Mapping the Underworld

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WHERE IS IT?

WHAT IS IT?

DOES IT TALLY WITH THE RECORDS?

CAN I SEE EVERYTHING?

AM I SAFE TO DIG?

MAPPING THE UNDERWORLD

UNIVERSITY OF BIRMINGHAM

UNIVERSITY OF BATH

The University Of Sheffield.

University of Southampton

UNIVERSITY OF LEEDS

*Fore*word

We bury things in the ground for all sorts of reasons, and there are many tales of things buried and lost because the precise location has been forgotten, or the map showing where the buried treasure is located has been mislaid. This talk of secrecy, and pirates and maps, is not so very far from the truth today; our buried pipelines are important assets and the records are considered by many owners to be valuable (i.e. commercially sensitive information).

The adventure stories often include maps that were lost long ago and found decades later by excited treasure seekers, who find that the surface landscape (the context) has changed when they go hunting with a map and a spade. This also has a direct parallel with today's utility pipelines, many of which are more than 100 years old, and therefore the records of their location (maps, sketches, descriptions) are of a similar age. The records often relate the pipeline's positions to the edge of a road, a building or other feature, and yet today's urban landscape will often have totally changed. The saving grace is that the routes of many of the roads in our cities tend to remain, so we might have a record of a pipeline in a street, although its position relative to the current road layout is unknown. This leads to another challenge: any attempt to transpose the records from an old map to a new one often leads to inaccuracy. Slightly disturbingly, the analogy of a treasure seeker with a map and a spade is not so very far removed from today's street workers equipped with utility records and a mechanical excavator.

There are several reasons why utility pipes, and later cables also, are buried in the ground: for protection from damage by surface activities, vehicles and the weather, to provide support to resist differential movements, to keep the unsightly arteries of civilised life hidden from view, and so on. The ground is therefore our friend in this endeavour, and in fact this is where I started my research career – researching flexible pipe support. However when we need to excavate to maintain existing, or install new, services, the ground becomes our enemy – a barrier to our being able to detect what is where below the surface. Unhelpfully, although we have utility records, they are known not to be wholly reliable (i.e. inaccurate and / or incomplete). Indeed, if we did have full confidence in them we might be able to work in the streets in a different way altogether – using one of the many trenchless technologies that would reduce the traffic congestion and surface disruption associated with the works. If only we had x-ray specs…

By a happy (though not lucky) coincidence, it was at this point that the EPSRC sandpit (or IDEAS Factory) came in. It is described in more detail later, but in short a research funding mechanism was developed for complex problems that were thought to need a wide range of disciplines to solve – gathering together the most relevant scientists, engineers and other specialists, setting them the challenge ('we need x-ray specs') and letting them create idea models (sandcastles) of how they might do it, knock them down and rebuild them until they represent an appropriate plan of campaign. The seed-corn funding was granted for a series of projects under the umbrella of Mapping the Underworld, and the rest is history, or rather the future. What we aim to show hereafter is that x-ray specs do, in fact, feature in a number of guises, as long as you suspend your disbelief.

Of equal importance to the research outputs is the creation of a community around this general topic. Having been asked to lead the Mapping the Underworld (MTU) initiative, it was important to create a research community and this we have done as a team – I should add here it is a privilege to have worked with all of the academics on this journey of discovery. The initiative would not, however, have been anywhere near as effective if it were not for the wider practitioner and stakeholder community that has contributed to and supported the researchers throughout, and likewise it has been a privilege to work with every one of them.

We have ambitious plans for taking the initiative forward into new spheres of influence, and, if we are successful in raising the funding, we hope everyone will join with us in advancing this novel area of science and engineering.

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EP/C547373 – Mapping the Underworld: Enhanced Methods for the Detection of Buried Assets

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Contents

A brief history of the Underworld

CDF Rogers (University of Birmingham) and CG Overton (UKWIR)

Mankind has used buried infrastructure for eight millennia, perhaps more. A supply of clean water and safe disposal of sewage have been prerequisites for civilisation's development, so it is not surprising that the earliest, and much of the subsequent, buried infrastructure involved water, sewage and drainage.

Figure 1. An early wooden pipe, or trunk main

Traces of drains and primitive cess pits dating back to 6000 BC have been found in the Indus Valley, together with copper water pipes (estimated to be 5,500 years old) and streets drained by covered sewers made of moulded bricks cemented with a mortar of mud. Earthenware pipes, made from clay and chopped straw, dating back to the same period have been found in Mesopotamia; these were made by jointing bottomless pots end-to-end, and sealing them with bitumen.

Large brick drainage systems, some with access holes similar to today's manholes, were in use 4,000 years ago in Babylon, together with earthenware and stone water pipes. At the same time, the Egyptians used clay and straw and copper pipes for both irrigation and sewage systems.

Between 3000 and 1500 BC, the island of Crete had elaborate sewage disposal and drainage systems resembling those of today, up to 3.5 m below ground. Tapered clay pipes were used for drainage, fitting together to form the first spigot and socket pipes. Many houses in ancient Greece were equipped with a closet or a latrine that drained into sewers beneath the streets, while the Greeks buried fresh water aqueducts up to 20 m below ground level to protect their drinking water supplies from their enemies.

Around 800 BC the Romans built enormous sewers, including the *Cloaca Maxima* which was built to drain the Forum, and some of these sewers still form part of today's sewerage system in Rome. Moreover to satisfy demand for water for drinking and bathing, the Romans laid vast underground systems using wooden and lead pipes. Bronze pipes carried water from the mainland to the island city of Tyre.

In the thousand years after the collapse of the Roman Empire, development of the underground was much more limited. This was in part due to an apparent aversion to cleanliness and, where infrastructure was built, water was generally conveyed in wooden and lead pipes.

The use of lead pipes was recorded in London in 1235, and in the 16th century, when piped water supplies were reintroduced to London, it was found cheaper to use wooden pipes (Figure 1) for all but the smallest sizes, for which lead continued to be used; this became standard practice for two centuries. Sewage was dumped on the street, or ran in open channels. Where covered sewers existed, these were crude brick walls topped with flat stones.

The first authentically recorded cast-iron pipe was laid in Germany in 1455 and carried water to the Dillenberg Castle. In 1664 King Louis XIV ordered the construction of a cast-iron main to carry water to fountains at Versailles. The Chelsea Water Works Company first used butt-jointed cast-iron water pipe in about 1746, but it was the introduction in 1785 by Thomas Simpson, Engineer of the Chelsea Company, of an effective spigot and socket joint that allowed the development of pressurised water supply systems.

The 19th century saw unprecedented growth of the underground infrastructure in the UK. The Metropolitan Paving Act of 1817 required water companies to lay cast-iron pipes – a response to the continual excavation of roads to find and stop leaks from wooden pipes. By 1850 nearly all of the old wooden pipes in London had been replaced by cast iron.

William Murdoch and Frederick Winsor's pioneering work on gas lighting in the early 1800s led to the installation of gas supply networks in major towns and cities across the land. In some areas, surplus rifle barrels from the Crimean War of 1854-1856 were screwed together to make gas pipelines. The introduction of pre-payment gas meters in the 1880s extended the network to many millions of poorer households.

The second half of the 19th century saw the introduction of electricity to the UK. The first public supply, along with street lighting, was introduced in Godalming in 1881, and by the end of the 19th century an underground distribution network of insulated cables was being installed. Electricity also powered the rapid expansion of the tram network between 1805 and 1905.

The introduction of the telephone in 1877 added further growth, with the first underground trunk cable laid in the 1880s.

In 1848, Parliament passed the Public Health Act, mandating sanitary arrangements in every house. The Government also allocated five million pounds for sanitary research and engineering, helping promote a major expansion of buried sewerage systems. A second Act in 1875 required local authorities to ensure adequate water supplies, while a growing need to provide firefighting capabilities for factory owners additionally led to further expansion of the underground water supply network.

Figure 2. Congestion at a Eastern Europe interchange circa 1900. Courtesy of www.sewerhistory.org

This pattern of underground infrastructure provision was replicated, though generally somewhat later, in other major cities around the world and congestion beneath our city streets often matched that above them (Figure 2). The 1950s and 1960s saw the introduction of ductile iron, PVC and polyethylene pipes in the UK and, in 1975, the first cable TV system was installed in Hastings. In 1980, the first optical fibre link was laid between Brownhills and Walsall in the West Midlands.

Since then our demand for newer and more modern methods of communication, such as broadband internet and television, has meant that many additional services have been laid beneath our streets. It is estimated that the UK utility industry spends £1.5 billion a year to carry out street works and another £150 million to repair damage to other services those works cause[1]. Moreover it is estimated that the cost to society and the economy amounts to an additional £5.5 billion due to the manifold impacts of street works – such as traffic congestion and delays.

Figure 3. Pipe laying in 1880, unencumbered by a proliferation of other buried utility services, and health and safety legislation. Courtesy of www.sewerhistory.org

In the early days of pipe laying, even though the works were evidently disruptive (Figure 3), the complexities of dealing with adjacent buried infrastructure were largely absent. Nowadays the situation shown in Figure 2 is closer to what we find beneath the streets, and thus knowing what is present in the ground before digging is vitally important if damage to the existing network of pipes and cables is to be avoided and surface disruption is to be minimised.

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How good are we at finding our own?

CDF Rogers (University of Birmingham)
AG Cohn (University of Leeds)

Anyone who has had experience of street works associated with buried utilities, and this will include almost all civil engineers, will recognise the problem of knowing precisely where the buried infrastructure is located before one starts. In this age of mechanical excavators and shallow-buried optical fibre cables that would cost £0.5 million to repair, we might be more acutely aware of the potential damage that can be caused when excavating a trench, though the same apprehension has always been experienced by a person wielding a pick or a spade.

It is well known that records are potentially incomplete and/or inaccurate, that excavation must proceed with caution, and that dry holes (that is, excavations that fail to find the pipeline or cable being sought) are common – in fact it has been estimated that 4 million holes are dug in the UK's roads each year and that a significant proportion are dry holes[1], which equates to an awful lot of unnecessary traffic congestion, pedestrian disruption, material wastage (material to landfill, new materials for reinstatement), use of people's time, energy expended, visual intrusion, noise and frustration all round. These unnecessary impacts have a very considerable cost[2], and such practices are clearly unsustainable[3].

Although the situation was known to be serious, quantifying just how serious was problematic. Accordingly UK Water Industry Research (UKWIR) commissioned a trial utility survey at Langley Mere in the late 1990s and recorded a 50% success rate[4].

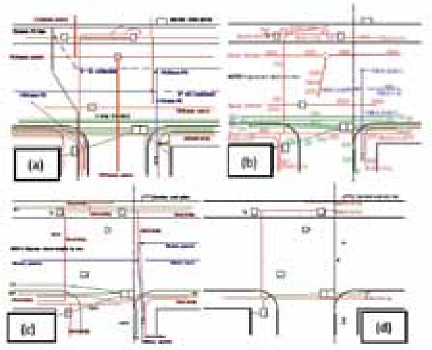

Figure 1. The UKWIR Trials[4]: (a) the utility services present on site; (b), (c) and (d) the maps produced by survey companies

It then commissioned a second trial at a road junction in Hereford[4] at which the complete surface had been removed and all utility services had been accurately mapped – this included 4 sewers, 11 telecommunication cables, 15 electricity cables, 3 MDPE, 2 cast-iron water mains, and 2 HDPE gas pipes (Figure 1a). The surface was reinstated and UKWIR invited three surveying contractors to use their own equipment and take as long as was necessary to map what they could see with their devices.

The results are shown in Figures 1b to 1d. Now the purpose of this is not to criticise the surveying industry some 12 years after this trial, or to report the detail, but solely to make the point that there was a need for greater comprehensiveness and certainty in the maps produced from such surveys. Indeed, the outputs of the surveys in Figure 1 necessarily (as a result of the brief) show something either to be present or not present; there is no grey-scale between the black and white.

