

REPORT

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Alternative Methods for Railway Tunnel Examination – A Review and Recommendations

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ABSTRACT

An investigation into alternative methods suitable for tunnel examination has been made. This investigation has identified techniques based on physical principles after a brainstorm with NPL staff. It has also identified techniques used in other industrial sectors that might also be relevant to this measurement problem. The techniques were ranked according to various relevant selection criteria and a more detailed examination was made into each technique that was likely to be suitable for this task.

After additional interactions with industry experts and visits to see plant and structures then a series of recommendations have been made into which techniques should be investigated further and are most likely to be successful, economic, efficient and suitably accurate for the task of tunnel examination for each of the classes of structurally relevant defects.

Preliminary investigations using trial data files has helped identify data acquisition issues and techniques that might be used for visualisation. Comparison techniques have been identified for comparing subsequent scans. It is expected that the data storage requirements for each technique will be similar if a similar scanning resolution is used for assessing a tunnel. The amount of data to be stored and processed may be very large so efficient ways of managing and comparing subsequent scans will be needed.

Recommended techniques for each class of measurement:

Shape of Tunnel

For this category image triangulation methods are the current best choice for high-speed measurements, when combined with imaging then interpretation will be much easier. 3D DIC can also be used for high-speed measurement, but will need more post-processing. TOF camera has borderline accuracy, but offers the real possibility of low cost high-speed measurement, with certain benefits of capturing full fields of data.

Crack opening measurements

The only viable techniques for this are DIC to measure crack opening and shear, and 3D-DIC to measure crack step. Additionally image stitching may improve positioning

Delamination

This is unlikely to be done at high speed unless the damage leads to a shape or crack opening change, but the techniques most likely to be successful are impact echo and GPR.

Water ingress

Water ingress measurements will require a multi-sensor approach, using imaging for dry to moist conditions, shape measurement and imaging for visible water flows and sound measurement for substantial water ingress.

Recommendations for data analysis and visualisation

It is recommended that the development of algorithms and software tools proceeds in parallel with the development of the measurement sensor systems, as the combination of both are required for an efficient easy to understand measurement system.

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Abbreviations used

Abbreviation	Definition
CCTV	Close Circuit television
DIC	Digital Image Correlation
ESPI	Electronic Speckle Pattern Interferometry
FOS	Fibre Optic Sensor
GPR	Ground Penetrating Radar
IR	Infra Red
LIDAR	Light Detection And Ranging
MPV	Multi Purpose Vehicle
NDE	Non Destructive Evaluation
NDT	Non Destructive Testing
NMT	New Measurement Train
RF	Radio Frequency
SAR	Synthetic Aperture Radar
SIC	Standard Industry Code
TOF	Time-Of-Flight (camera)

1. Introduction

Network Rail has issued a project outline “Research Project into Alternative Methods of Railway Tunnel Examination” (Appendix 1). This outline highlights seven work streams and this project is designed to address the requirements of work stream one: “The Evaluation of existing practices using alternative technologies for railway tunnel examinations and overall project methodology plan.”

The decreasing availability of track access to accommodate modern train operations means possession availability to accomplish detailed tunnel examinations is at a premium. Detailed examinations will become more challenging if the aspirations of the 2030 railway network are to be met. To meet this challenge, and appropriately manage the risks associated with tunnel assets, it will be necessary to develop alternative techniques for tunnel examinations that will meet future demands of reduced track access and increased train operations. Current examinations are of a tactile nature with examiners traversing the internal length of the tunnel closely inspecting the lining using high-level access equipment. In many cases it is necessary to employ road-rail mobile extendable working platforms to ensure full lining tactile coverage, this adds greatly to the cost of an inspection.

Network Rail is responsible for 703 operational tunnels across the network; this equates to 335 km of tunnel structures. It is not uncommon for a large proportion of this tunnel length to remain unchanged between examinations. Current inspection regimes and practices are therefore time consuming and may be conducted unnecessarily where there is little detectable change over time. Of this stock of tunnels the average number requiring regular special inspections by engineers is 63 equating to approximately 51 km of tunnel. There is a need to investigate the value of using alternative techniques to confirm the stability of the large proportions of tunnels that remain unchanged. This will allow examination resources to be targeted to the areas of concern bringing about logistical efficiencies and corresponding cost savings.

2. Project Methodology

This project is divided into four work packages (WP). WP1 consists of a desk-based investigation of existing lab-based techniques. WP2 has investigated applied techniques currently used across various sectors. WP3 consists of an investigation of available software for the high-speed evaluation of data outputs from measurement techniques, reported in Section 8. WP4 consists of the development of a programme methodology and project plan for development and implementation, reported in Section 11.

For the purposes of reporting the outputs of WP1 and WP2 have been combined so that all the applicable techniques can be considered together, Sections 3-7.

3. Investigation into potential solutions

From Appendix 1, examination techniques and technologies will be needed to ensure that the following degrading trends in common tunnel lining condition defects are monitored:

- Cross sectional deformation including bulging.
- Lining face loss or lining thickness loss.
- De-lamination, honeycombing or voiding within the lining.
- Mortar loss in joints in brick linings.
- Water ingress.
- Fractures and cold joints.
- Missing brick or masonry units.

These degrading trends can be assessed using techniques that measure the following;

- Measurement of the tunnel shape
- Cracking in the tunnel surface
- Tunnel lining delamination
- Degree of water ingress.

For tunnels made of brickwork, masonry block and cast and sprayed concrete.

To investigate potential solutions two main approaches were taken. The first approach used expertise at the NPL to identify all the possible physical measurements that were likely to be relevant according to the specification in Appendix 1.

For this purpose a brainstorm activity took place with NPL Technical Area leaders in all the relevant physical measurement areas.

The second approach used a standard list of industry codes used to classify all industries extracted from *UK Standard Industrial Classification of Economic Activities 2003* from the Office of National Statistics. These were then refined to those industries which shared some aspects with tunnel inspection, varying from using similar tunnels and structures but for different uses, such as water transport, to completely different applications like medical body shape scanning, which measured similar things, like form and shape.

Once all the likely techniques were identified then they were assessed against a simple set of selection criteria to see if any techniques were clearly superior and could measure all the four physical measurement categories.

It was found that no single technique could measure all the measurement categories and so a more detailed ranking process was carried out to assess the combinations of techniques, which were likely to be most successfully deployed. Each of the techniques were then subject to more detailed study and literature review to enable a series of recommendations as to which techniques and combination of techniques were most likely to successfully meet the remit in Appendix 1.

3.1 Summary of initial brainstorm of laboratory techniques

A brainstorm activity took place with NPL Technical Area leaders in all the relevant physical measurement areas identified in the remit in Appendix 1. The following preliminary selection criteria were used for this exercise.

Cost of equipment?

- H >£150k
- M £20k-£150k
- L <£20k

Time of measurement?

- H – Hours (static)
- M - Minutes (slow moving vehicle)
- L – Seconds (fast moving vehicle)

Technology Readiness Level (TRL, see Appendix 4.)?

- TRL 8 and above
- TRL 4-8
- < TRL 4

How much of the measurement problem does it solve?

- How many of the seven measurements criteria can be measured with the same technique.

Likely accuracy?

- + meets
- - does not meet

The results of this initial brainstorm can be found in Appendix 2 as a list of techniques and in Appendix 3 scored using the above preliminary criteria.

To further identify the techniques most likely to be successfully deployed for tunnel examination several tables were generated.

