the paint guarantee period, Kuhn suggests, as the paint layer can't be breached at this stage.

The robot can also be used to carry out actual maintenance work, including wrapping a butyl rubber system onto the cable, or PE welding to repair storm damage for example.

These time-savings may help address a shortage of capacity needed to meet the required schedules of checks. "Germany has about 270 cable-supported bridges but not enough inspectors," says Eric. "Today there is no excuse – you can inspect cables very quickly."

It is less efficient to inspect the main cable of a suspension bridge with a robot because of the relatively short distances between hangers. However Alpin Technik has also developed a new system that could be used in these situations, making it easier to reposition the system each side of the fixings.

The question always comes up as to whether the system can evaluate images automatically. "The question can be clearly answered – no," says Kuhn. Automated evaluation is only possible for surfaces with a repeating pattern, such as a grid. It would be impossible for it to recognise



Development of sensors that can be incorporated directly into cable stays is under way *(Photo: Geocomp)*

Remotely-operated aerial vehicles are now being used for bridge inspections - they can be deployed in minutes *(Photo: USAV)*

every spider or bird dropping for instance; too many anomalies would be identified.

One of the most recent technologies to move across into the bridge inspection sector, is the use of remotely-operated aerial vehicles. These enable a flying camera to be in place in moments, offering an inspector a view of underneath a bridge or high above the deck.

US Aerial Video is a family company that has been in business for less than a year. "We are very excited about this technology," says head engineer Luke Wylie. "We believe this is the future." The technology will be commonplace in a few years, he predicts, as it is safe and cheap. But there will be a challenge in convincing people who are used to the more traditional methods, he acknowledges.

Cameras are attached to remotely operated aerial vehicles and can be manoeuvred into hard-to reach areas to gather high-definition images and videos. ROAVs are able fly less than a metre from a bridge in calm conditions, or could move out and take shots from hundreds of metres away.

"One of the ways this can be used is for visual inspection purposes," says Wylie. "Our technology is a tool – we are not trying to replace the hands-on inspection." It can also be used for damage assessment or in monitoring traffic patterns. Producing publicity films of completed projects is also proving a popular idea.

The ROAV is controlled by a two people: a pilot and a camera operator. The inspector would typically be on site, monitoring the incoming footage through a screen and instructing where the ROAV should look next. "By communicating with the pilot and camera operator, the inspector can look at anything he or she wants," says Wylie. The inspector doesn't even have to be on site as the entire bridge could be documented for later review. "The technology is also there to stream the footage anywhere in the world so that someone could monitor it in real time," says Wylie. The observer could even issue directions to the pilot and camera operators.

The systems are industrial versions of the kind of kit popular with hobbyists and USAV has several sizes up to about 1.2m. Depending on the payload, they can fly for up to about nine minutes, which also has the benefit of keeping the footage to a manageable level.

Wylie explains that the company normally shoots high-definition video and that stills can be extracted from this. The main cameras used are high-definition digital SLRs.

Access all areas

Of course one of the most effective and traditional weapons in a bridge engineer's armoury is the close-up, hands-on inspection of a structure. But even this can become a time consuming and expensive process when special equipment is needed to access all parts of the bridge. Luckily a huge range of options is now available, ranging from rope access to specialist floating systems for low-headroom bridges over water, and manufacturers are continually improving their products to address the issues that modern bridge owners face.

Bridge inspection unit manufacturer Barin's managing director Romeo Bagliolid sees the most important new trend in the maintenance of existing bridges as the gathering of information using special bucket-type bridge inspection vehicles to work both underbridge and overhead.

Barin's latest innovation is a new concept

Modern structures such as these cable-supported bridges in Hong Kong pose specific challenges to inspection equipment designers *(Photo: Barin)*

product recently developed in response to customer's requirements. Bagliolid says that this AB 23/SL model is the largest bridge inspection unit in the world. It was developed for the inspection of the Lantau Link bridges system in Hong Kong.

Equipment manufacturers are now looking for new markets in Asian and Australian countries, says Bagliolid, as the European market is almost saturated. The dramatic economic crisis which hit Europe has forced manufacturers of bridge inspection units to look to the Far East and South American countries.