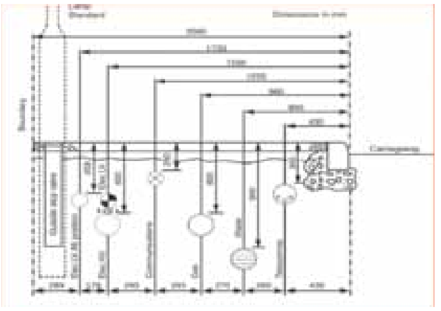

Figure 2. Recommendations for the placing of utility services

The reasons for the incompleteness and inaccuracy of surface surveys are evident when the problem is analysed in the context of our congested urban streets, where the competition for the communally available underground space is intense and the creation of our networks is necessarily piecemeal over very many tens of decades. There are standards presented for the ideal layout of buried services (see Figure 2), and while these neatly arranged service lines at different recommended depths to the side of the carriageway might be helpful for greenfield sites containing new developments, they are of no help at all for existing urban streets where services have repeatedly to change depth and direction to weave in between the existing pipes and cables (Figure 3).

Figure 3. Typical congestion beneath our city streets

If the reality is therefore that we can only in some cases approximate the depth and location of the services (sewers tend to be larger and deeper than other services, taking advantage of gravity flows where possible; optical fibre cables are typically shallow and away from the carriageway to avoid traffic loading), that services do not necessarily travel in straight lines and it would not be uncommon to find one service running in the same direction and lying below another, then it is not surprising that the utility records (typically lines on a 2D plan with occasional depths marked against them as attributes) do not always reflect reality.

Moreover exactly the same problems are being faced in all cities worldwide, and we are adding to these problems daily by installing new services, and in some cases abandoning what is in the ground when it no longer serves its purpose. Following the publication of the UKWIR report[4], a gathering of consultants, contractors, other practitioners and academics from the UK, the US and The Netherlands was convened in 2003. The assembled group of approximately 30 was set the challenge of how we might deal with this problem when faced with the need to install new, or maintain existing, buried services. Over three days, a comprehensive programme of research was developed (Figure 4) ranging from the short-term, immediately implementable ('making the best of what we have') to the long-term radical solutions that might obviate the need for such surveying ('doing things differently'). All ideas were trialled amongst the group and, once we had agreed the overall programme, were fleshed out with likely methodologies, timescales and costs[5].

Figure 4. A programme of research to address the problems of uncertainty of existing buried pipe and cable location[5]

	A	B	C	D
	Making the best of what we have	Improved surface-based survey techniques	Below ground survey techniques	Doing things differently
1	User need requirements	Development of a multi-system location tool	Mapping pig	Smart pipe technology
2	Data collection and exchange standards	Improving GPR	Through wall in pipe visualisation	Asset tagging
3	Best practice for existing technologies	New technologies for buried asset location	Keyhole access	Novel approaches to undergroud infrastructure
4	Real costs of buried assets		Asset avoidance for directional drilling	
5	Better regulation			

UKWIR immediately commissioned some of the smaller, short-term studies (e.g. the study of the real costs of street works[2]), since this would help make the case for substantial additional funding. However, it was recognised that by far the largest beneficiaries of the research were the economies and societies served by the utility services, and that no utility company, or group of companies, could justify making the very substantial investments necessary to do the job properly – the estimate was in excess of £10 million to get the full programme underway.

So we had a problem that was well known and well defined, a set of potential solutions had been outlined in the form of an integrated research programme, and the benefits of carrying out the research had been estimated to be very large indeed. It was clear that every available avenue would need to be explored and exploited by a highly multi-disciplinary team.

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A brief history of Mapping The Underworld

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The problems of location of existing buried utilities are emphatically not unique to the UK, and have been presented for example at the International No-Dig (or Trenchless Technology) conferences ever since they started in 1986. Indeed they are reflected in the discussions of any worldwide gathering of those engaged in trenchless technology and pipeline engineering. It was in 1996 that Tony Rachwal, then Director of Research at Thames Water, crystallised the arguments by stating that we needed a 'bodyscanner for the street' (Figure 1).

The previous section described the industry's response to the challenges, but a parallel activity in academia, albeit guided by practitioners, reinforced the research need. This occurred as a result of an Engineering and Physical Sciences Research Council (EPSRC) Engineering Programme Network in trenchless technology (NETTWORK[1]) hosted at the University of Birmingham.

NETTWORK was established as an academe-industry forum to help shape the UK's research programme in trenchless technology and deliver better focussed outputs, in terms of industry and society need. The issues of inadequate utility location were introduced, debated and collectively agreed to be of major importance to the trenchless industry, and hence one of the foremost research priorities, at the first of the workshops hosted by NETTWORK early in 2001. The interest was sufficiently great that the topic formed the subject of a report commissioned by UKWIR[2], which was then used to prime the discussions at the international workshop referred to earlier. Following significant lobbying by UK industry and an acknowledgement of the importance of the issue by the UK government, EPSRC chose this topic to be the subject of its first sandpit (or IDEAS Factory)[3].

A sandpit is a means of awarding funding to the UK academic community based on the outcomes of a week-long residential interactive workshop involving 30–40 participants, essentially academics or other research providers and a number of independent stakeholders. One of the founding principles of the sandpit concept is that the researchers should consist of a highly multi-disciplinary mix to facilitate lateral thinking and novel or radical approaches to addressing the particular research challenge in question.

The Mapping the Underworld sandpit identified the need for a combination of different sensing technologies if all buried services in all ground conditions were to be detected, thus yielding the concept of a multi-sensor location device[4]. Parallel research included precise and accurate mapping in urban canyons[5] (i.e. areas in which sightlines to satellites, the basis of global positioning systems, could not be guaranteed), and a means of finding a common basis for the creation and sharing of records between utility service providers (data and knowledge mapping). These two projects combined to create Project VISTA, a DTI-funded project with 22 industry partners[6]. The final research project concerned 'asset tagging', i.e. the inclusion of a remotely detectable label fixed to a pipe or cable so that new or repaired utilities can be subsequently located and identified. This addressed the question of 'what would we do now if we were starting again?' and, via follow-on EPSRC funding, has resulted in a commercially available system[7] marketed by OXEMS. The IDEAS Factory also identified the need for a new Engineering Programme Network dedicated specifically to the topic of Mapping the Underworld (MTU). It is clear that the MTU projects funded from the sandpit map fits nicely into the fifteen projects shown in Figure 4 of the previous section and thus provide a solid core of the programme created at the international workshop in 2003 (Figure 1).

Grants totalling £1 million were awarded by EPSRC and a further £200,000 was provided by UK Water Industry Research (UKWIR) to facilitate stakeholder interaction. This initial investment included research to prove the concept that a multi-sensor surveying device would be feasible and to define the detailed avenues of research needed to bring such a device to fruition. It should be added that it was always recognised that considerable further support, much deriving directly from the stakeholder community via an effective academe–practitioner partnership, would be required to complete the research.

The multi-sensor feasibility study was a success and helped to define a rigorous and detailed four-year programme of work termed the MTU Location Project, or Multi-Sensor Device Project, which was funded by a grant of £3.5 million by EPSRC along with in-kind funding of £1.36 million from 34 formal practitioner project partners. This stage of MTU started in 2008 and is now due to finish in the summer of 2013 (with a no-cost extension to cover a break in research staff contracts).

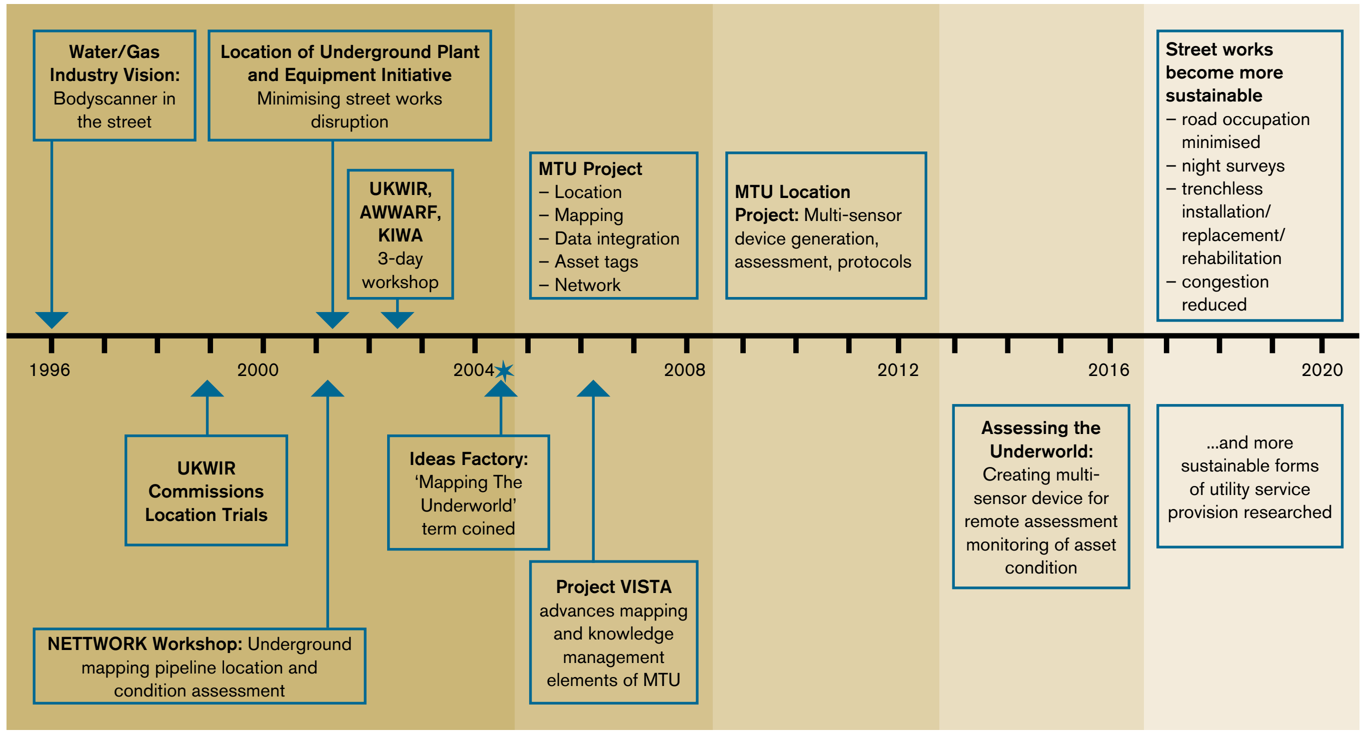

Figure 1. The Mapping The Underworld timeline showing its 25 year Vision

This report primarily covers the findings of the current MTU Location Project, the majority of the research for which is now complete. The elements that have been delayed due to staffing breaks are the final, and most sophisticated, GPR developments, the data integration and map creation work (which in turn requires the final outcomes of the GPR sensors, of course) and some aspects of the Low-Frequency Electromagnetic sensor research. However sufficient progress has been made in all areas to warrant this report being published, and the MTU Final Event and Exhibition held, in December 2012 as originally planned.

A great deal of additional activity has developed in the recent years of the MTU timeline shown in Figure 1, much being industry-focussed, and this is reported in the later section on the impact of MTU. Moreover, the timeline shows an ambition to take the multi-sensor approach into a whole new sphere of influence by using the sensors to determine the condition of the buried infrastructure, and the ground in which it is buried and the roads that overlie it (Assessing The Underworld). A proposal to do this has been submitted and is described in the section on future plans. Whatever develops after the MTU Location Project it will necessarily be driven, guided and supported by the MTU network of practitioners and other stakeholders, without which MTU's developments would be much the poorer.

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Advanced sensing technologies
Ground Penetrating Radar

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GPR is used to 'see through' the ground, either to establish the structure of the ground or to find buried objects. In our case we are seeking to detect pipelines that might be made of a variety of materials (e.g. metal, plastics, ceramics, concrete) with a variety of contents (e.g. water, gas, optical fibre cables). The radar signal, an electromagnetic wave, is transmitted into the ground and reflections, whether from sub-soil interfaces or buried objects, are captured by a nearby surface-mounted receiver.