Table 1 shows the techniques classified by “Cost of Equipment” versus “TRL” the techniques in the green area are preferred to those in the amber or white area using this classification, with techniques to the lower right being most favourable for rapid low-cost deployment. Table 2 is another classification of the techniques this time looking at the number of measurement criteria a given technique can meet versus its TRL. Once again techniques in the green areas are more favourable with those in the upper right the most favourable.

High >£150K	Robotics Microwave induced thermography Surface Rayleigh wave Shearography Thermal pulse + interferometry Template + interferometer Impact echo	Flash thermography	IR thermography, gas detection using
Medium £20K - £150K	Gas analysis Airborne ultrasonic (sub-surface)	RF conductivity Fibre optics Radar Microwave reflectometry Acoustic range finder (surface only) Wireless point sensors Correlation techniques (DIC) Fluorescence Projected images 3D-DIC Stereo Photogrammetry	Thermography Laser scan Triangulation optical
Low <£20K	Pressure pulse response Vibrational analysis of whole structure Presence of organisms / calcites Leaching of chemical tracer Water sensitive paint	Resistance Wave guide Localised resonance Visual SLAM	Humidity sensor array /train mounted
	<TRL 4	TRL 4-8	>TRL 8

Table 1. Techniques classified by Cost of equipment vs. TRL

6 to 7	Robotics Pressure pulse response Vibrational analysis of whole structure Template + interferometer		RF conductivity Radar Microwave reflectometry Fibre optics Wireless point sensors
4 to 5		Correlation techniques (DIC) Projected images Stereo photogrammetry Acoustic range finder (surface only) 3D-DIC	Triangulation optical Laser scan
1 to 3	Presence of organisms / calcites Leaching of chemical tracer Water sensitive paint Airborne ultrasonic (sub-surface) Thermal pulse + interferometry Impact echo Microwave induced thermography Surface Rayleigh wave Gas analysis	Resistance Wave guide Localised resonance Fluorescence Flash thermography Visual SLAM	Humidity sensor array /train mounted Thermography IR thermography, gas detection using
	<TRL 4	TRL 4-8	>TRL 8

Table 2. Number of measurement types for each technique vs. TRL

6 to 7			RF conductivity Radar Microwave reflectometry
4 to 5		Correlation techniques (DIC) Projected images Stereo photogrammetry 3D-DIC	Triangulation optical Laser scan
1 to 3	Airborne ultrasonic (sub-surface) Impact echo	Flash thermography	Humidity sensor array /train mounted Thermography
	<TRL 4	TRL 4-8	>TRL 8

Table 3. Number of measurement types for each technique vs. TRL. Only techniques that meet specification are included.

However if those techniques are eliminated that require a fixed infrastructure like Fibre optics and Wireless Point sensors, and the sensors that were unlikely to meet specification then Table 3 is produced. It is this list of techniques that will be carried forward to the next level of selection.

3.2 Identification of potential solutions within industry

A list of Standard Industry Codes was produced from *UK Standard Industrial Classification of Economic Activities 2003* from the Office of National Statistics. These were then analysed to see which ones would have relevance to tunnel examination, Appendix 5. The industry sectors from this list of codes were expanded and then used as a basis for consultation with NPL Business Development and Knowledge Transfer specialists who had experience in the relevant industry sectors that were highlighted. The purpose of this first pass was to identify industry sectors rather than techniques, to ensure that no techniques in other sectors might be missed, Appendix 6.

From this list an internet/literature survey was undertaken to identify techniques that might be relevant. Typically these techniques will have a high TRL as they may be well established in a particular industry sector, Tables 4.1- 4.11.

Activity	Links/ References	Notes
Service Activities Incidental to Oil and Gas Extraction Pipeline inspection Tunnels for telecoms Utilities	[1-3]	Mainly FOS for strain and corrosion also ultrasonics for metallic pipe inspection

Table 4.1. Pipes and tunnels

Activity	Links/ References	Notes
Mining and Quarrying	[4]	Scanning system for vertical mine shafts
	[5]	Laser scanner resolution 3.9mm manufactured by Sick
	[6]	Laser scanner in a small bore
	[7]	Robotic total station but only 250 points per second
	[8]	3D laser scanning of mines

Table 4.2. Surveying enclosed areas

Activity	Links/ References	Notes
Textile weaving, Manufacture of carpets and rugs, wallpaper Machining wood	[9]	Optical scanner
	[10]	3D scanning technology
Manufacture of flat glass Cold rolling of narrow strip, treatment and coating of metals	[11]	Optical scanning of galvanised strip
	[12]	Multi-beam fibre-optic laser scanning system for surface defect recognition

Table 4.3. Scanning moving objects for defects

Activity	Links/ References	Notes
Manufacture of aircraft and spacecraft Examination of wings and rotors	[13]	Location and shape measurement using a portable fringe projection system BAe using DIC for wing shapes
Ships	[14]	Sub mm laser measurements about 0.25mm using coherent laser scanning
Submarines	[15]	Measuring dynamic sub hull shape
	[16]	Combination shape via laser tracker and U/s but needs human to move mouse around.
Civil engineering structures like underpasses, subways Transmission of electricity, cables, pylons	[17]	GPR for investigating concrete bridges
Wind turbines	[18]	Lock-in thermography v. interesting for this work, but times in minutes to hours for cm's penetration?
	[19]	Subsurface c-scan using moving water bath

Table 4.4. Scanning large static objects for defects

Activity	Links/ References	Notes
Site preparation	[20]	Total stations resolution 2mm and 2ppm
General construction of buildings and civil engineering works, Construction of motorways, roads, railways Bridge construction, tunnel boring,	[21]	TMS Tunnelscan laser scanner
	[22]	Leica Red line control system
Dams	[23]	Laser scanning a dam SAR interferometry <1mm resolution
Spillways	[24]	Solution from Japan for scanning of tunnels, 0.2mm crack resolution, plus infrared thermography for delimitation in concrete. National Institute for rural engineering
Architectural and engineering activities and related technical consultancy	[25]	UK Companies

Table 4.5. Surveying

Activity	Links/ References	Notes
Urban and suburban passenger transportation by underground, metro and similar systems	[26]	Rail inspection using ultrasonics
Railways	[27]	Monitoring of wooden railway sleepers
	[28]	New measurement train
	[29]	GPR in Japanese concrete tunnels
	[30]	Tunnel examination projected light camera

Table 4.6. Transport via railways

Activity	Links/ References	Notes
Satellite Imaging: Sea level measurement etc.	[31]	SAR interferometry 1-2m resolution for topography and mm for relative displacements
	[32]	Urban SAR 0.1m resolution
Land use, Forestry, Farming	[33]	LIDAR accuracy 10--50 mm
Robotics	[34]	Structured lights and robotics , 0.1mm resolution
Medical imaging	[35]	120x90 cm at a subject distance of 2.5 m can be covered with each scan. Measuring time in fine mode (307,000 points) can be reached in 2.5 seconds and in fast mode (76,800 points) in 0.3 seconds. The system achieves a resolution 0.008 mm in the z coordinate.
Archaeology	[36]	Laser pantograph
	[37]	3D laser scans of buildings

Table 4.7. Research and experimental development on natural sciences and engineering

Activity	Links/ References	Notes
Stents Endoscopes/Borescopes	[38]	Laser scanner built in endoscope

Table 4.8. Medical

Activity	Links/ References	Notes
Range finding Radar technologies Satellite Imaging Assessing damage	[39]	Laser rangefinder
Mine detection	[40]	Speckle noise in a continuously scanning multibeam laser Doppler vibrometer for acoustic landmine detection

Table 4.9. Military use

Activity	Links/ References	Notes
Sea wall defence		
Academia	[41]	Tunnel modelling