But while the importance of regular inspection is now widely accepted, it is somewhat ironic that the design of many modern bridges make access for inspection difficult. On European bridges there is an increasing need to take account of tall sound barriers, explains Christine Moog, who is general manager of bridge access, inspection and maintenance equipment at specialist Moog. Although this has been an issue for the last six years or so, the barriers are now getting higher. Some are more than 5m tall, with a shape which adds to the difficulties.

Heavier counterweights and longer reaches may be required to get past the obstacle and a particular challenge is to keep inspection units within the normal weight limits for road traffic.

She says that the company must offer a far greater choice of machines than ten years ago. "In general, the machines have to be much more flexible and we have to offer a bigger variety because of the different requirements," she says.

Until two or three years ago, machines delivered to China tended to be standard ones, with long platforms but no other special requirements. But in the last few years many have had special requirements to cater for sound barriers of up to 4m. It provides an additional challenge in China, where the bridges tend to be very wide.

Wider bridges do not in themselves pose a technical issue – but width does affect the machine weight. "A lot of design offices are planning fixed inspection gantries for those bridges," Moog adds. Luckily, most of the bridge design firms also have to provide the inspection plans, she says, encouraging them to think about the issue in advance. It is becoming increasingly common to be asked to look at a bridge at the design stage and discuss suggestions, she finds.

In Eastern Europe, a lot of bridges are of simple concrete designs and these don't have many special requirements. "When it comes to more architectural bridges, it is no longer that simple," she says.

Permanent gantry installations tend to be installed on bigger bridges in busy areas, where it would be difficult to close even one lane at night; sometimes a bridge's design even precludes the use of a mobile system. The company has recently delivered a very simple, small gantry to an Austrian bridge where the cable design precludes any access by a mobile unit.

Top down

No single access method suits every situation but rope access is one of the main methods used for inspecting structures. Most companies that carry out rope access for bridge inspections tend to offer it alongside other methods such as mobile platforms, finds Paul Bingham, who is contract and health and safety director at Vertical Access as well as being chairman of the health and safety committee of

Inspecting the Sheikh Zayed Bridge in Abu Dhabi *(Photo: Moog)*

IRATA International – the Industrial Rope Access Trade Association.

"One of the main aspects you have to consider for rope access is whether there is suitable anchor at the top," says Bingham. Factors such as lane closures have to be assessed to see which method is the best, safest and causes least disruption.

Rope access inspections have to be carried out by people who are trained and certified in the technique. Vertical Access works mainly with consultants, and they are usually on site at the time of the inspection. "It's even better when the consultant has at least one person who can get on the ropes."

However many of today's young engineers lack enough adventurous spirit to learn to use the ropes. "If you talk to older engineers, they will tell you that younger engineers want to sit in front of the computer," he says.

Use of rope access requires at least the entry level of IRATA International's training and certification scheme. Otherwise the engineer will have to stay on the ground, reliant on photos, videos or descriptions as recorded by someone else.

Most bridge inspection companies such as Vertical Access do have engineers on the staff. But by no means will all the people working on a job be engineers. Ideally someone from the consultant can work with the team, says Bingham. The next best situation is to have an engineer on site to talk to the team carrying out the inspection. "The worst case is where you just hand the data over."

A lot of people are prepared to use a rope – for instance, charity abseils are popular. "But there is a big difference between being able to get on a rope and being comfortable on it," says Bingham. "If you are nervous and unhappy you are not going to be able to focus on the job."

There are currently 51,000 people in 45 countries registered under IRATA International's training scheme. As well as the entry level, there is a level for lead technicians and one for site supervisors. Most engineers in the UK would only have the level 1 grade as they don't use the technique very frequently, he says.

Some bridges present particular challenges, modern ones in particular, says Bingham. "Concrete bridges can be very difficult to work on if the client doesn't allow you to place anchors in them," he says.

Otherwise solutions have to be found such as using a vehicle or boxes filled with weights as anchors. Steel structures are generally easier – wire strops are normally passed over part of the structure.

Undercover work

While rope access techniques usually involve descending from the top of a structure to examine it in detail, accessing the underside of a bridge to give it a close-up inspection can pose similar challenges.