Unlike radar used for navigation of ships and planes, electromagnetic signal penetration and reflection in the ground is very short range, usually limiting GPR exploration for pipeline detection to 1–2 metres. Novel technological approaches are required if we are to see deeper and more accurately discern the targets. Our research is therefore exploring the use of new techniques such as Orthogonal Frequency Division Multiplexing (OFDM, which is now used in Digital TV, Digital Radio and Wireless Local Area Networks) to improve pipeline detection. To maximise positional accuracy the frequency bandwidth of the GPR system should be large, and MTU is consequently researching ultra-wideband electronic (UWB) systems and antennas. It is also exploring whether a transmitter or receiver can be placed in a deeply buried pipeline, thus allowing one-way signal propagation and doubling the potential depth of pipe location, as well as a 'look out' mode from the pipe by both transmitting and receiving.

GPR is complicated by the fact that in addition to reflections from the complex array of pipes and cables buried beneath our streets, there are many other features in the ground that produce a multitude of small reflections. A second important feature of the research is therefore focussing on sophisticated mathematical signal processing techniques to remove the clutter of unwanted reflections, hence making the pipes more clearly visible. Moreover, we are seeking to produce images that are more easily understood than traditional data presentation methods (Figures 1 and 2).

To explore the idea of placing part of the GPR system in a deeply buried pipe (such as a sewer), MTU has investigated long, thin antennas that can fit into pipes[1,2] – previous UWB antenna schemes do not fit this shape requirement. Antenna configurations for more traditional use of GPR deployed at the ground surface were also investigated. The in-pipe measurement scheme has been shown to identify the 'local' permittivity of the ground surrounding the targets[3], which greatly improves our ability to focus GPR data into images of the sub-surface.

The MTU research has improved our understanding of propagation effects that can cause the well known problem of poor GPR detection of cast-iron pipe targets[4]. This came about due to the wide range of expertise within the group on electromagnetic propagation and device modelling combined with expertise on decay processes of pipes within soils. Extensions of this research indicate that the propagation effect is also likely to be applicable to bitumen-coated or leaking gas pipes, which can also be problematic to detect with GPR.

UWB electronics systems were explored and developed from first principles[5] to investigate the burgeoning area of OFDM radar[6] and its associated signal processing to identify target positions more accurately. In addition, a technique for improving the more conventional Frequency Modulated Continuous Wave (FMCW) GPR was developed by linearising the frequency sweep more accurately[7], allowing clearer resolution of targets. The development of OFDM, FMCW and SFCW (the stepped frequency variant) radar capabilities facilitated comparison of the GPR modes and comparison with traditional pulsed radar mode of operation for GPR. This also facilitated the investigation of multi-antenna schemes for traditional surface based radar, novel in-pipe 'look out', and novel through ground radar modes of operation[4,7]. Such schemes were investigated to aid more rapid data capture in GPR surveys, particularly in multi-antenna deployments for simultaneously observing large areas of road. Data capture time is often a major source of a survey's cost.

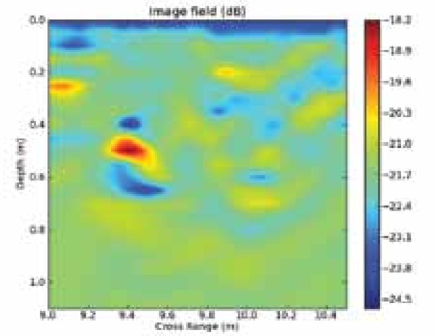

Figure 1. Example image formed from data measured with commercial GPR over a test site. Target is at a depth of 0.5 m and 9.4 m in Cross Range.

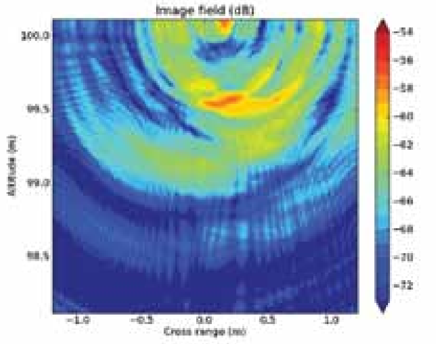

Figure 2. Image formed from measurements with the MTU experimental GPR over a target at altitude 99.3 m (0.82 m below the surface), cross range 0.25 m. Positional accuracy of this target is approximately 50 mm.

> *"The MTU research has improved our understanding of propagation effects that can cause the well known problem of poor GPR detection of cast-iron pipe targets[4]."*

The research also developed signal processing techniques applicable to OFDM, SFCW, FMCW and pulsed radars that improve the registration of responses from individual desired targets and clutter, and reduce the effects of noise[5–8]. Based on these techniques, better target identification has been realised by combinations of individual signatures. An important advancement, forged with MTU's computer scientists at Leeds, is the proof that focusing GPR data, rather than relying on human interpretation of hyperbolae in B-scans, is able to improve automatic detection of targets[8–10]. This is particularly successful when analysis includes accurate determinations of ground permittivity and conductivity, as gained from site measurements using novel instrumentation[11], in-pipe GPR investigation[3] or the KBS developed by Birmingham in MTU (see later section on Ground Intelligence).

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Advanced sensing technologies
Vibro-Acoustics

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Vibro-acoustics, or structural acoustics, is the study of mechanical waves in structures and how they interact with and radiate into adjacent fluids and media. In the context of MTU, the structures of interest are generally buried pipes (water, oil, gas), and the adjacent fluids/media are the fluid contained within the pipes and the ground/soil/fluid in which they are buried or immersed.

The principle behind all of the vibro-acoustic techniques that have been explored in MTU is that when one part of the pipe/soil structure is mechanically excited in a controlled manner, waves will propagate away from the excitation point, interact with the surrounding structure or fluid and be subsequently measurable at some remote location(s) on the ground surface. By analysing the nature of the measured response(s) at the surface, the location of the buried pipe(s) can then be inferred.

Three complementary vibro-acoustic techniques for locating buried services have been developed in MTU:

(a) Vibration excitation applied directly on a pipe.

This is applicable when a buried pipe can be accessed from the surface (e.g. a fire hydrant). The exposed pipe is mechanically excited at low frequencies (<1 kHz) resulting in waves that propagate along the pipe and in any fluid contained within the pipe. The energy of these waves then radiates to the ground surface where it is measured, using geophones, and from which the location of the remainder of the pipe can be inferred. Current detection systems operate on this same principle, but employ only one ground vibration sensor; furthermore, only the amplitude information is taken into account. Reports on the performance of the systems described above vary, but under ideal conditions (no road traffic noise, pipe depth <0.5 m, straight pipe) it may be possible to follow a pipe for up to 100 m, but a more typical range would be around 10 m, and possibly even less. Significantly more information can be gleaned both by using an array of sensors, but, more importantly, taking account of the phase information in the measured signals. Herein lies the novelty of the MTU approach[1,2].

The pipe excitation technique has been found to be very successful for locating both plastic and metal water pipes, laid under grass and under tarmac. Figure 1 shows an example result at a single frequency for an 18 m long medium-density polyethylene (MDPE) water pipe. When using magnitude information alone, only the excitation point (at (0,0)) and the pipe end (at (0,18)) can be seen; the unwrapped phase clearly reveals the entire run of the pipe.

FIgure 2 shows an example result for a cast-iron pipe laid under a combination of grass and tarmac. Here too, the run of the pipe is clearly evident. Furthermore, in this plot, the waves radiating cylindrically out from the excitation point are also apparent.

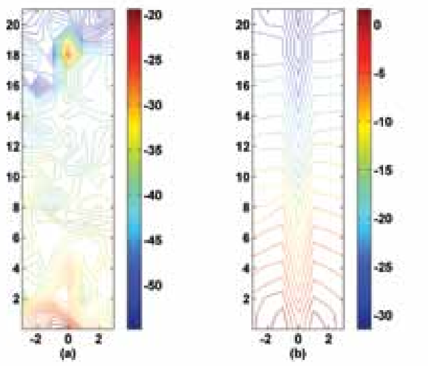


Figure 1. Contour plots of magnitude and phase of frequency response at 62Hz. (a) dB relative to velocity measured by geophone adjacent to excitation point, scaled by the square root of the distance from excitation point to measurement point; (b) spatially-unwrapped phase in radians. The x- and y-axes are in metres relative to the excitation location; the pipe runs up he centre-line in each plot

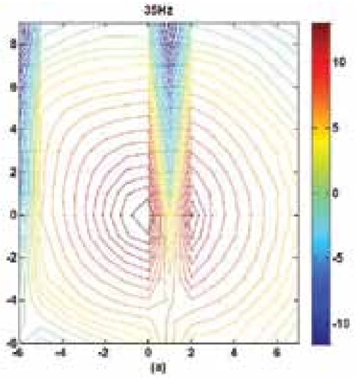


Figure 2. Contour plot of unwrapped phase of frequency response at 35Hz. The x- and y-axes are in metres relative to the excitation location.

(b) Vibration excitation applied at the ground surface (shear wave method).

This is applicable when the general vicinity of a buried service is known, but attachment of an exciter is not possible; at present, there is no commercially available detection system of this sort. Directional shear waves are generated at the ground surface and the subsequent reflections arriving at the ground surface detected and analysed. Cross-correlation functions between the measured ground velocities and a reference measurement adjacent to the excitation are used to generate a cross-sectional image of the ground using a time domain stacking approach[3,4]. Figure 3 depicts a typical experimental setup. The shear wave method has been successful at detecting both plastic and metal water pipes and air-filled metal pipes[3,4]. Figure 4 shows an example image, the first results of their kind, of the area around and above a live MDPE water main, with the pipe (the dark red area) clearly visible.

Figure 3. Arrangement of shaker and geophones for ground excitation measurements using shear waves

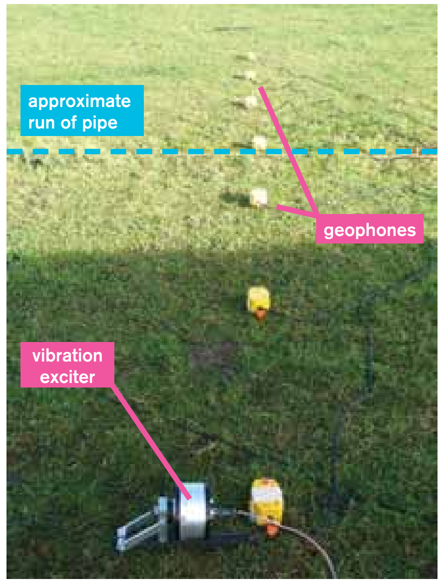
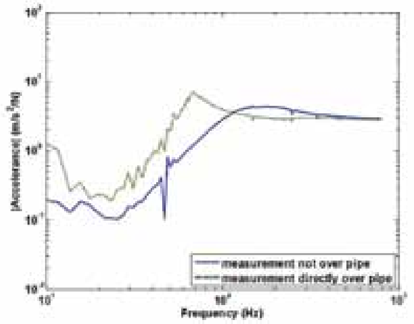


Figure 5. Two point accelerance measurements in the vicinity of an air-filled MDPE pipe buried at a depth of 30 cm



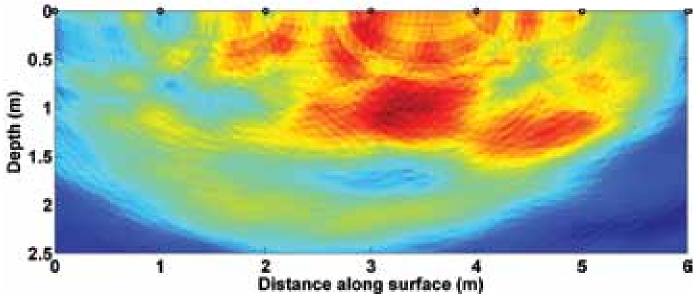


Figure 4. Cross-sectional stacking image; the dark red region identifies the location of the pipe

(c) Vibration excitation applied at the ground surface (point measurement method).