Table 4.10. Environmental monitoring

Activity	Links/ References	Notes
Technical testing and analysis NDE	[42]	Measurement of Subsurface Defect Shape by Photoacoustic Microscopy
	[43]	ESPI but vibration too much of a problem
Security and related activities	[44]	Forensic and security
	[45]	SIGUARD Laser Scanner LS4 Panoramic Security
Anti-counterfeiting	[46]	NPL using DIC and image comparison
CCTV Motion picture and video production Motion capture	[47]	Structured light and LIDAR for Radiohead video, real time capture like laser scanner on NMT
Sporting activities Motion capture, Hawkeye, body scanning	[48]	Resolution mm in a 2x1x1m box.
Maintenance of civil engineering structures	[49]	Bridge system preservation and maintenance: scanning for innovation.
	[50]	Civil engineering example of laser scanning
	[51]	Uncertainties for practical measurements, laser scanning
Manufacture of optical sensors and gauges	[52]	Fibre optic sensors
Nuclear	[53]	Nuclear plus ships
Processing of nuclear fuel New build Storage Deep geological disposal: integrity	[54]	Improvement of fracture mapping efficiency by means of 3D-laser scanning Internal components

Table 4.11. Engineering related scientific and technical consulting activities

From the sector review the following techniques were identified that may have relevance to tunnel examination

- Laser scanning as large a structure as a dam
- Coherent laser scanning that can achieve about 0.25mm resolution
- Lock-in thermography
- SAR interferometry <1mm resolution
- Structured light scanners for robotics, 0.1mm resolution

The following commercial instruments may be useful too.

- A laser scanner with resolution of 3.9mm as a standalone module manufactured by Sick.
- Whole human body scanners about 100,000 points per second, resolution of 0.008 mm in the z coordinate.
- Laser Doppler vibrometer for acoustic landmine detection
- Solution from Japan for scanning of tunnels, 0.2mm crack resolution, plus infrared thermography for delamination in concrete developed by National Institute for rural engineering

There was also a US Report on bridge system preservation and maintenance: “Scanning for Innovation” that provided useful information about practical laser scanning of bridges and other structures.

Discussions with Scorpion Machine Vision specialists identified another technique that has just become commercially available, a time-of-flight camera. This allows many parallel measurements of distances in the range of 1-10 metres to be made simultaneously with a sub-cm resolution, but at very high data rates, easily equivalent to a train travelling at >100 mph. So in addition:

- Time-of-flight (TOF) camera

These will be added to the list of techniques for further study

4. Additional information relevant for selection

In addition to the selection criteria used in section 3.1 some additional criteria for the suitability of a method for tunnel examination were developed after consultation with industry experts and visits to see tunnel inspections and likely measurement platform vehicles.

A visit was made to see a routine inspection of Holme tunnel, Lancashire (14/10/09). Whilst this tunnel has some unique characteristics the visit indicated the type of environment and conditions sensors would need to operate in. In particular the variability of the tunnel wall as a result of many repairs and patches was much greater than anticipated, as was the amount of water flowing on the tunnel wall surface. The additional instrumentation and tunnel wall supports indicated that any technique, which requires close contact or has a small stand-off from the wall is unlikely to be successful.

A visit was made to see the potential vehicles that could be used as a measurement platform and also to see some of the vehicles currently used for gauging and track examination purposes (17/11/09). This identified that the multi-purpose vehicle (MPV) would likely provide a suitable platform for medium to fast tunnel examination

techniques (at up to 60 mph). The performance of the track positioning GPS system was also seen, as was the data collection capability of the new measurement train.

Golder RMT were visited (7/12/09) to discuss the use of impact echo techniques for delamination and ring separation measurement. From the discussion it was concluded that impact echo would be a viable method but the difficulties in automating the process were identified.

Scorpion Machine Vision were visited (10/12/09) to get information on techniques that might be useful and are presently used for robotics, machine vision and part identification and orientation. This is primarily for automated manufacturing within the many industrial sectors. This visit identified time-of-flight cameras as a viable measurement technique.

Discussions were also had with Omnicom(20/08/09) and ScanTech (16/12/09) about laser scanning measurements and data sets have been obtained from both parties and are presently undergoing analysis. The discussions highlighted the real speed that these measurements could currently be made at and some of the practical consideration that are needed for useful measurements. Preliminary examination of the datasets indicates that visualisation techniques will be key to understanding trend data and there is a formidable challenge in realistically estimating what the likely error from these measurements will be.

These discussions identified relevant questions to ask when considering each potential technique:

- **Resolution limits,**
 - Can the technique meet the specification required, if not how much development is needed and what is the likely time scale?
- **Speed of acquisition,**
 - Can the technique be done in one shift within a tunnel possession, can it be done automatically without possession, or can it be done from a moving train at slow speeds or high speeds?
- **TRL,**
 - Is the equipment ready to deploy, does it need some or major modification, is it a research idea?
- **Cost of sensors,**
 - Are the sensors cheap and robust, are they expensive but only a few are needed or are many needed?
- **Cost of the service,**
 - Are any consumables required, do the sensors need special care, is there much setting up required, is an extra infrastructure like targets required, are skilled staff needed?
- **Time of tunnel possession needed,**
 - Is there much setting up required, can the measurements be made quickly, can they be made bi-directionally, can both sides of the tunnel be surveyed from one track in a pair?
- **Time for deployment of each technique,**
 - Can feasibility studies be started, is time needed to build kit, or is it off the shelf?

- **Ease of data interpretation,**
 - Is the data easy to understand, do we get an indications of the accuracy of the data during measurement, is it prone to artifacts, are they easy to spot?
- **Time to post process**
 - Are there particular extra requirements to process the data, does it need proprietary or specialized hardware, will this affect archived data?

The information gained from these discussions, visits, analysis of data sets will be used in conjunction with the original problem specifications and above questions to develop the recommendations in section 9.

5 Ranking of solutions: recommendation for further study

Potential solutions	Crack opening detection	Shape of tunnel	Delamination	Water ingress
3D-DIC	y ¹	y		y ²
Laser scan		y	y ³	y ²
Projected images/structured light		y		y ²
SAR		y		
Coherent laser		y		
Triangulation optical		y		
Correlation techniques (DIC)	y ⁴			y ⁵
TOF Camera		y		y ²
Ground Penetrating Radar/Microwave reflectometry/RF conductivity			y	y
Thermography: Flash/microwave induced			y	y
Fluorescence, IR spectroscopy				y ⁶
Vibrometer/ Airborne ultrasonic (sub-surface)			y	
Impact echo			y	
Humidity sensor array				y

Table 5: Sensor techniques

¹ Needed for measurement of crack step

² Water flow causes change of shape

³ If delamination is preceded by shape change

⁴ Needed for crack opening and shear

⁵ Capturing an image of water flow

⁶ Probably measuring the difference between dry and damp surfaces

6 Detailed investigations

So from Table 5 the following groups of techniques have been identified for further study. Grouping of techniques has been done since some techniques are very similar in their performance and requirements.

- **Laser scanning**
 - Laser scan,
 - Fixed point (overlapping scans)
 - Continuous (moving scan platform)
 - Coherent laser
 - TOF Camera
- **Projected light imaging methods**
 - Projected images
 - Structured light
 - Triangulation optical
- **Digital Image Correlation**
 - Correlation techniques (DIC)
 - 3D-DIC
- **Radar methods**
 - SAR
 - Ground Penetrating Radar/Microwave reflectometry/RF conductivity
- **Thermography**
 - Continuous or Flash/ microwave induced
- **Water detection**
 - Fluorescence, IR spectroscopy
 - Humidity sensor array
- **Acoustic methods**
 - Vibrometer/ Airborne ultrasonic (sub-surface)
 - Impact echo

These technique areas will be discussed in more detail in the following sections.

