Fibre-optic sensing has been used for a number of years in a variety of applications within the oil and gas industry. Technological developments such as distributed acoustic sensing are now evolving to meet the growing needs for efficiency and security.

**REMOTE SENSING** applications developed to monitor pipelines, wells and storage vessels include distributed temperature sensing (DTS) and strain sensors. DTS has been used in downhole applications to monitor well production as well as downstream to show vessel skin temperature and as a leak detection tool within LNG terminals. Strain sensors have been utilised in risers, flexible pipes and jackets to signal fatigue. Such methods have their limitations, yet recent developments in sensing techniques and algorithms are pushing out the boundaries of fibre-optic sensing applications.

**DISTRIBUTED ACOUSTIC SENSING**

One of the most significant developments in the sector is distributed acoustic sensing (DAS). The first DAS systems were installed to detect third-party interference within the right-of-way of pipelines in 2008. Now DAS is not only being used to protect pipelines from accidental or malicious damage, but is also being used as a condition monitoring tool, allowing the operator to control and schedule its deployment of cleaning pigs and inspection gauges as well as an online leak detection system for liquid, gas and multiphase products.

DAS was originally developed within the telecoms industry to locate fibre-optic cables that carried no metallic components and were therefore impossible to trace. It was soon adopted within the security and defence sectors to protect large perimeters, borders and roads. The ability to protect long linear assets made this an obvious technology choice within the pipeline sector.

Using algorithms developed over 40 years of sonar deployment, knowledge gained within the defence sector, the technology has been developed to detect, locate and classify intrusion events such as personnel, vehicles, manual and mechanical digging. The same techniques are now being deployed to locate and track the speed of cleaning pigs and pipeline inspection gauges, as well as detecting and locating the presence of leaks.

The OptaSense DAS system converts a standard single-mode fibre-optic cable buried adjacent to a pipeline (often the same cable used for SCADA communications) into an array of virtual microphones. A highly stable laser is pulsed at 10,000 times a second and the Rayleigh backscatter is monitored for signs of ‘excitement’ within the fibre molecules. This is called coherent optical time domain reflectometry (C-OTDR) and the response has a number of unique advantages including the ability to detect, locate and classify activity simultaneously to the vicinity of the pipeline.

**OPERATIONAL SECURITY**

The DAS system was originally developed as a security product and it is therefore this application that is most mature and widely adopted around the world. To date, such systems have been deployed in most regions, including South America, North and West Africa, the Middle East, Europe and Asia. They can detect, locate and classify activities such as personnel, manual and mechanical digging, tunnelling, vehicles and even low-flying aircraft. However, experience has shown that a majority of threats are not malicious. The image of an organised syndicate installing hot taps and drawing down product at will is one that has been widely used in the past. However, the common threat to operational security is that of the local farmer digging a bore hole for irrigation, or construction worker digging foundations with a back hoe.

OptaSense’s pipeline DAS product is currently deployed on over 12,000km of pipeline and has evolved to use the information as a forensic tool, where alarms should not only be classified but also prioritised. Activity during daylight hours may not be classed as a threat, but the same activity in the dead of night could be different. Likewise, in a busy town this may be considered normal, but a remote location where activity is scarce has a different threat level. It is during this initial consultation period that providers help to develop an action plan with the client. This will include integration into other systems such as supervisory control and data acquisition (SCADA) and distributed control systems, CCTV or even unmanned air vehicles (UAVs). Along with this may be an escalation plan to formulate how the threat will be handled. This could include email or SMS to internal reaction teams or collaboration with local police or government forces to manage the security of the asset.

**PIG TRACKING**

As a pig or inspection gauge passes through a weld, a pressure pulse is released along the length of the pipe. This can travel for kilometres depending on the product and pipe construction. The speed of the pressure wave can vary according to the product type. The cleaning pig is located at the apex of
this chevron. Using the latest pig-tracking software tool, OptaSense has been able to provide location, speed and estimated arrival time at the catcher location. Current runs can also be compared to previous operations, thereby providing a greater picture of the changes over time, and hence an indication of hydrate build-up. Working with in-line inspection operators and end users helps to reduce the time taken to perform the operation. Providing this service facilitates control of the pipeline pressures to manage the headway between multiple gauges or regulate the speed of a single unit to ensure the warranty is not breached and the tool is not damaged.

**FIBRE-OPTIC LEAK DETECTION**

Many methods of leak detection have been and are being deployed on pipelines throughout the world. Some are widely recognised by API standards, while others have become more regional or product-specific according to their limitations.