Again, this is applicable when no direct access to the pipe is available. Here, vertical excitation is applied at the ground surface at several points along a line and accelerance (acceleration/force) is measured at each point. Changes in resonance frequency can be used to detect the presence of a buried object close to the surface[5]. This, too, is a completely new idea which potentially can be extremely quick to implement.

The point vibration technique, has been used successfully to detect a number of shallow-buried services[5]. Figure 5 depicts two example point accelerance measurements in the vicinity of an air-filled MDPE pipe. Here, the resonance frequency is seen to reduce by a factor of about 3 directly above the buried pipe.

Results for all three techniques are extremely promising. Together the three techniques constitute an innovative and powerful tool and a substantial step change in the way buried pipes can be detected using vibro-acoustic methods.

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Advanced sensing technologies

Low-Frequency Electromagnetic Fields

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Low-Frequency Electromagnetic Fields (LFEM) are a method of measuring anomalies in the electrical resistivity of the ground using non-contact methods.

Archaeologists have known for many years that buried objects such as foundations and pipelines alter the electrical resistance of the ground when measured at the surface. Traditionally, an electrical resistivity measurement is made by inserting an array of four electrodes into the ground (Figure 1).

A current is injected into the outer two electrodes, whilst the resulting voltage is measured on the inner two electrodes. The ratio of voltage (V) to current (I) is proportional to the apparent resistivity of the ground. The measurement will be repeated on a regular grid and the resulting image frequently reveals the underground infrastructure.

The advantages of such an electrical resistivity technique are that the equipment is simple, low-cost, reliable and able to detect non-conducting assets such as gas pipes. The disadvantages are that a survey is very slow (thus expensive), cannot be conducted over a paved area and can typically only detect assets to a depth of one-third of the electrical array length.

This research programme has addressed each of these disadvantages by applying appropriate technological solutions[1]. The costs associated with slow survey speeds have been addressed by using non-contact electrodes. By injecting a sinusoidal alternating current into the ground, the sensed voltage may be measured on two capacitively coupled plates moved along the surface. In reality, these are simple copper plates glued to a thin plastic wear-plate and surrounded by an electric field screening can (the yellow boxes shown in Figure 2). The survey can now be conducted at a 'slow walking pace' – dramatically faster than a traditional electrical resistivity survey.

A major advantage of the capacitive coupling method is that the electrical fields in the ground may also be sensed above paved areas where the traditional 'galvanic electrode' approach would fail.

Remembering that a traditional electrical resistivity technique will detect assets to a depth of one-third of the physical electrode array and that a sewer might be 6 m deep, the implied conclusion would be that a deployment in an urban street would be impossible due to the unwieldy size of the array. However, by separating the injection electrodes from the sensing electrodes, deep assets might still be detectable whilst using a modestly sized, mobile, sensor cart.

The vision for a future urban survey operation would be to place capacitively-coupled injection electrodes at either end of a street – in reality this could be two cars, or vans, acting as large metal plates. These widely separated electrodes are known as a 'bipole'. A small survey cart would then be manoeuvred around the street carrying two smaller sensing electrodes, known as a 'dipole'. So our geophysical survey technique might be known more formally as a non-contact, bipole-dipole, electrical-resisivity measurement!

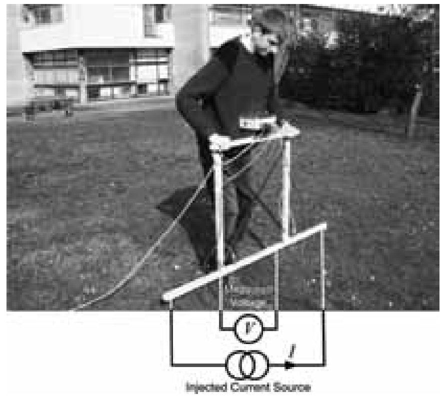


Figure 1. Traditional electrical resistivity survey (picture courtesy Rory Dickerson)

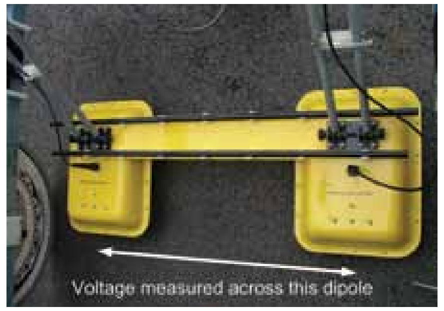


Figure 2. Non-contact electrodes

So why has nobody ever attempted this before? The reason is that by breaking the geometry from a fixed linear array of electrodes maintained by a simple block of wood, one now needs to know the position and angle of the dipole with respect to the bipole to a high degree of accuracy[2].

Figure 3. Typical dipole-dipole resistivity survey

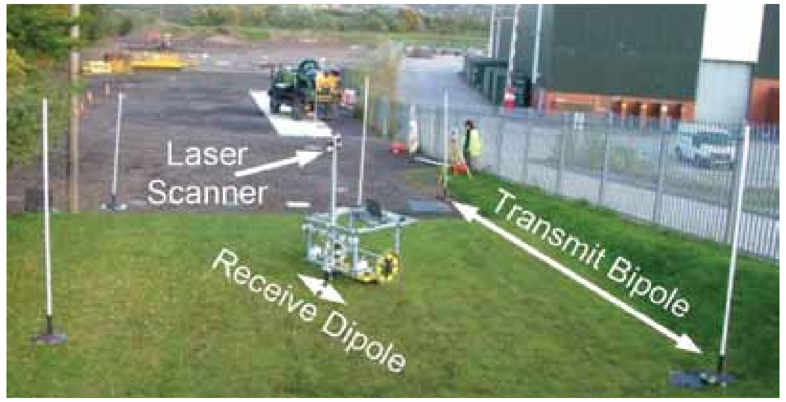
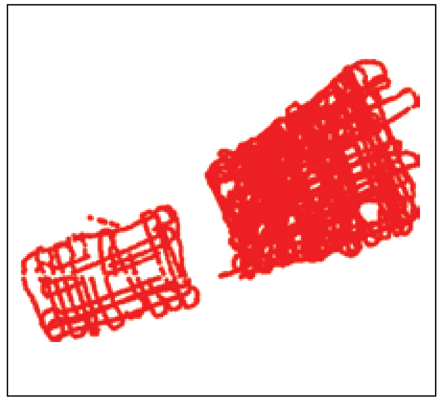


Figure 4. Typical survey track



Positioning equipment based on Global Navigation Satellite System (GNSS) satellite constellations only provides limited-accuracy position-fixing information and is incapable of providing heading data. Magnetic compasses have shown typical reciprocal-heading errors in excess of twenty degrees in urban areas, so alternative solutions were sought. Eventually, low-cost scanning laser range-finders, normally used above toll booths to validate the size of vehicles, were incorporated into the survey cart. These devices can measure the range and angle of reflections from trees, fences, buildings and lampposts. Small diameter objects such as lighting columns and telegraph poles provide the best navigation cues – with temporary white posts being added to the survey area when natural features are lacking. Enhancements to the traditional Simultaneous Localisation and Mapping (SLAM) algorithms, used by indoor robot navigation researchers, have been developed to operate in a real outdoor environment and integrate with the Ordnance Survey coordinate system.

The cart may now be pushed around freely within the survey area, ideally blanketing as much of the area as possible. A typical survey of the area, illustrated in FIgure 3, would be conducted in less than two hours and reveal a track followed by the operator shown in Figure 4.

Knowing the position and heading of the cart it is possible to compute the expected received voltages above an ideal homogenous ground. The measured signals may be compared with the ideal case and anomalies highlighted.

The movement of the plates above the ground introduces significant noise artefacts (equivalent to the havoc played by a windy day to an outside news presenter). Similarly, small errors in the position and heading will degrade the results. Thus a significant amount of spatial and temporal signal processing has to be implemented to improve the quality of the results. Modified spatial Lomb-Scargle periodograms, borrowed from the astronomical community, are used to interpolate the non-uniformly sampled spatial data onto a regularly sampled grid. Spatial band-pass filters tuned to the characteristics of underground assets are then applied to extract the desired features. An example of the results obtained from a different site is shown in Figure 5.

In summary, a non-contact method that appears capable of detecting 'difficult' assets under paved areas has been developed[3]. New methods of urban position fixing and heading measurement have been required. Advanced models have been derived for the propagation of ultra low frequency signals in a geologically layered medium.

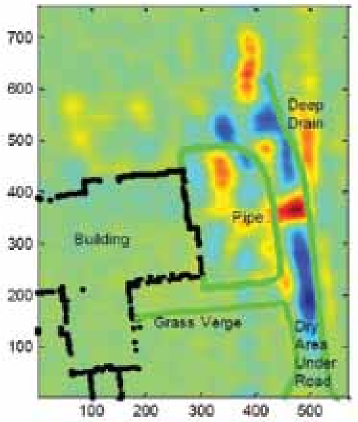


Figure 5. Results obtained over paved and grassy areas

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Advanced sensing technologies
Passive Magnetic Fields

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The current flowing in an electric cable produces a magnetic field. The magnitude of this field is inversely proportional to the distance from the cable. In principle, we can use measurements of the magnetic field to detect and locate buried electric cables passively, i.e. without needing to inject any signals into the cables.

The most basic magnetic field sensor is a simple coil of wire. Figure 1 shows a coil of copper wire and the voltage induced in it by a nearby power cable. The largest component in the detected voltage is at the power system frequency (50 Hz), although some higher frequency harmonics are also present[1].

An array of 27 coils has been mounted on a frame and used to measure the magnetic field above buried cables (Figure 2). A large number of coils is needed to measure the strength of the magnetic field in three dimensions. The frame is large to allow us to measure the difference in magnetic field between sensor coils (the differential field).

A data logging system is used to collect the voltage data from all coils simultaneously. After a set of measurements has been acquired the frame is moved and the measurements repeated.

Immediately after taking each set of measurements the data are processed to filter them and extract a few important frequency components. This significantly reduces both the noise level and the volume of data. The data for each set of measurements are reduced to a 3D array of complex numbers that define the phase and amplitude of each harmonic in each coil for each time window.

The cable location software works by comparing the measured magnetic field values with those predicted by a simple numerical model of one or more cables[2,3]. The parameters of the model are adjusted to minimize the error between the magnetic field predicted by the model and that measured by the coils.

Trials have been carried out in the laboratory and on site. These show that the system is not only capable of detecting the route of the cable, but also gives a good estimate of cable depth, often with an accuracy of a few centimetres. The time taken to acquire data at each position is only a few seconds.

The results are normally presented as an error map, which shows contours of the difference between the predicted and measured magnetic field as a function of the location of the cable assumed in the model[4]. The lowest error is the most likely location for the cable.

Figure 3 shows results from a laboratory test as a cross-section through the ground. The dark blue area represents the lowest error (4%). The red circle indicates the real position of the cable.

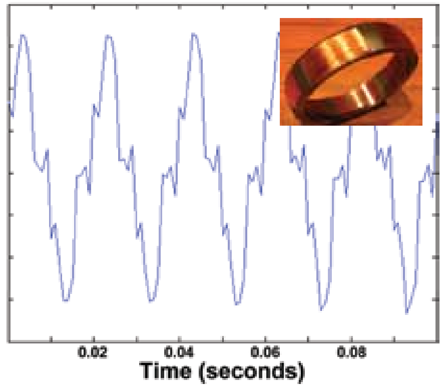


Figure 1. Copper coil and voltage induced by a power cable

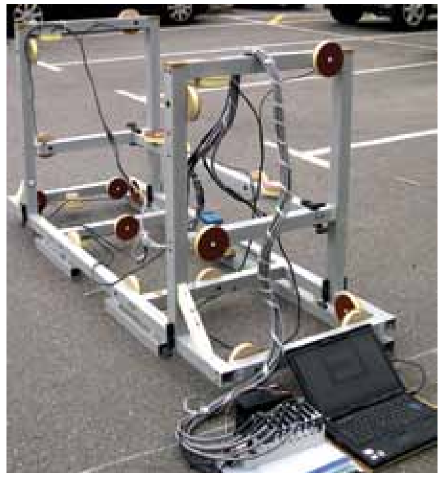


Figure 2. Frame of 27 search coils each having a diameter of 100 mm, and 2000 turns of copper wire

Figure 4 shows results from a field trial. The measurements give a clear prediction of the cable location. The red circle indicates the location of the cable as shown on the utility records. It looks highly likely that the cable is actually about a metre away from the position marked on the records and somewhat shallower.