6.1 Laser scanning

6.1.1 Introduction

Laser scanning essentially uses a time of flight approach or a frequency-modulated beam to measure the distance from the emitter to the point of reflection. It is a mature technology and in widespread use as a rangefinder [39], security scanner [45] and is used in surveying instruments such as total stations [20]. When it is combined with a scanning head then full field 3D measurements [55] are possible and the system has been widely used for many applications including nuclear fuel processing [54] and more commonly surveying and measurement in mining and quarrying [4-8] and archaeology and architecture [37].

The scale of scanners and objects scanned can vary considerably with scanners mounted on aircraft for large-scale structure and city measurement [23][33]. There are even examples of miniature scanners being used in endoscopy within the human body [38].

6.1.2 Variants

Laser scanner

There are various solutions that already exist for tunnel examination these include TMS Tunnelscan [21], which is aimed primarily at assessing the shape of the tunnel at a relatively limited set of points to compare with plans. Recent work carried out for Network Rail by Omnicom, ScanTech using a continuous moving scanner and a fixed aligned scanner that is moved down the length of the tunnel between each radial scan.



Figure 1. A commercial laser scanner

The continuous moving scan produces a cylindrical spiral scan, which produces a point cloud extending the entire length of the tunnel. Using a fixed point scanner, Figure 1, and then moving it is more time consuming, but may give better accuracy, and additional data processing step is also required to fuse the overlapping point cloud data together.

In these systems the typical error in the range measurement (radial direction) is probably about 2-5 mm, (depending on the scan speed) [56], but there is also an additional error introduced by positioning accuracies in the circumferential and along the tunnel caused by the positional accuracy of a rapidly moving scanning mirror. The effect of these inaccuracies can be seen when the 3D point cloud is visualised. This also means that cracks less than 5 mm might be very difficult to detect using this system [57].

Coherent laser scanner

By using a heterodyned frequency approach such as a coherent laser scan then the accuracy of the range measurement may approach 0.25 mm even for quite large surfaces [14-15]. This can be carried out for large structures like ships and potentially is a more accurate version of a more common laser scanner. However for the same scanning speed it is expected that the location accuracy perpendicular to the radial direction would be the same as the more common time-of-flight laser scanners.



Figure 2. The Metris Coherent laser radar. The only commercial coherent laser scanner currently available.

TOF Camera

A time-of-flight camera is a new type of camera that has only recently become commercially available, demonstrated at recent optics and camera exhibitions [58]. The camera has each of its individual pixels as an independent time-of-flight distance ranger, so it is similar in operation to having many laser rangefinders work in parallel. The number of pixels can be as large as 484x648 pixels and although less accurate than conventional laser rangefinders they can make measurements at 100 frames per second. They are a solid-state device with no moving parts and should be reliable. They have a range of up to about 60 metres, with a distance resolution of 5-10 mm. They may use semiconductor lasers or LED's as light sources [59].



Figure 3. The Mesa time-of-flight camera

6.1.3 Current state of development

Of the three variants of laser scanners the conventional laser scanner is the most well developed the scan speed has steadily increased up to about 50-100,000 points per second whilst maintaining accuracy. The coherent laser scanner emerged after 10 years of development and extensive use in the Department of Defence, Department of Transportation, Department of Energy, NASA, Boeing and privately funded research in the US. It has a niche market in large-scale metrology measurements because of its superior range resolution.

The TOF camera is a recent development and is likely to increase in performance and size of the array quite quickly as it is essentially all solid state.

6.1.4 Commercial Availability

Laser scanners are commercially available from Leica, Z+F and Faro amongst others with performances ranging up to nearly 1 million points scanned per second. They typically might cost £60k.

Coherent laser scanners are only available from Metris, Figure 2.

TOF cameras are commercially available from Mesa Imaging and PMD amongst others and may cost £6000.

6.1.5 Limitations

For any optical measurement system there will be practical problems caused by high humidity leading to mist and fog, although snow or heavy rain is unlikely to be a problem for tunnel examination. Water surfaces, unless thin, appear black using laser scanners and slightly thicker water layers can lead to anomalous reflection problems

with ghost positions that are too far away. Changes in humidity will have small effects on the speed of light and hence the range measured but this will generally be smaller than the current distance error unless very large ranges are measured.

Shadowing will be a problem for a fixed-point laser scan in somewhere like Holme tunnel where there was girder support. However a continuous moving scan wouldn't be affected so much although information behind the supports would be unavailable for any optical system.

6.1.6 Accuracy

The coherent laser scanner easily exceeds the accuracy required and the commercial laser scanners equal the ranging accuracy required of about 5 mm. The TOF camera may just meet the specification in Appendix 1.

The laser scanner rotation speed and steadiness of platform will influence the accuracy of the measurements perpendicular to the ranging direction and this may be problematic for very accurate measurements like crack size determination

6.1.7 Time to make measurement

The highest speed scanners can make measurements at up to 1 million points per second. For continuous moving scanner heads such as those used by Omnicom then this means speed of tunnel measurement of 1-2 metres per second. Using a custom laser scanner such as one designed for robotic navigation might enable 3 metres per second but with a lower density of points measured [60].

Using a fixed position scanner with reference targets and then moving and scanning again currently takes about 5 minutes per position (every 15m), of which 3.5 minutes is for scanning, so it takes 13 hours for 3500m or about 0.1 metres per second.

The TOF camera can capture 176 x 144 pixels at 54 fps (although there are higher performance devices available), which means a scan with a lateral spacing of 3 cm could be made at 250 metres per second! By interleaving frame capture with movement scan spacings of 1 cm could be made at 80 metres per second or well in excess of 150 mph.

For the higher rates of acquisition the stability of the measurement platform maybe the limiting factor and stabilisation systems like gyros and steadicams might be required. There is a possibility of matching and aligning the data afterwards, particularly for devices like TOF camera that capture a whole frame at a time, but the additional computation would be time-consuming and would negatively affect the accuracy of the measurement made.

6.1.8 Issues to be resolved in feasibility trials

- Stability of measurement
- Manufacturers claims on accuracies
- The effect of variably wet surfaces for tunnel measurement
- Steadicam style devices to ensure alignment.

6.2 Projected light imaging methods

6.2.1 Introduction

This category is concerned with solutions that use projected light either in stripes or patterns and images the surface from an angle to determine how the light pattern has moved and hence the shape of the surface. In contrast to laser scanning the measurements are more accurate the closer the surface is the camera/light combination. As the system works by triangulation then the longer the baseline the more accurate the measurement but the more likely is that shadowing effects will cause missing data.

This is the solution used by Network Rail for current structure gauging, although there is now higher quality hardware available to improve the resolution and measurement speed.

6.2.2 Variants

There are some optical systems, which use minimal triangulation, or none at all to simply image the surface [9, 11, 12, 24, 27, 61].

Systems using portable fringe projection have been tried [13]. Systems using structured light in the form of grids or stripes [34, 35, 48] have been used for whole body scanning and can achieve high spatial resolution, high point density and high speed scanning, but usually in a relatively limited volume of the order of 2 x 2 x 2 metres [62]. Such systems have been used to create realtime video rate 3D data acquisition for Radiohead videos [47].

Simpler systems that project a simple disk of light have also been recently developed these are a more modern version of the sensor on the Network Rail Structure Gauging train [30, 63, 64]. These systems have been trialled by Network Rail and have been steadily modified to improve reliability, Figure 4.