Specialist Harcon Corporation approaches from the other direction, working on more than 500 structures a year, with more than half accessed from one of its four bucket boats, which have a working height of more than 20m. Using boats to look at the underside enables engineers to identify damage that would otherwise be difficult to see. A regular inspection of two bridges that used to take the client two weeks with other means now takes just six hours by boat.

Harcon has also added a third model of its patented Bridge Tracker to its range; this is a rubber-tracked bucket truck that can drive into water. The largest and newest, the T63, has a working height of 19m.

"The main advantage is that we can get underneath bridges and up inside them without lane closures," says Harcon president Harry Stoltzfus. The bucket tracks and boats can be in place and working within minutes.

An inspector's initial concern is usually how stable the platform will be, Stoltzfus finds. "They discover that we've designed them to be extremely stable," he says, "and they are always amazed. After they have been on board for an hour or so they forget they are on a boat."

The latest Bridge Tracker is able to operate in 3m of water, but would generally keep to slightly shallower depths of perhaps 2.4m in case of any uncharted holes in the river bed.

The boats are particularly useful for getting under movable bridge spans, Stoltzfus says; by their very nature these spans tend to be close to water level and are difficult to access by other means.

Up to now, most of Harcon's work has been with consultants acting as subconsultant for transportation departments. "But we are starting to see DOTs express interest in contracting directly with them," he says. Lane closure issues mean that they recognise the advantages of using Harcon's water-based techniques, even when they have their own access equipment.

Installation of floating platforms or nets can provide inspection areas underneath a bridge. Pontoons have been around for centuries in one form or another, but today's lightweight plastic versions open up new opportunities for accessing the undersides of bridges.

LIghtweight plastic pontoons are one option to access low bridge soffits *(Photo: Work on Water)*

Work on Water has been established for eight years and is now the UK and west European distributor for the Magic Float pontoon system.

Steel barges can often be unsuitable for use in inaccessible, remote places, says operations director Julian Whyte, but modular plastic HDPE pontoons can provide the ideal alternative. In essence, they can be used to create land over water, he says. Clients include consultants carrying out inspections of the many bridges that cross small streams and rivers.

Individual units measure 500mm by 500mm by 400mm. They are essentially plastic boxes that float; joining them together makes a larger floating plastic box. Two joined together weigh 12.2kg and so can be carried by hand if necessary. The smallest size that Walk on Water typically supplies for a small bridge is about 1.5m wide by 2m long.

"Generally we arrive on site with pre-built platforms," says Whyte. Larger platforms can be craned into the water from the delivery truck if there is access to the waterside. "Using ready-assembled sections we can build a floating structure of considerable size very quickly." Two of his team could install a platform of about 200m^2 in under a day. Alternatively platforms can be delivered to a nearby boat club; the platform is then effectively turned into a small barge and moved into position along the river.

Even with a pontoon in place, extra height may be needed and so Work on Water also supplies equipment such as tracked access systems to reach structures up to 19m.

A popular size is a 5m by 6m platform, fitted with barriers and used in conjunction with a lifting system. Sometimes it is equipped with an engine; alternatively it can be manoeuvred using a boat. The platform will often need moving several times during multi-span inspections

Harcon's largest Bridge Tracker in use on a bridge in Little Orleans in Maryland, USA

Exp's net system which can be attached directly to the bridge

lasting several days.

Specialist Exp provides a net system that is fixed directly to the bridge. Wood planks are placed within the net to create a stiff surface on which the inspectors can walk, while attached to a safety cable.

"It's like walking in a large hammock; the net gently swings from side to side," says Exp senior vice president Vincent Latendresse. "After a couple of seconds you get your balance. You have a very up-close view of deck elements."

On small bridges, Exp will typically use only this method. For other projects, mechanical access may be used as well. The most typical example of combined use on a truss bridge is the classical rope access for the top and bottom chords and net access for the stringers and floor beams, he says.

Usually, the guard rails are used to attach the net to the bridge. The net is supported by two steel cables, which are adjusted at their ends to fit the width of the bridge.

The maximum width that can be inspected is around 9m. "If we use the net on wider structures there is too much slack in the middle and the inspector cannot reach the bridge deck to inspect," he says. "We can inspect any length of bridge since we reposition the net longitudinally at will."