Recent trials have been carried out with single-core buried cables carrying relatively low currents (about 3 A). The results (Figure 5) show that although the location is less well defined, particularly in respect of cable depth, it is still possible to detect the cable. The results in Figure 5 were obtained at a location where there are two cables and suggest that the two cables are not parallel at this location. The results are consistent with the utility records and give us greater confidence that we can distinguish between adjacent circuits where multiple services are installed below city streets.

Figure 3. Laboratory test results for a single cable

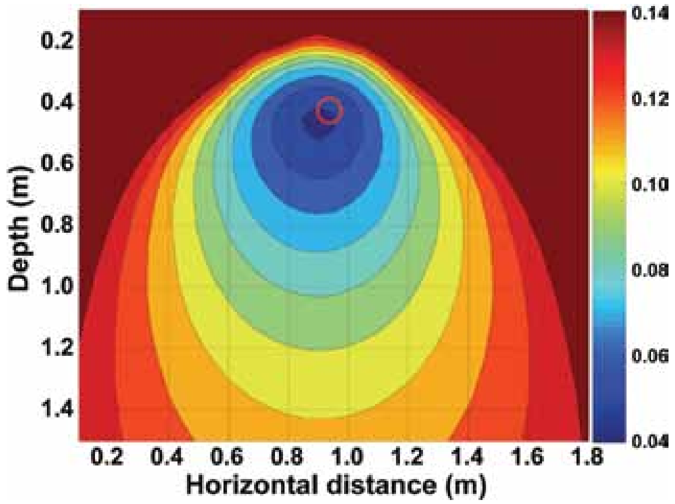
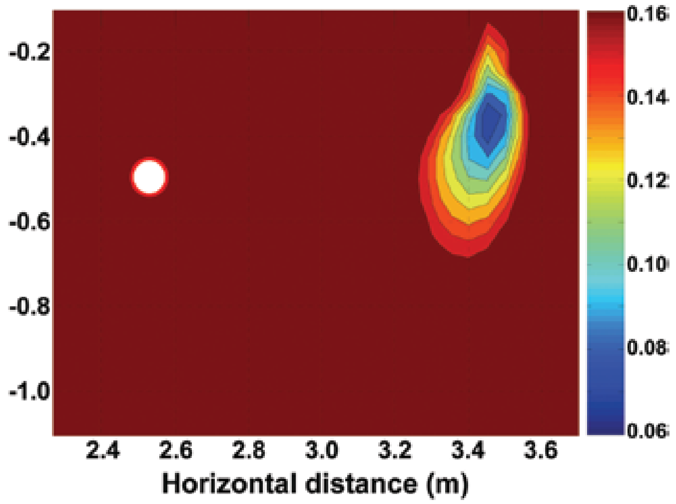


Figure 4. Results of a site survey seeking a single cable



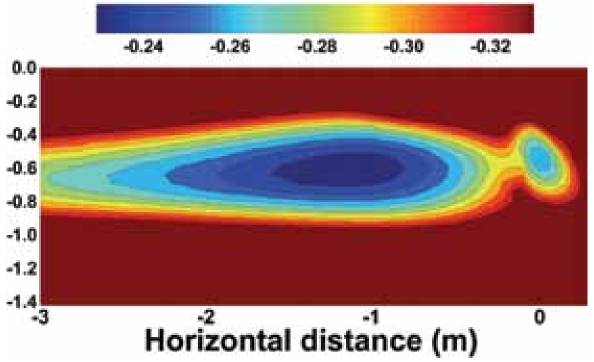


Figure 5. Field survey to detect a cable carrying a small current at a location where two cables are known to exist

We have demonstrated that using a relatively simple sensor it is possible to locate power cables using passive magnetic field techniques, i.e. using the magnetic field due to the 50Hz current flowing during normal operation rather than injecting a ‘tone’ signal into the cable.

The system is not only capable of detecting the route of the cable, but also gives a good estimate of cable depth, typically with an accuracy of a few centimetres. Data are acquired at each measurement position in only a few seconds, making the technique suitable for incorporation in a multi-sensor device.

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A multi-sensor device – putting it all together

SR Pennock (University of Bath),
CDF Rogers (University of Birmingham)

The primary outcome from MTU should be a sufficiently strong evidence base that, subsequent to the research, a device could be developed commercially and deployed routinely. It should be emphasised that this is not simply a question of bolting a series of sensors to the same trolley and looking at each of the outputs in turn: if the device is to achieve MTU's goals, and make a step change in utility surveying practices, then a truly integrated approach to testing, analysis and interpretation must be adopted, taking advantage of all possible information.

Integrating the MTU sensors has occurred at two levels – physically co-locating the hardware on a single measurement vehicle, or 'mobile laboratory', and signal processing to effectively superimpose the outputs. The 'mobile laboratory', which has been successfully used, and refined, in measurement campaigns at the various trial sites, is manufactured from non-metallic square hollow section members with side arms that can be lowered when deploying the vibro-acoustic geophones and GPR antennas, and raised for movement to the next site (Figure 1).

A serious potential issue when co-locating the sensors and their associated computer control and data logging hardware was signal interference. Exhaustive trials resulted in the layout shown in Figure 1, with interference issues resolved such that all sensors can be operated simultaneously with no signal degradation. For example, it was shown that distortions to the readings occured when the magnetic sensor coils were positioned close to metal objects or sources of 50 Hz power signals, thus they had to be located at least 750 mm away from the other sensors.

In the MTU Location Project we aim to determine the position of buried assets to within 50 mm in plan and depth. In addition to the research on the sensor systems and the accuracy each sensor can achieve, the position of the sensors must be known to this precision along with their attitude (the street environment is rarely horizontal). The ambition is to be able to determine and record the position of the asset such that throughout the asset's working life we could return to it knowing where it is to the nearest 50 mm.

Integration of sensors onto a single trolley removes uncertainty in the relative positions of the sensors as they are physically connected. Determining the 'absolute' position of the measurements taken during the trials has been successfully done using an automatic total station, i.e. standard land surveying equipment (Figure 2). While this is perfectly adequate for research purposes, a system of automatic 3D location measurement is needed. Techniques that relate positions to known reference points, or where atmosphere-corrected differential GPS can be employed with acceptable positional accuracy, are being trialled, noting the 'urban canyons' and tree cover problems of sight lines to satellites.

The integration of 'attribute' data from existing records and of the ground properties from the Knowledge Based System (KBS) has produced intelligence on the likely permittivity of the ground. However, it is well known that the ground properties can vary significantly in a local area and it has been shown that the properties change with water content[1]. Nevertheless, GPR is a technology that is used in different circumstances to interrogate ground structures and ground properties can be inferred by back analysis. Combining such thinking with new measurements of permittivity (see later) has facilitated the production of more informative focussed images than traditional GPR B-scan hyperbola, and importantly images that can be superimposed on those from the other sensors.

Research into multiple processing of focused GPR, magnetic, vibro-acoustic and low frequency electromagnetic data, and their combination, has been shown to produce better clutter reduction and make targets more discernible. In its current form, this operation requires a trained surveyor, though research is underway to explore how effectively this process might be automated.

As expected, combining data from the four sensors has been shown to produce a more reliable assessment of buried targets, i.e. has increased the confidence in utility location. This is most apparent when the sensors produce target signatures that agree in plan and depth, and therefore reinforce each other. However we would not expect all sensors to register all targets for the reasons outlined earlier; any agreement thus provides increased confidence.

Figure 1. MTU Mobile Laboratory

Figure 2. Determining the position of the MTU Mobile Laboratory using an automatic total station

	Road Furniture Cable	Single phase cable	Three phase cable	Pot-ended cable	Plastic gas service pipe	Plastic water service pipe	Metal gas service pipe	Metal water service pipe
V–A	1	1	1	1	2	2	2	2
PMF	2	2	2	1	0	0	1	1
LFEM	2	1	1	2	2	2	2	2
GPR	1	1	2	2	2	2	2	2

	Plastic Gas mains pipe	Plastic Water mains pipe	Metal Gas mains pipe	Metal Water mains pipe	Asbestos cement water pipe	Drains	Telecoms duct shallow	Large Telecoms duct deep
V–A	2	2	2	2	1	2	1	1
PMF	0	0	1	1	0	0	1	0
LFEM	1	1	1	1	1	2	2	1
GPR	2	2	2	2	2	2	1	2

Figure 3. Matrix of operational capability – 2 = confidence of detection, 1 = lesser confidence, and 0 = little or no confidence [V-A, PMF, LFEM and GPR refer to the four sensor technologies]

Moreover, the combined data have been shown to help identify the type of buried asset. Most obviously, if the sensors indicate two targets, and the Passive Magnetic Field (PMF) sensor indicates one, it would be evident that the targets are a power cable or metallic pipe (depending on the PMF signal strength) and a non-metallic pipe. Where the sensors indicate anomalies in the ground, but no clear indication of pipes or cables, this also is of value in informing those carrying out street works: either further detailed surveying, or perhaps local vacuum excavation, could be carried out if the operation is sensitive (e.g. a gas pipe is suspected beneath a busy road, where trenchless options might be considered or the works must not be delayed) or excavation should proceed with care (perhaps using hand tools).

The diversity of approaches means that where one or more of the sensors are performing poorly due to ground conditions, the remaining sensors can still provide target information. Thus combining data from several sensors produces a more resilient system that can operate in a wide variety of situations and detect a wide variety of targets, the capabilities of the sensors in relation to target type being shown in Figure 3.

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Creating the map – combining data and records

AG Cohn (University of Leeds)

It is normal practice to obtain utility maps prior to invasive street works, but, as already noted earlier, these are typically inaccurate and incomplete. Our objective in the MTU project is to create a revised map showing the true location of all buried assets, by exploiting the knowledge gained from the sensors.

However, when available, utility records still provide useful expectations of what might be found underground, and roughly where. Thus our aim in the project is to develop techniques to fuse geo-referenced information from multiple sensors and to combine this with an integrated database of buried asset records to increase confidence in their presence and location, and to identify when there are missing asset records. Put another way, the aim is to build the most probable map of what lies underground, based on the expectations from the utility records combined with information from the MTU sensors and surveys of relevant street furniture.

The outputs from the four MTU sensors present themselves non-symbolically – i.e. the delivered data are essentially an image representing what the sensor 'sees' underground. In contrast, utility records are almost universally represented symbolically – i.e. they are stored in a spatial database as records with a vectorised representation of their spatial position, along with attribute information (such as material and diameter). The objective therefore is to construct a modified vectorised and attributed map – like an integrated form of the utility records map, but corrected to take account of the sensor information.

We assume that a street furniture survey has been conducted, and at least the spatial positions of manholes have been recorded. The system is also designed to take advantage of attribute information for these recordings (what kind of asset is involved) and if the cover has been lifted, then the number and approximate directions of assets that can be seen as entering/leaving the void. Other street furniture, such as traffic lights and street lighting, which can be expected to have power connections, can also be provided as input if available.

We also assume that the utility records are available in a suitable form for processing, such as those resulting from the first MTU and VISTA projects which researched and developed data integration methods for the heterogeneous records found across the utility sector – the VAULT system, now live in Scotland, is based on this research. It would, of course, be possible for the system to operate in the absence of any such prior records, in which case the map supplied by the system would be based purely on the sensor information and street furniture survey.