6.2.3 Current state of development

The techniques using structured light and optical triangulation are well developed. The increasing resolution of image sensors that are also increasingly able to capture images at high speed have added to the accuracy and speed of measurement. Some systems can capture video rate data at high resolution, and some can capture very large point cloud datasets at very high accuracy in a very short period of time. As camera imagers improve then so will the measurement accuracy and speed.

6.2.4 Commercial Availability

Human body scanners are available from Konica Minolta and others that can capture data using structured light over a body-sized volume in a few seconds. A range 7 scanner costs typically \$80,000.

Balfour Beatty recently acquired LaserRail and now has the LaserFlex system that is commercially available and capable of tunnel examination. The Mermec T-Sight 5000

is a similar system also designed to use the triangulation method to measure tunnel geometry.



Figure 4. The Balfour Beatty LaserFleX system in operation.

6.2.5 Limitations

The same provisos on atmospheric conditions and potentially the effect of wet surfaces that exist for the laser scan systems will apply to these optical methods too.

Additionally because the laser or projector and camera are offset then there will be a limitation on the angle of surfaces that will be possible to be imaged. For narrow deep holes or slots then it may not be possible to image the bottom of the hole.

For body laser scanners they are usually optimised for very accurate measurements in a relatively small volume (say 2 x 2 x 2 metres).

In some situations shadowing may take place too.

6.2.6 Accuracy

From manufacturers data sheets the following accuracies are claimed:

For a Konica Minolta Scanner using projected light it is possible to measure a 120x90 cm area at a distance of 2.5 m with each scan. The measurement time in fine mode (307,000 points) is 2.5 seconds and in fast mode (76,800 points) is 0.3 seconds. The system achieves a resolution 0.008 mm in the z coordinate.

For the LaserFleX and Mermec systems an accuracy of about 2 mm is claimed at 8 metres per second with a measurement spacing of about 2 mm at typical tunnel

distances. The LaserRail system is quoted as an accuracy of 10 mm typically at 5 m/s, with the capability of making measurements at >30Hz.

6.2.7 Time to make measurement

A Konica Minolta scanner could make tunnel measurements at 3 metres per second per scanner at a very high resolution.

The LaserFleX and Mermec T-Sight 5000 systems can make measurements with an accuracy of about 2mm at 8 metres per second. Although reduced accuracy measurements at up to 200 km/h are claimed.

6.2.8 Issues to be resolved in feasibility trials

- Steadiness of system during measurement
- Whether extra targets could improve positional accuracy at speed
- Effect of sunlight
- How well does it work on flowing water on surfaces

6.3 Digital Image Correlation

6.3.1 Introduction

Digital image correlation (DIC) is a technique used to measure deformation of a surface by comparing two images [46, 65-67]. The images are essentially before and after something of interest has taken place. They can then be processed using DIC software such as [68, 69] or NPL in-house software to produce images showing deformation in x and y directions for all points within the field of view. This is done by matching small image subsets from one image to the other and determining the resultant deformation needed to match these sub-images.

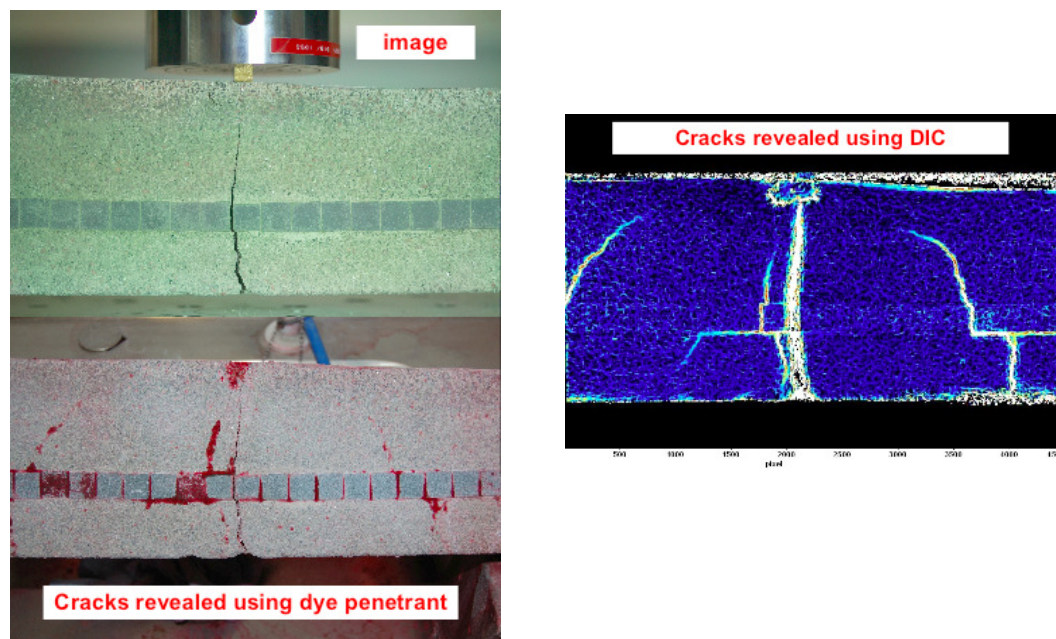


Figure 5. DIC used to identify crack opening in reinforced concrete

The technique is well developed for use in the laboratory but it has had limited trials for in-situ measurements of large-scale structures [65]. However recent developments have identified the ability of the technique for measuring crack opening [66-68], Figure 5, and detecting changes in images [46] which is ideal for tunnel examination when the images compared are those acquired months or years apart.

6.3.2 Variants

If a single camera is used to capture the images then deformation in the plane of the image is measured. If a pair of cameras separated by a fixed distance on the camera baseline are used to capture a pair of images simultaneously then out-of plane or shape measurements can be made in a similar fashion to human stereoscopic vision.

If this process is repeated then both 3D to examine shape and 2D to examine change due to crack opening can be made for the same measurement run.

6.3.3 Current state of development

The necessary algorithms, computer hardware and high-resolution cameras are available to make high-resolution measurements of tunnel walls, probably using multiple cameras pointing at different parts of the tunnel.

6.3.4 Commercial Availability

The necessary hardware required for image acquisition for DIC is a high-resolution camera, which are readily available. The storage of uncompressed images is relatively easy and cheap. The necessary software is commercially available [69, 70] although for the large amount of processing needed dedicated high speed computing hardware will be required. Bespoke solutions are unlikely to be readily available, but could be developed easily for this application.

6.3.5 Limitations

The usual limitations for optical measurements would apply. Shadowing effects would occur for the 3D measurements.

Lens aberrations and the accuracy effects caused by the tunnel walls being curved would need to be calculated, although the shape could be determined by 3D DIC measurements.

The data storage requirements would be high but the complete visual record of the interior of the tunnel would also be useful. Having a series of overlapping images would help with image alignment and position measurement within the tunnel.

6.3.6 Accuracy

The accuracy depends on how much of the tunnel wall is in each image. For a crack opening resolution of 0.1 mm then an image size of 1 pixel per mm is needed using a high resolution camera with a 60 MPixel sensor would result in a field of view of about 9 metres by 7 metres. To combine 2D and 3D measurements then a 50% overlap would be needed which would mean a picture would need to be taken every 3.5 metres and three cameras would be needed to image left, top and right.

At this spacing the shape resolution would be 0.1 mm for a camera at a working distance of 3.5 metres.

Any optical imaging system can be used to capture the images, including a TOF camera. In this case the extra distance information might be useful to help improve the reliability of the measurement. However the current spatial resolution of a TOF camera means that the lateral resolution for 2D DIC and the 3D position resolution from 3D DIC would be much less than that from even quite modest conventional digital cameras.