Distributed fibre-optic sensing has been used to detect temperature variations in cryogenic products such as LNG. This provides a significant delta at the leak point and has become an accepted solution for receiving and export terminals. Natural gas pipelines provide a smaller change at leak and liquid products can soon reach ambient temperatures, especially when combined with the attenuation effects of the ground.

Although some DAS solutions are able to utilise Distributed Temperature Gradient Sensing (DTGS) as a measure, OptaSense, for instance, are evolving to expand upon this single leak phenomenon by deploying three other measures. The combined detection of negative pressure wave, temperature change, orifice noise and environmental strain provides a robust ‘AND gate’.

The most obvious signature of a pipeline leak can be the failure of the pipe itself. The rupture event and the subsequent rapid pressure drop inject vibrational energy into the pipe wall and fluid, and cause propagating modes down the pipe. Similar to the signature of a pig, these can propagate for kilometres. Unlike the pig, they are static in location. DAS leak detection algorithms detect leaks and localise the alert quickly (typically less than 30 seconds) to the nearest 10 metres at the apex of the signal ‘V’ shown in Figure 2 above. The increased speed and accuracy of DAS leak systems allow remedial action to be planned immediately, reducing product exposure and excavation costs.

**FOR THIS LEAK DETECTION MODE, DAS HAS AN ADVANTAGE OVER OTHER ACOUSTICS-BASED PRODUCTS THAT USE DISCRETE ACOUSTIC PRESSURE SENSORS BECAUSE, BEING INHERENTLY DISTRIBUTED AS A SENSOR, IT CAN DETECT THE ‘NEGATIVE WAVE FRONT’ OR ‘RAREFACTION WAVE’ ALONG THE ENTIRE ROUTE OF THE PIPE.**

If a small leak develops within a pressurised line, even if there is no major rupture event, the turbulent flow through the small orifice generates a distinct acoustic signature that can be picked up by DAS.

As indicated above, OptaSense’s DAS-based leak system also uses DTGS, which can be used to measure temperature changes, and thus also exploit this sensing modality. DTGS does not measure absolute temperature, but instead measures the rate of change in temperature with an extremely low noise floor using thermal strain and thermo-optic effects read out by the Rayleigh, rather than Raman scattering phenomenon in the fibre.

High-pressure gas pipelines will not only see effects of temperature gradient change but will also experience a ground heave within the surrounding environment through Joules Thompson expansion. Fluid lines may also experience wash-out of surrounding soil caused by consistent flow and saturation, thus changing the relationship between surround and sensing cable. The latest DAS developments enable the detection of the low-frequency changes caused by these short-term strain effects.

Advanced DAS-based leak detector toolkits will rarely rely on one of the above phenomena alone. All leaks or breaches affect multiple aspects, depending upon the product and the conditions. By fusing this information together, the systems are able to reliably detect and classify these events. By matching the leak location with the position of the maintenance team, response times, spill rates and excavation costs are reduced to an absolute minimum.

**IN-WELL MONITORING**

In addition to the uses of DAS for pipeline protection, the technology is also being used in a number of downhole applications with OptaSense at its fore. Once installed – either permanently behind the casing, semi-permanently on the production string or temporarily deployed in the well via wireline or coiled tubing – the fibre can be used to listen to activity along the entire well bore. Used during the completions phase, fibre installed behind the casing is being used to monitor the initiation of perforations, setting of plugs and the identification of bypass events in addition to the main application of hydraulic fracture profiling to determine the relative amount of fluid and proppant entering each limited-entry perforation.

During the production phase, fibre – either permanently or semi-permanently installed in a well – is now being used to provide an on-demand flow-monitoring capability. Furthermore, DAS is also being used in enhanced oil recovery applications. By performing a vertical seismic profile (VSP) acquisition using fibre installed in either single or multiple wells, it is now possible to perform low-cost 4D imaging of the reservoir. With the time-lapse information, it is possible to optimise well design and field development plans. Given the broad range of downhole applications, DAS is increasingly being seen as a disruptive technology for permanent in-well monitoring.

The success of DAS fibre-optic sensing within the oil and gas industry is largely down to the fact that the systems are relatively simple to deploy, intrinsically safe, high temperature and pressure ranging and are available in a small form factor. This enables them to be deployed safely, over large distances and with little or no future maintenance as all data-gathering hardware is generally located in a safe environment.

Expect the trend to install fibre sensors to continue into new areas as new applications are tried and tested. The future is bright for fibre sensing.