For each of the sensor modalities for which we have data (including commercial GPR), we have developed techniques to automatically extract symbolic hypotheses about the presence of a buried asset[1,2]. Of course not all these detections may actually correspond to utility assets, and equally there may be assets which are not detected by the sensor (either because the sensor cannot detect that kind of asset or the environmental conditions are unfriendly – such as saturated clay for GPR). Figures 1 to 3 show images from different sensors, with a marked position showing the location extracted as a symbolic hypothesis – in fact we associate a probability distribution with every such hypothesis reflecting possible errors in the measurements and hypothesis extraction process. These x, y, z positions are used as input to the next stage of the mapping system.

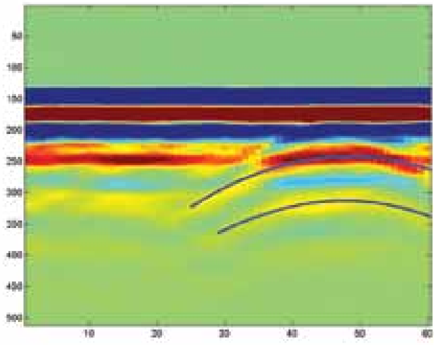

Figure 1. Objects manifest themselves as hyperbolae in GPR b-scans; here 2 hyperbolae have been automatically detected

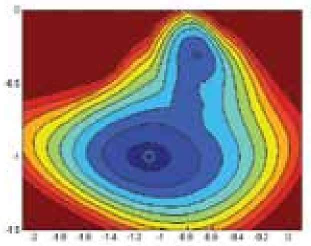

Figure 2. Error rate from passive magnetic field sensor given a particular hypothesis. The hypothesis with the minimum error rate is chosen (indicated by the small green ellipse)

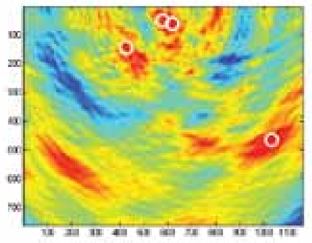

Figure 3. Vibro Acoustic sensor image and hypotheses generated showing possible object locations (highest probability is at bottom right)

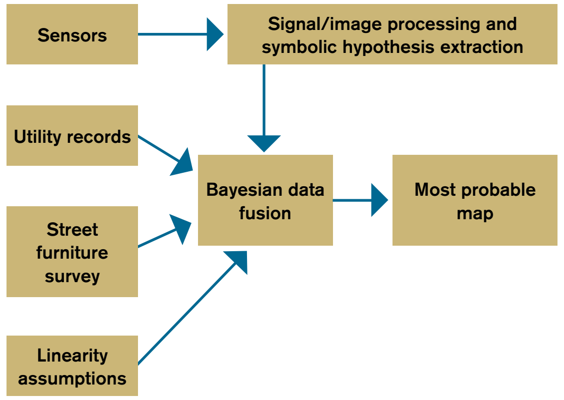

Figure 4. Bayesian Data Fusion Mapping Architecture

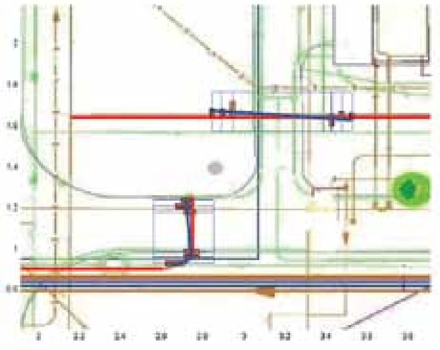

Figure 5. 2D visualisation of most probable map superimposed on the existing utility records for two vibro-acoustic surveys at a test site. The survey lines are marked in blue and the most probable location of the two pipes is show as a thick blue line – which in fact coincides well with the pre-existing record (in red).

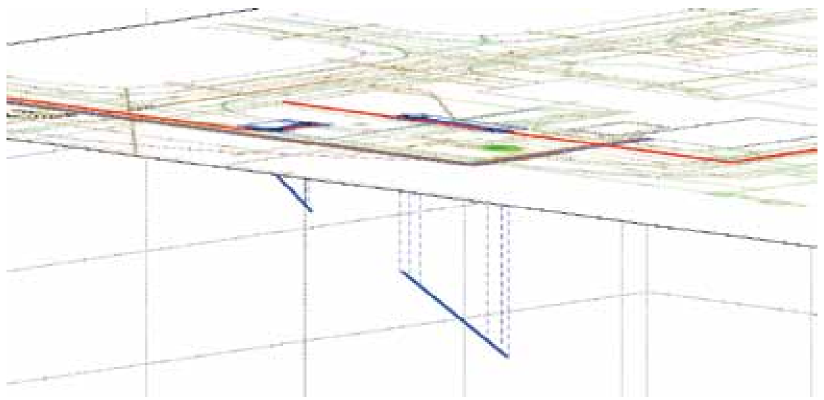

Figure 6. 3D visualisation of the same situation as in Figure 5

The main mapping algorithm relies on a Bayesian approach[1] – finding the most probable interpretation of the sensor readings, given expectations from the utility records, the street furniture survey and taking account of the fact that utility assets generally (but not always) run in linear stretches. A schematic of the process is shown in Figure 4. The hypothesis extraction phase also includes signal processing steps to help remove noise in the input signal.

The most probable map can then be displayed in both 2D and 3D (see Figures 5 and 6).

We have successfully reconstructed maps in the scenarios we have investigated so far, though our ability to verify the accuracy of the maps has been limited by the availability of the actual underground truth. With the availability of the new national MTU Centre of Excellence site at Wigan this situation will change. Meanwhile, we have conducted experiments with simulated GPR data in a simulated environment in order to test our Bayesian Data Fusion algorithm[3,4] – the resulting maps bear a close resemblance to the simulated ground truth, even when noise and errors are introduced into the sensor inputs and the simulated utility records.

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Ground intelligence – making the ground transparent

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Shallow geophysical surveying methods are strongly influenced by the ground type and conditions. Notably, the ground affects the velocity and the attenuation of the geophysical signals. Among shallow geophysical surveying techniques, GPR is one of the most widely used for utility detection. However, the performance of GPR is largely dictated by the ground properties, and particularly by the soil water content, which in turn affects the electromagnetic (EM) properties of the ground. Important EM soil properties are the permittivity and the electrical conductivity.

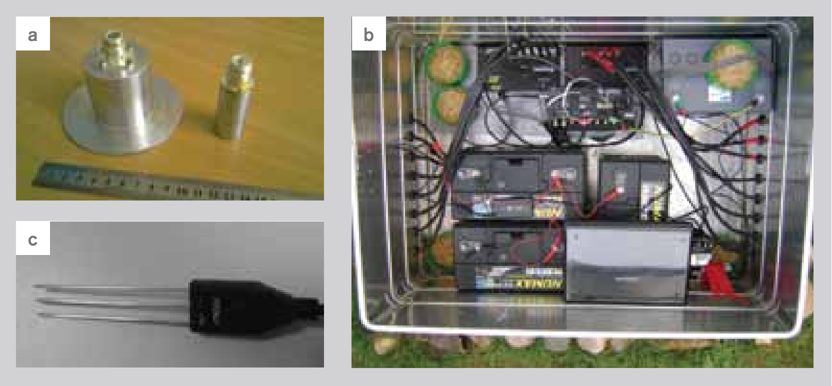


Figure 1. (a) open ended coaxial probes to be used with VNA; (b) TDR field monitoring station, and (c) example of a TDR probe

Permittivity, also called dielectric constant, is the ability of a material to transmit an electric field. It consists of a 'real part' describing the storage of energy and an 'imaginary part' describing the loss of energy. Conductivity is the ability of a material to conduct electric current. Permittivity regulates the speed of an EM signal, while conductivity controls its attenuation. Knowledge of the soil permittivity is thus useful in helping to achieve more accurate estimations of the depth of the targets, while knowledge of the soil conductivity is helpful in determining the signal penetration depth. Broadly speaking, GPR is more successful (penetrates deeper, produces clearer images) in dry and sandy soils rather than in wet clays. A better understanding of the influence of, and knowledge of, the soil properties is therefore valuable when planning shallow geophysical surveys and when interpreting the survey results.

This aspect of the MTU research has consequently focussed on studying and predicting the EM soil properties and their relationship with geotechnical soil properties. The main achievements are:

(a) Constructing and testing open-ended coaxial probes (Figure 1a) to be used with a Vector Network Analyzer (VNA). These probes measure the complex dielectric permittivity (i.e. real and imaginary parts) of the soil in the frequency domain and were trialled successfully both in the laboratory and in the field.

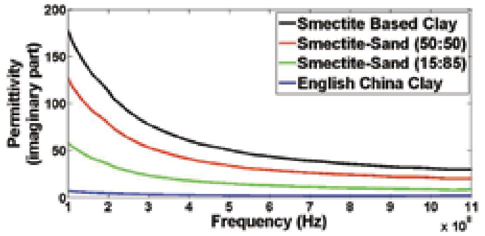
(b) Conducting extensive and detailed laboratory studies on a range of soils, including highly dispersive soils (i.e. whose permittivity varies with frequency), such as smectite-dominated clays, with the aim of producing an improved model for predicting the permittivity of soils at different volumetric moisture contents and with different percentages of fine- and coarse-grained particle sizes, in relation to signal frequency.

(c) Developing a long-term field monitoring station at the University of Birmingham (UoB) campus using commercial Time-Domain Reflectometry (TDR) equipment[1] (Figures 1b and c). TDR was used for monitoring the permittivity and conductivity of a sandy soil covered by grass over a period of approximately two years in order to establish the seasonal variation of the EM soil properties and their impact on GPR surveys. GPR surveys were regularly conducted over specifically buried targets at this site.

(d) Developing a Knowledge-Based System (KBS) for predicting the EM soil properties from existing information on the geotechnical soil properties[2]. Geotechnical databases, such as the ones held by the British Geological Survey (BGS), were shown to be useful in determining how shallow geophysical techniques such as GPR might perform on a specific site in the UK, by using prior knowledge of the ground.

Laboratory tests on soil mixtures containing different proportions of low and high dispersive clay types and pure sand showed that clay mineralogy, not only clay content, is important in determining the EM behaviour of the soil. This is evident in Figure 2, which shows a significantly higher dispersion caused by a smectite-dominated clay compared to the kaolinite-dominated English China Clay. Based on the laboratory tests, a new model for predicting the EM properties of highly dispersive soils has been proposed.

Figure 2. Variation of the imaginary permittivity with frequency (i.e. dispersion) for different soil types and mixtures



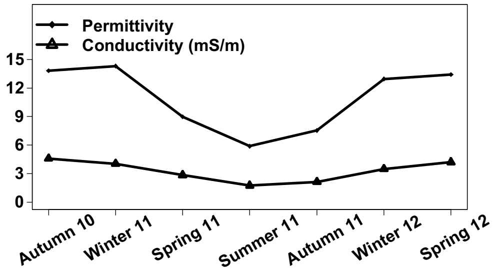


Figure 3. Seasonal means of permittivity and conductivity measured by the TDR monitoring station at the UoB campus

Figure 4. Structure of the Knowledge-Based System

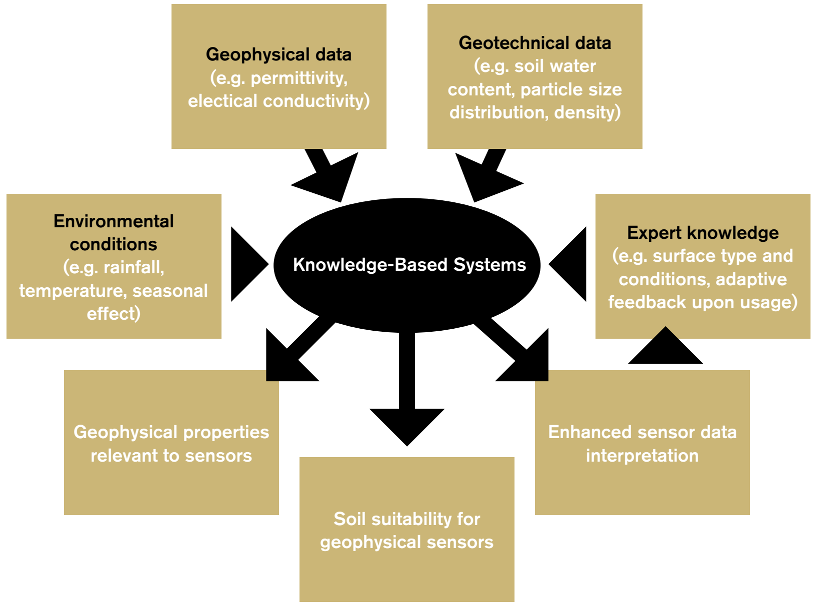


Figure 3 shows the seasonal means of the permittivity and conductivity up to 1 m depth as measured by the TDR monitoring station at Universty of Birmingham (UoB). The permittivity changed significantly with seasons, while conductivity remained low and almost constant because of the sandy nature of the soil. Both parameters were affected by rainfall and soil water content. The research showed that care should be taken when using typical permittivity values for soils as the real values could be significantly different. In addition, GPR surveys were shown to be less effective during wet conditions as the image quality deteriorates significantly, demonstrating the importance of understanding the effect of the soil and environmental conditions on GPR.