6.3.7 Time to make measurement

If an image is needed every 3.5 metres and the camera can process images at 1 per second means a tunnel measurement speed of 3.5 metres per second. This assumes that the vehicle doesn't need to be stopped to make the measurement. With a short enough shutter exposure time or the use of flash illumination this is likely to be the case.

6.3.8 Issues to be resolved in feasibility trials

- What effect is there if the tunnel wall is painted to identify the cracks, is too much detail for lost accurate image registration?
- What effect if the tunnel is changed, say with extra instrumentation?
- Or water appears on the surface?
- Can DIC work in problematic conditions, like water on surface or fog etc. so at least a quality of the measurement is reported?
- How many pixels per mm are really needed for sufficient crack opening detection?
- If images are captured that overlap can large panoramas be constructed that will that help in accurate positioning?
- Can measurements be made at high speed, are there effects that cause image blurring?

6.4 Radar Methods

6.4.1 Introduction

Radar techniques use the travel time of an electromagnetic wave, in the radio or microwave range, reflected off an object to measure its position. Radio and microwave waves can travel through air and through tunnel construction materials with attenuation and so can be used to measure the shape of a tunnel or to measure internal structure within the tunnel lining, although generally not at the same time.

6.4.2 Variants

Microwave measurements, can be used to measure water content, but this application will be discussed in the section on water detection methods.

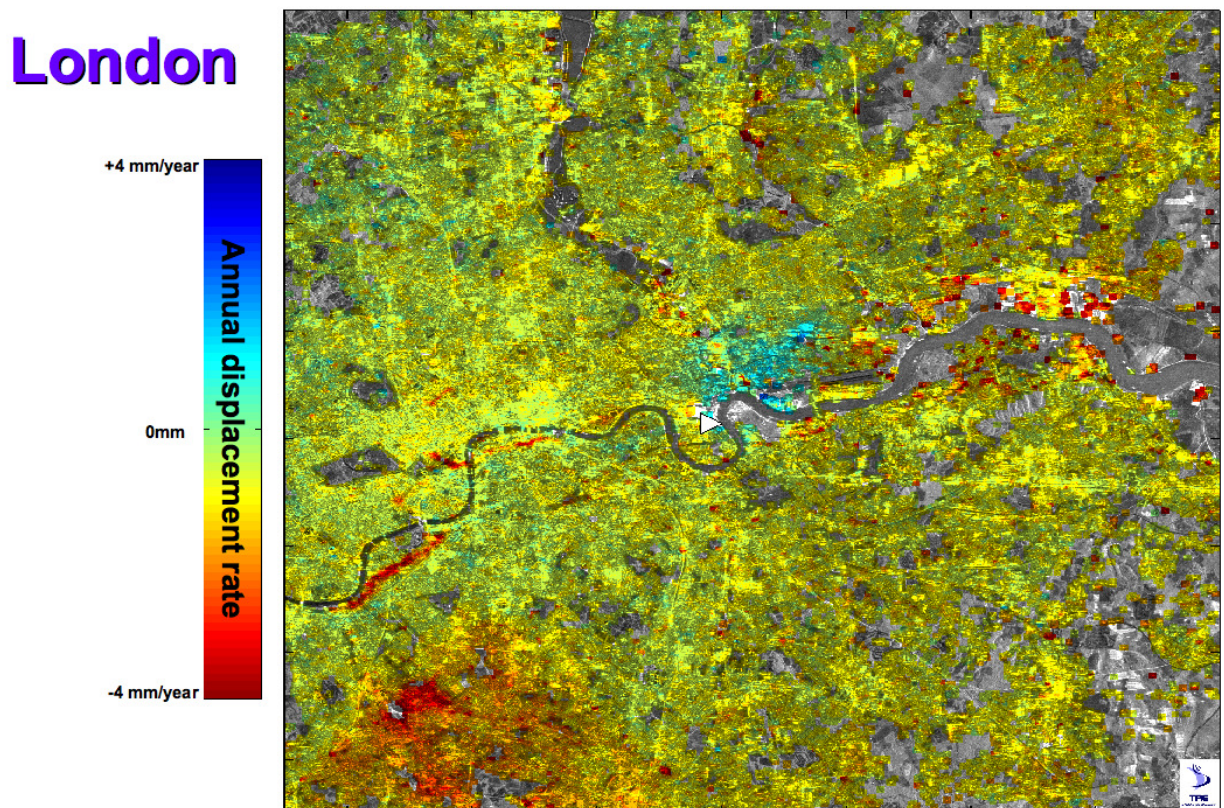


Figure 6. An example of satellite based INSAR measurement from [74]

The two main variants of interest are radar measurements used to make distance measurements in air such as synthetic aperture radar (SAR) and ground penetrating radar (GPR).

SAR has been used for satellite measurements of terrain [31, 71] and also for the monitoring of medium resolution movements of urban developments. For satellite measurements SAR can achieve 1-2 metre height resolution, and using phase measurements a few cm resolution for lateral motion, like glacier movement. When aircraft mounted then SAR resolutions of 10 cm are possible [32], whilst if interferometric techniques are used (INSAR) then very high resolution measurements

may be made, on objects like dams, with typically 1mm resolution at ranges of 100's metres with pixel sizes 30x30 cm [23, 72-74].

Ground penetrating radar is a well-developed technique that has been used in many different applications where information about subsurface structure is required and there are no metal or conducting layers acting as screens. Examples are in archaeology and historical conservation [75, 76], but also in locating underground assets like pipes and tanks [77].

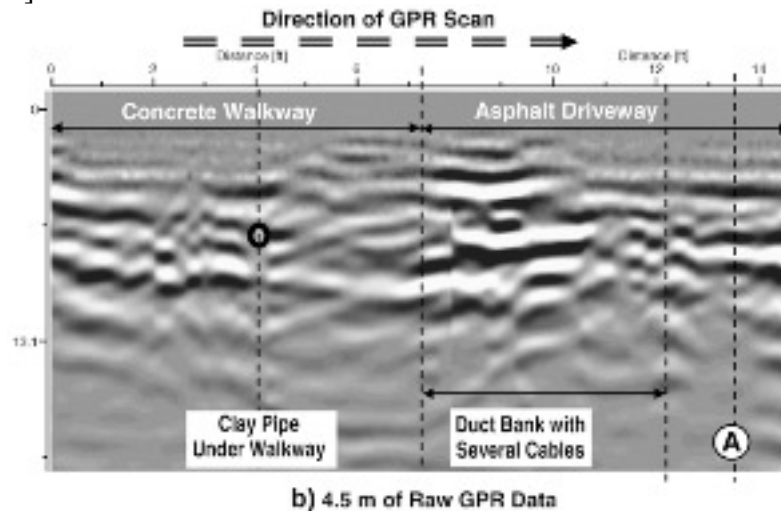


Figure 7. A typical GPR scan from [77].

GPR has been used for the examination of concrete structures like, for example, bridges [17] and tunnels [29] and considerable research has been made into the resolution and detectability of various surface and sub-surface defects.

GPR with laterally separated emitters and detectors have been used to measure the extent of cracks in concrete using frequencies of 1 GHz. [78]. This technique can measure large cracks that are deeper than 10 cm and are 0.2-4mm in width.

GPR can also be used to detect cracks parallel to the surface such as delaminations and ring separation in laboratory tests of concrete linings, where GPR with a frequency of 1.4 GHz can detect various defects down to 0.2m in depth and with a depth resolution of 2 mm [79]. Other studies have indicated detectability of defects at 0.5 m. However the interpretation of GPR data can be quite difficult as internal reflections between defect, front surface and back surface of tunnel lining can occur. Additionally the radar signals can travel through an air-filled voids and produce reflected signals from behind the void further complicating interpretation.