Figure 4 shows the structure of the KBS. The KBS implements existing models and known relationships between EM and geotechnical soil properties[3,4], and new knowledge from the MTU project, in order to predict the EM soil properties; in particular the signal propagation velocity and attenuation loss. The KBS includes inputs for environmental conditions and additional information such as surface type and condition. For example, by using knowledge of the existing soil and site information, the KBS can provide a 'suitability class' for GPR at that site.

In summary, the laboratory and field testing has created a greater understanding of the effects of different soil types on the electrical properties of the ground, and this has enabled the effects on shallow geophysical techniques, such as GPR, to be quantified. Seasonal variation of the EM soil properties of unpaved surfaces has likewise been shown to be significant. The Knowledge-Based System has been shown to predict well the EM soil properties from prior soil information (e.g. as held by the BGS). Although we have not been able to make the soil transparent, the research conducted as part of the MTU project will help to better plan and interpret the results from shallow geophysical surveys, particularly GPR.

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So just how effective is the MTU device? – the proving trials

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The underlying principle of the multi-sensor device is the contention that different sensors work well in different (ground, environmental, surface) conditions and when seeking different targets. The proving trials strategy developed for the project aimed to test this contention.

Initially the four sensing technologies were developed in isolation using facilities created especially for this purpose at the various institutions. Once it became apparent that the four sensing technologies had the potential to detect buried pipes and cables, they were combined on a platform (the mobile laboratory) and combined testing took place at a number of the dedicated facilities. These included Bath's 'sand pit' with a simple arrangement of pipes and a cable, a bespoke facility established at Birmingham to investigate changes in GPR performance with changes in season, sites provided by MTU's project partners, and the newly created MTU Centre of Excellence[1].

The philosophy underpinning MTU is to utilise as much intelligence (conceptualised as data streams) as possible to improve the likelihood of utility detection: e.g. measurement data from multiple sensing technologies, information held in existing utility records, and site measurements supporting the ground intelligence held in the British Geological Survey (BGS) database. This is being underpinned by research to increase our understanding of how the soil responds to the sensing technologies, and, when combined, allows optimisation of the deployment strategy for the multi-sensor device[2] (Figure 1).

Therefore the criteria for a suitable test site were extensive:

- Known (plan and depth) locations of utilities.
- Multiple utility types: e.g. pipelines made from different materials, water-filled and gas-filled pipes, communication cables, and live power cables (that are drawing current).
- Access to pipes to allow pipe excitation.
- Various ground conditions and surface covers
- Permission to excavate, take soil samples and insert probes to measure parameters *in situ*
- Permission to insert pairs of electrodes with 1 kV potential difference between each pair.

MTU has benefited from the large number of partners that have volunteered to participate in the project, and a number of these partners offered various sites, both in the UK and abroad, for the purposes of proving trials. Of these sites, two were selected as they met the selection criteria, while a third was constructed by JK Guest according to the concepts developed as part of the MTU project for a national test site.

The first site, provided by South Staffordshire Water, was chosen for its simplicity: the site housed a straight section of water filled plastic pipe (with access points at various locations along its length) and a live power cable crossing the pipe, both lying beneath grass and tarmac. This site therefore represented a very simple utility layout, and thus was ideal for initial performance testing. The results were encouraging[2].

The second site, provided by Bristol Water, contained several buildings, roads and grassed areas. It had been developed since Victorian times and as such had pipes of varying ages, constructed using different materials, at different depths and running in various directions, so there were services running both parallel and crossing at various locations. Moreover, the site is being used as a training centre for the location of leaks, with a variety of leaking pipes buried beneath different surface coverings. The facility is sufficiently large to be treated as several discrete sites, which were surveyed repeatedly over an 18-month period, allowing both proving trials and research into how the sensing technologies' performance changed with seasonal weather variation. Furthermore, new works at the site are to include the excavation of trenches crossing one of the areas repeatedly surveyed, thus resulting in the exposure of the identified targets and providing direct evidence of the success of the MTU surveying trials.

Testing also took place at the MTU Centre of Excellence[1] (Figure 2). This site, part of the Construction Skills Academy, was constructed to designs created by the University of Birmingham. Outcomes from the testing at the second and third sites are being prepared for publication.

The MTU Centre of Excellence was developed to offer dual function: a location to research and develop shallow geophysical sensing technologies, and a location to train operators in the use of shallow geophysical techniques and provide certification[1]. The site includes several test bays which range in complexity of ground conditions and utility layouts. The simplest bays incorporate one or two utilities in single soil types, thus allowing for initial training / deployment of newly created sensing technologies. The most complex contain pipes and cables that incorporate changes in direction and depth, crossing at various locations with some of these buried in changing ground conditions, in an effort to present a challenging environment in which to survey. Additional bays, with utility layout complexities lying between those of the simplest and most complex, also formed part of the design concept. Three bays are dedicated research bays, the pipes and cables running either parallel or perpendicular to one another. Buried sensors are incorporated at various locations within the research bays to enable measurement of certain geophysical properties *in situ* at the time of the survey. Groundwater control facilities are in place to ensure a relatively constant phreatic surface within these bays. Three additional training / research bays were constructed in which the utility layout differs beneath two surface coverings (Figure 2), with large and small diameter pipes that vary in depth and change direction.

Figure 1. Flow diagram illustrating the principles behind the MTU multi-sensor device1

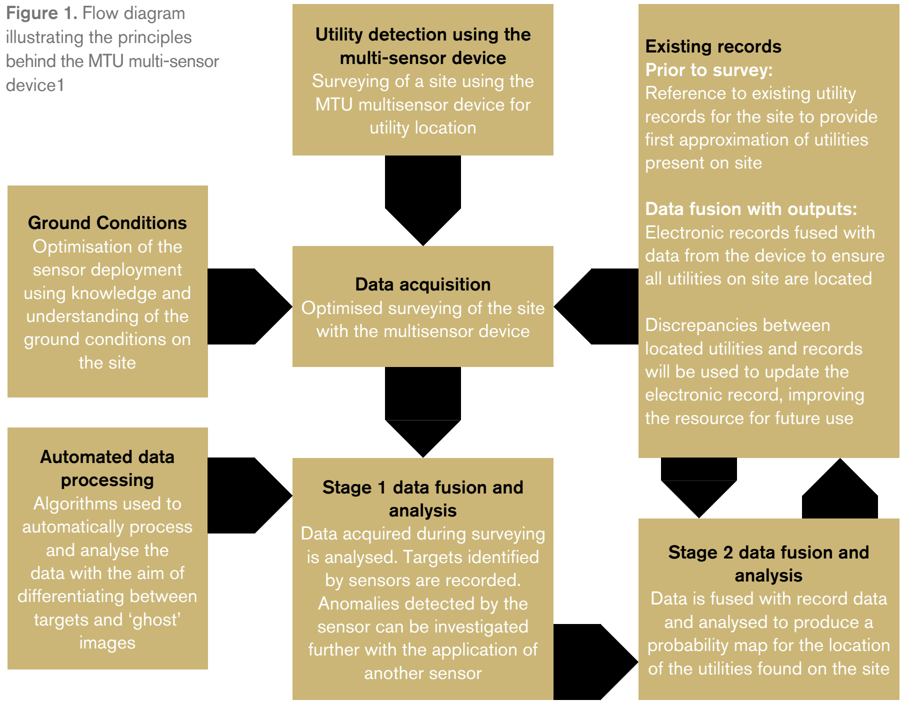

Figure 2. Testing at the MTU Centre of Excellence test facility.

The conceptual design required the majority of the test bays to incorporate three soil types: granular soil, man-made fill and a clayey soil. The utility layout in each soil has been designed to allow for the effects of changing ground conditions on sensing technology performance to be quantified. Utilities of different materials and diameters are included, some being water-filled, others gas-filled. A water recirculation system is able to create flow through a number of the pipes. Telecommunication and power cables are also included in the design, with the cables energised and able to draw current, while drains and sewer pipes are also present. It is envisaged that 'in-pipe' sensing technologies will become deployed more routinely in the future, therefore the concept included access points incorporated into a number of the utilities (open ended pipes or commercially available valves).

The approach adopted by MTU for utility location, and the development of the test facility, have attracted the attention of practitioners and academics from the USA and Australia to China and Malaysia, with a Malaysian delegation of surveyors being one of the first groups to try out utility detection on the MTU Centre of Excellence site in 2012. Such attention is welcome, suggesting that the UK is leading research and development into utility location.

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Making an impact – from BACK to the future

N Metje, CDF Rogers (University of Birmingham)
J Parker (UKWIR)

Mapping the Underworld evolved from a meeting of minds between industry and academia. The relationship was nurtured and full collaboration enabled by EPSRC funding, which allowed the ambitions of all to be realised. It is therefore perhaps inevitable that this major funded programme of research has acted as a catalyst for changes in industrial practice.

It would be wrong to claim that changes in industrial practices would not have occurred without MTU – their need was most certainly recognised by all who engage in street works – yet the analogy of a catalyst as a reaction enhancer is a good one: the rate of change and profoundness of understanding of what is and is not possible is the key outcome.

The impact of MTU over the past 7 years has been both direct and more intangible. It has brought together more than 50 stakeholders in its network, all of whom strive to further improve the utility mapping, detection and location industry, and in turn its contribution to improving utility street works. This impact has been evident through the excellent attendance at MTU's annual meetings, the 'sandpit' event to advance the research (Assessing the Underworld, see below) and the policy-makers' workshop in 2011.

Moreover, MTU has stimulated industry's thinking. This was most notably shown in the collaboration between MTU and JK Guest leading to the design and ultimately the construction of the MTU Centre of Excellence, i.e. the UK's new national test facility. Much has already been written in this brochure on the technical specifications of the test site, but little has been said on how this collaboration was initiated. It was after a No Dig Live presentation in Wakefield in 2009 that we were approached by Jon Guest, who liked the idea of a national test site. Jon was keen to collaborate on its specification as MTU had done significant research to compare and contrast existing sites in the UK and worldwide. This led to an investment of £2 million and the opening of the test site in September 2012[1]. With the test centre in place, this was also the opportunity to develop vocational qualifications for utility surveyors at different levels and there are now 15 NVQ modules on offer[2]. These will ensure a consistent competency level across the industry.

In parallel, MTU is supporting the development of a Publically Available Specification (PAS) for utility mapping, depiction and location, currently being drafted through the British Standards Institution (BSI) with a publication date in the autumn of 2013. This will ensure that a standardised approach to obtaining and recording underground utility information is taken across the industry, making the industry more transparent and providing a better understanding of the different levels of surveys available and delivered. This will bring the UK in line with the USA, Canada, Australia and Malaysia who all have their own standard. While there has been significant industry lobbying to initiate this development, MTU has played its part through our involvement in the ASCE Utility Standards Committee and by reporting on the experiences and lessons learned from existing standards in our annual MTU events.

A key ambition of MTU, from its inception, has been to ensure the engagement of a wide group of stakeholders, including those who do not normally engage with engineering research. Therefore, it was vital to view the research and, more generally, utility street works through different lenses (Figure 1).

This led to MTU organising a policy-makers' workshop (Figure 2) aimed at local councillors, civil servants and MPs, since the vision of MTU has always considered that governmental changes and pressures might be necessary to bring about a step change in the utility streetworks industry.

The key messages from the workshop were:

- Communication, coordination and collaboration are essential between all parties who have an interest in the impact that excessive excavations can have on the industry, businesses, commuters and local authorities, and information on the extent of the works planned should be readily available to residents and local businesses.

- Both the direct and the indirect (social and economic) costs of excavations are of importance when considering the impact of street works on the UK economy and the benefits of any potential solutions.

Figure 1. Utility street works viewed through different lenses

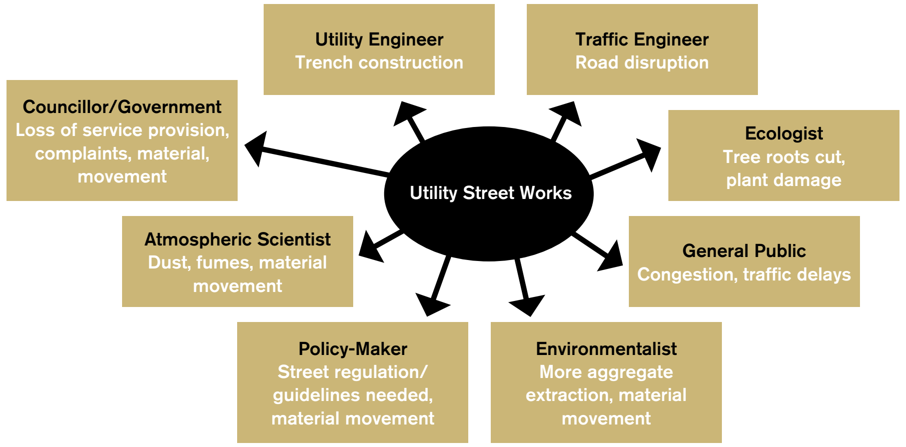

Figure 2. Policy-makers' workshop at the Institution of Civil Engineers in March 2011

- Significant technical challenges, wider social and environmental issues, and costs result from different approaches to the location of, and excavations associated with, buried assets.

- The inability to gather and share location data and other information is a major concern.

- There were differing views on whether further regulation is required.

The ambition of MTU to involve a large range of different stakeholders led to the BBC Radio 4 programme 'Mapping Britain's Underworld', broadcasted in May 2012 to an audience of approximately 600,000. The programme was presented by Adam Hart-Davies and focussed on the MTU project, with Adam coming out to our test site at Bristol Water to see and try out the different technologies for himself. Clearly, this spreads the message rather than making an immediate impact, but hopefully it has brought utility street works and the issues of inaccurate location of underground assets closer to the general public's psyche. Additional efforts in this regard included the creation of an MTU animation video[3], which demonstrates the MTU concept in a simple and immediately accessible way.

The industry landscape has changed noticeably since the inception of MTU. There are still many initiatives that the aim to improve further different aspects related to utility street works. However, notably there are two organisations – the Utility Mapping Association[4] (UMA) and the Buried Assets Centre of Knowledge[5] (BACK) – which both aim to bring together the different industry sectors with the vision that any works in the vicinity of the underground asset infrastructure do not result in injury, damage or unnecessary disruption. MTU is represented on both of these initiatives and currently is centrally involved in the analysis of a questionnaire issued by the UMA[6] to (a) raise awareness of what is currently available, (b) raise awareness of what is proposed, (c) assess how the industry currently perceives Utility Detection and Mapping, and (d) assess how users/providers of such data feel about both the development of the PAS and a system of practitioner qualifications and company accreditations that will support the implementation of such a standard. The questionnaire will be open until the end of 2012, so please fill it in if you have not done so yet as we do want your opinion. At the same time, MTU is working closely with members of BACK to identify the real costs of utility street works.

Being involved in the above initiatives ensures that the outcomes of the MTU research will be considered fully by those who matter and that any future initiatives or guidelines take account of the full potential of the MTU multi-sensor cart.

The success of MTU has also had an impact of other research such as the Smart Pipes project led by the University of Birmingham, which aims at installing millimetre-sized sensors on and around pipelines to measure the condition of the pipe and its contents, thereby supporting a pro-active asset management[7]. Field trials will be carried out as part of a recently awarded Technology Strategy Board (TSB) grant in the next three years.

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Where do we go from here?

CDF Rogers (University of Birmingham)

MTU has focussed exclusively on buried utility detection and mapping – any additional information (e.g. on the properties of the ground) has solely been used to make the ground invisible (or less visible) to the sensors. However the sensors have a far greater potential: apart from *looking through* road structures and the ground, they could *look at* them; moreover the recorded signals (e.g. GPR reflections) can reveal information on the condition of the pipes or cables, as shown in a preliminary study[1].

Broadening the MTU thinking[2], our surface urban transport infrastructures (roads, cycle ways, pedestrian areas, etc.) are supported by the ground, and hence the properties of the ground must significantly influence their structural performance. The utility services infrastructure (the pipes and cables being sought by MTU) is usually buried beneath our urban streets, that is it lies below the surface transport infrastructure and is likewise supported by the ground. It follows that if trenches are excavated to install, replace, repair or maintain these pipes or cables, they will not only disrupt traffic and people movement, bu they will also often significantly damage the surface transport infrastructure and the ground on which it bears.

It is clear, therefore, that the ground and the surface and buried infrastructures exist according to a symbiotic relationship: intervene physically in one, and the others are almost inevitably affected in some way, either immediately or in the future. Moreover the physical condition of the pipes and cables, of the ground and of the overlying road structure, is consequently of crucial importance in determining the nature and severity of the impacts that street works cause[2].

The MTU team has therefore proposed a new programme of research to build on the many advances made in MTU. Entitled Assessing the Underworld (ATU), this new programme aims to use geophysical sensors deployed both on the surface and inside water pipes to determine remotely (i.e. without excavation) the condition of these urban assets.

The MTU sandpit, and subsequent research projects, brought together an academic team and an extensive group of project partners that has grown to be acknowledged as international leaders in this field. ATU seeks to broaden the skill-base of the MTU team by introducing leaders in climate change, infrastructure policy, engineering sustainability and pipeline systems so that collectively we can take the research into a new sphere of influence in line with the 25-year vision to make street works more sustainable.

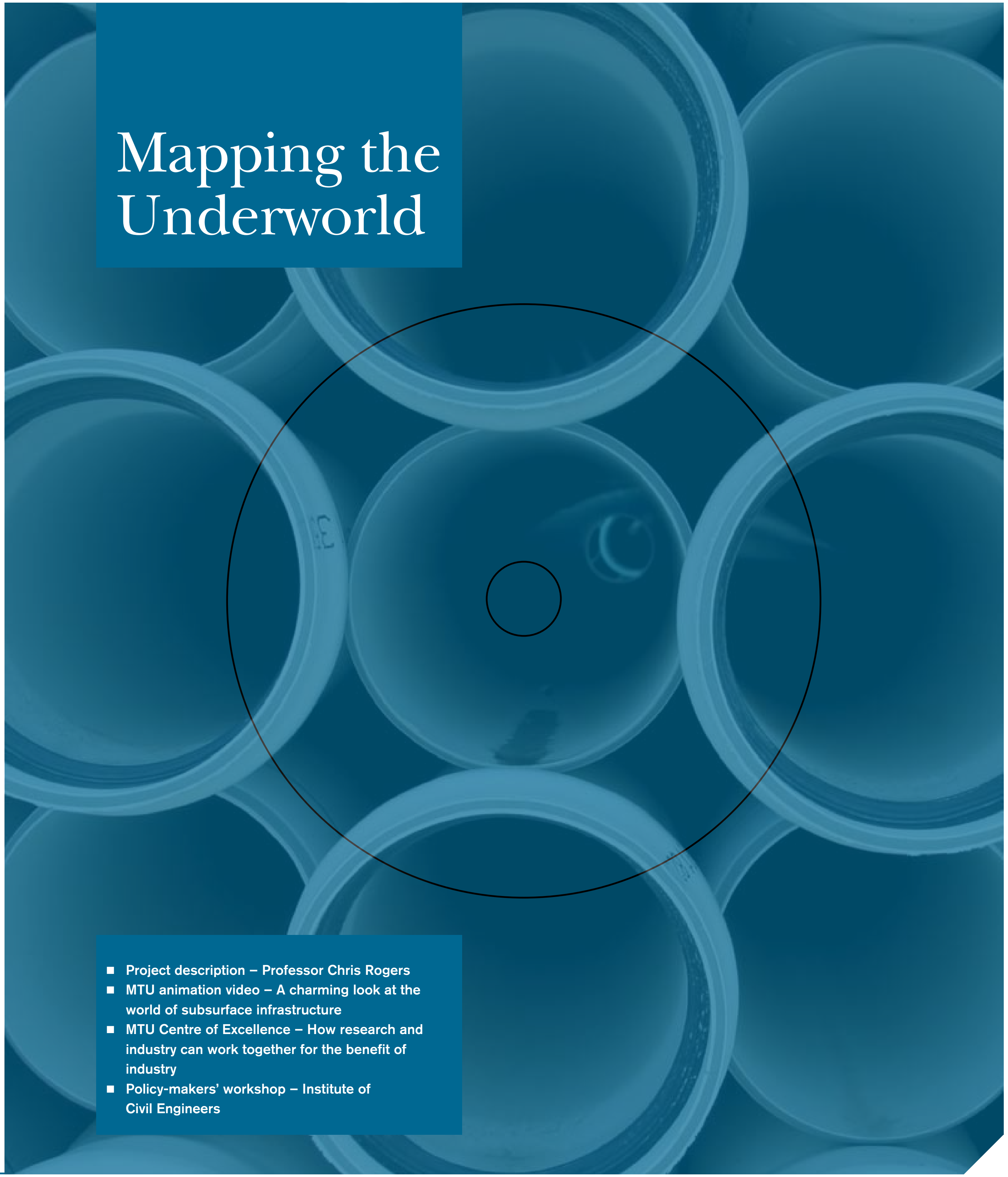
ATU proposes to develop the geophysical sensors created in MTU to look for different targets: indications that the buried pipes and cables are showing signs of degradation or failure, indications that the road structure is showing signs of degradation (e.g. cracking, delamination, foundation wetting) and indications that the ground has properties different to unaltered ground (e.g. wetted by leaking pipes or via a cracked road surface, loosened by trenching).

For example, a deteriorated (fractured, laterally displaced, corroded or holed) pipe will give a different response to the geophysical sensors than a pristine pipe[1], while wetting of the adjacent soil or voids created by local erosion due to leakage from a water-bearing pipe will result in a different ground response to unaltered natural soil or fill. Similarly a deteriorated road (with vertical cracks, or with a wetted foundation) will give a different response to intact, coherent bound layers sitting on a properly drained foundation.

Combining this information with records for the pipes, cables and roads, and introducing deterioration models for each of these physical infrastructures, will allow a means of predicting how they will react if a trench is dug at a particular point in a particular road.

References

1. Wazlan S, Chapman DN, Rogers CDF, Foo KY, Nawawi SW (2012). Assessing the Condition of Buried Pipe using Ground Penetrating Radar (GPR). *Proc. of 11th Int. Symposium and Exhibition on Geoinformation (ISG2012)*, Kuala Lumpur, Malaysia, 25–26 September.
2. Rogers CDF et al. (2012). Condition Assessment of the Surface and Buried Infrastructure – A Proposal for Integration. *Tunnelling and Underground Space Technology*, **28** (1), 202-211



Mapping the Underworld

- **Project description – Professor Chris Rogers**
- **MTU animation video – A charming look at the world of subsurface infrastructure**
- **MTU Centre of Excellence – How research and industry can work together for the benefit of industry**
- **Policy-makers' workshop – Institute of Civil Engineers**

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