For materials more pertinent to this study such as brickwork and masonry little work has been done, however [80] describes how GPR was applied to the NDT of brick masonry arches in the laboratory. From the experiments undertaken the scattering coming from the inconsistency of the mortar that bonds the rings, as well as from the inhomogeneity of the brick blocks can be misleading when interpreting the data. Although hairline cracks cannot be detected, significant mortar loss between the masonry arch rings could be detected. This work was sponsored by Brian Bell, Network Rail.

6.4.3 Current state of development

INSAR is a research tool at the moment and is mainly used with satellite-based instrumentation. The availability of portable devices is limited but there have been some examples of its use in the railway infrastructure [74].

GPR is a well-developed technique and works well when the materials and wavelength combination means the sub-surface medium appears homogeneous. For common civil engineering structures, particularly those made of reinforced concrete then various comparisons have been made between different sub-surface defect detection techniques, including for the UK Highways Agency [81-84]. These conclude that GPR is a good investigative tool for both concrete and masonry buildings and bridge.

The shallowest detectable defect using GPR is at a depth of $1/3$ of a wavelength and the best practical resolution of half a wavelength, and GPR measurements can be made at 30 metres per second.

Impact echo (to be discussed in a later section) was as good as GPR but much slower. Thermography was generally for shallow depths only. GPR can detect delamination and voids, but not cracks.

6.4.4 Commercial Availability

There are commercial INSAR solution providers who have developed the IBIS system [72]. This can be used in a 1D model where it makes measurements from a reflector or in a 2D mode, but the pixel size is quite large.

There are many commercial GPR solutions including StructureScan™ Professional [85], which safely locates embedments within concrete structures prior to drilling, cutting or coring up to a depth of 50 cm. Also BridgeScan™ [86] is a GPR system that provides a tool for quickly determining the condition of aging bridge decks, parking structures, balconies and other concrete structures. Subscan Technology Ltd. [87] offers a wide range of services aimed at the detection and avoidance of underground utilities.

GPR is also used to detect the depth and quality of the ballast underneath rail track whilst a train is moving at up to 300 km/h with a depth resolution of 5cm and a scan every 60 cm [88].

6.4.5 Limitations

GPR techniques are quite well developed for looking at reinforced concrete but are more problematic for brickwork although some work has been done [80].

6.4.6 Accuracy

For reasonable depths of concrete up to 50 cm then quite small defects might be visible. For brickwork interpretation issues limit the detectability of ring arch separation, although imaging up to 350 mm into the arch is possible.

6.4.7 Time to make measurement

Where practical use has been made in tunnel examination, it appears that close contact is required between the sensor head and the concrete [29]; during inspection of a bridge deck [83] this could be done at high speed because of the simple shape of the structure being scanned. It is expected that high-speed tunnel examination will only be possible if the tunnel is a simple shape. In normal situations GPR may be quite slow as the system must servo the sensor close to the tunnel wall, this could be problematic if there are loose bricks, outcrops or instrumentation.

6.4.8 Issues to be resolved in feasibility trials

- Can GPR be used with sufficient stand-off?
- Can GPR be used to detect delamination in brickwork, [78] is not clear.
- How is GPR data interpreted or can the changes between subsequent scans be used?

6.5 Thermography

6.5.1 Introduction

Thermography is a potential technique for determining sub-surface structure due to the different effects it has on thermal conduction and hence surface temperature. Various ways of introducing the heat into the surface are used, but all rely on a transient heating which causes a transient temperature profile on the surface of the specimen. This is usually measured with an IR thermal camera.

The transient heating can be caused by the appearance of sunlight in the morning, which causes a façade on a building to heat up at different rates depending on its moisture content and the presence or absence of voids below the surface (at up to 5 mm depth) [89]. It has also been used for detecting plastic landmines in sand soils by measuring the surface distribution of temperatures shortly after sunrise [90].

6.5.2 Variants

The main variation in the types of thermography are due to the way the heat pulse is applied to the surface. In the examination of tunnels the heating will need to be provided by high power heat lamps either continuously or in a flash mode. Alternatively high-powered microwaves can be used to warm the surface quickly.

6.5.3 Current state of development

As a way of improving signal to noise levels a lock-in technique can be used where a sinusoidal variation in surface heating is applied and the thermography measurements made over a period of time and locked-in to this frequency [18]. Although this may give improved sensitivity it will need measurement times in minutes to hours for only a few cm's penetration.

6.5.4 Commercial Availability

For concrete lined tunnels that are essentially dry and unblemished then thermography is a viable way of detecting damage and moisture ingress. For these applications there are several commercial systems including a system for investigating spillways [24] in combination with image analysis techniques. For tunnels Mitsubishi have developed a train for tunnel examination [91, 92] that uses a combination of thermography and image analysis to detect delaminations at 1 cm deep and 1 mm width cracks, whilst moving at 0.3 metres per second.

In the Paris Metro a similar train has been developed that can travel at up to 1.5 metres per second and combines an optical measurement with laser illumination, and claims a 0.2mm crack width resolution. It uses an IR thermal camera for water ingress measurement [93].

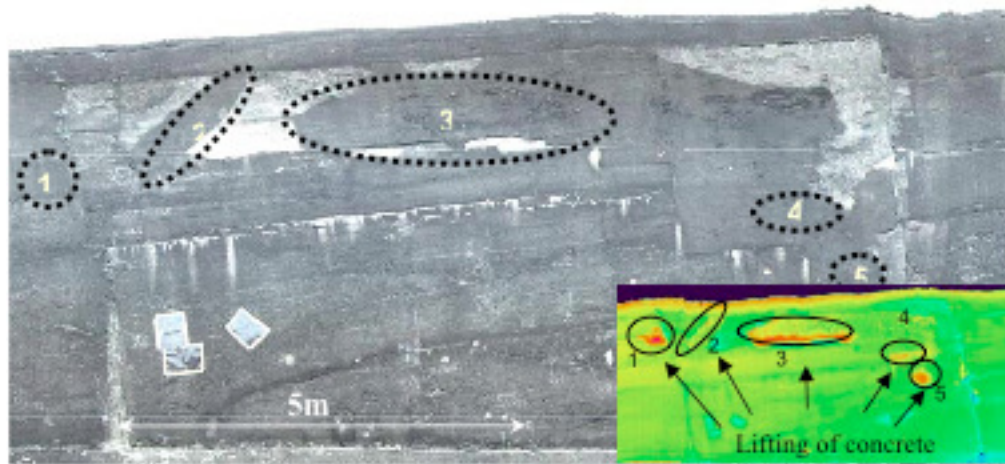


Figure 8. Output from a combined optical and thermography scan (inset) from [24].

6.5.5 Limitations

Liquid flows will mask any thermographic effects and stop any local heating of the surface.

6.5.6 Accuracy

The accuracy is a function of the time for measurement and for the amount of power that can be introduced into the surface. The inhomogeneous surface of a masonry or brick lined tunnel will make the interpretation very difficult. The measurement is more likely to be a measure of moisture content of the brickwork rather than delamination.

6.5.7 Time to make measurement

Even in perfect conditions the technique is limited to shallow depths [82] if reasonably fast measurements are needed.

6.5.8 Issues to be resolved in feasibility trials

- Will it work for brick delamination, and to what depth?
- Can it work with wet surfaces?
- Does it measure saturation of brick work?
- How long does it take to make a measurement?
- Interpretation?

6.6 Water detection

6.6.1 Introduction

Water has a major part to play in tunnel integrity. Often cracking, deformation of the tunnel shape and delamination/ring cracking can be due to varying amounts of water present in a tunnel. The techniques that are required for investigating tunnels vary widely according to the type of tunnel and the amount of water that is present. For concrete lined new tunnels with few cracks then the interior of the tunnel may be completely dry, if this status is to be maintained then examination of the tunnel walls using technique for detecting cracks such as DIC or for detecting local slight water ingress like thermography can be quite effective in determining area which may be damp as opposed to completely dry.

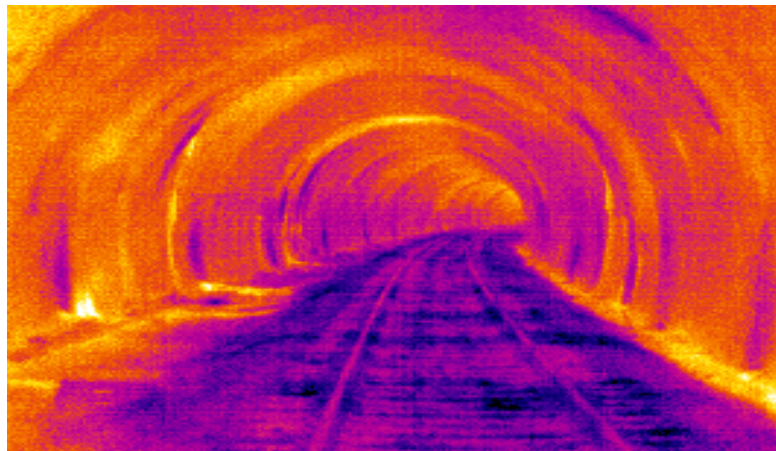


Figure 9. A thermal camera image of a tunnel interior, the colours correspond to temperatures and are strongly influenced by water content on the tunnel lining.



Figure 10. Damp and wet patches, low water ingress



Figure 11. An example of medium water ingress.

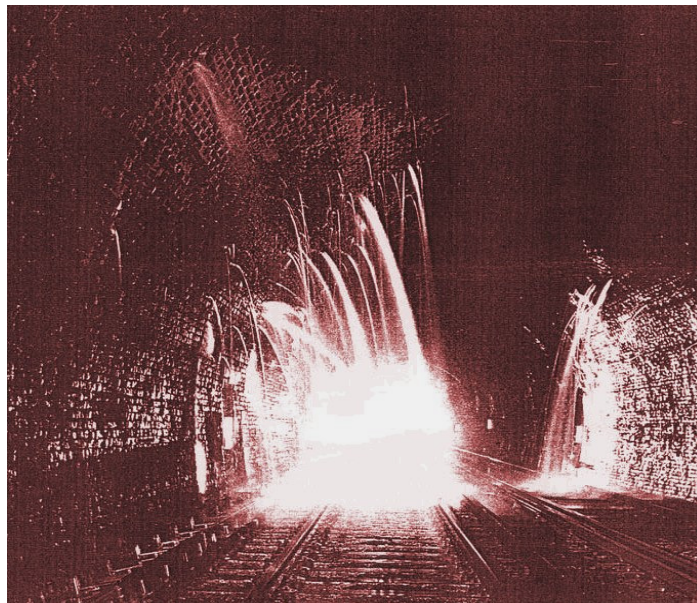


Figure 12. An example of severe water ingress.

In more realistic scenarios like Holme tunnel or the examples shown in Figures 10, 11 and 12 where progressively more and more water is present then a different approach will be needed.

6.6.2 Variants

To deal with the different levels of water ingress then a multi-sensor approach will almost certainly be needed.

To measure the extent of dampness in an otherwise dry structure then eddy currents can be used to measure the change in conductivity within the tunnel wall, by using long

aerials then substantial depth measurements can be made [94]. There are other techniques for identifying water in otherwise dry structures using other electromagnetic techniques [95] and spectroscopic techniques [96]. However the dryness of the structure required for these techniques will be found infrequently in most NR rail tunnels.

To measure dampness within the tunnel lining with no surface evidence of water then systems using absorption of microwaves using GPR is probably the most likely technique to be successful [97, 98] and have shown promise in identifying underground leaks,

If the bricks are partially to fully saturated then GPR can still be used [99] to assess the water and salt content.

If there is water evident on the surface of otherwise dry surfaces then spectroscopic [96] or photographic techniques can be used where the change in appearance is attributable to moisture.

As the water ingress approaches that shown in Figure 11, then it becomes problematic how to measure this unless a photographic technique is used. Any shape measurement using optics might be confused by the transparency of the water stream.

For the amount of water evident in Figure 12 then a sound recording method may be of use.

6.6.3 Current state of development

Each individual technique is reasonably well developed for the different types of water ingress, but the combination of techniques is an area for research.

A humidity sensor array attached to a scheduled train may be a cost effective way to make a qualitative assessment of the tunnel state and would provide a rapidly deployable low-cost system, if the technique does show suitable discrimination.

6.6.4 Commercial Availability

The MoistureVision [95] and the spectroscopic technique [96] are commercially available, as is GPR equipment, photographic and sound recording equipment.

6.6.5 Limitations

The wide range of potential water ingress rates makes this a very difficult measurement to make.

6.6.6 Accuracy

The accuracy is difficult to assess but it is likely that this type of measurement will be semi-qualitative.

6.6.7 Time to make measurement

All these measurements can be made quite quickly and it is anticipated that measurements at many metres per second would be possible. At high speeds the acoustic recordings might be overloaded with noise from the instrument platform.

6.6.8 Issues to be resolved in feasibility trials

- Do the appropriate techniques work in typical tunnel conditions?
- Is there sufficient overlap between techniques?
- Can the measurements be made less qualitative?
- Could a humidity sensor array be a simple low-cost alternative and be easily mounted to a vehicle?

6.7 Acoustic Methods

6.7.1 Introduction

Acoustic methods for investigating the health of tunnels are largely confined to being used to examine sub-surface defects in the tunnel lining, in particular delamination or ring separation.

Acoustic techniques are well known in NDT applications where c-scan [19] can be used to image defects deep within a specimen bulk and for very fine scale measurements photo-acoustic excitation can be used to generate sound pulses from high intensity laser light [42], but both of these techniques will be ill-suited to the very inhomogeneous nature of a typical tunnel lining. Even larger scale techniques that used synthetic apertures to help localise pulse-echo measurements are likely to be severely limited by the scattering nature of the many brick/mortar interfaces likely to be present [100].

There are techniques that might be useful to assess the overall integrity of the tunnel as a whole such as generating shock or seismic waves in a tunnel lining and measuring time of flight [101, 102] but these too are likely to be strongly attenuated by the brick/mortar interfaces present, they are also unlikely to give local information about structure.

The two most likely candidates either use a global vibration, with a local measurement of the effect of the vibration, or to introduce local vibration and measure it locally.

Face delamination with bricks, masonry, concrete or stone is likely to be possible and ring separation is only for bricks by definition.

6.7.2 Variants

With acoustic measurements, there is a problem getting energy coupled into the surface without reflection interfering with the measurements, i.e. if sound techniques are used then the echoes will probably make the measurement impossible or very slow. An alternative is to use a vibration source directly coupled to the tunnel structure to make the structure vibrate. Then if a scanning laser Doppler vibrometer is used then the local vibration can be measured at each point. This is likely to be strongly influenced by the local stiffness of the structure and should be very sensitive to delaminations and ring separation. An alternative to a global excitation of the structure might be to use directed sound [103, 104] where arrays of loudspeakers can direct the sound to one small area of the tunnel surface. This technique has been used to detect landmines after the ground has been vibrated using loudspeakers [40].

An alternative is to use impact echo systems perhaps using projectile tapping so there are less problems with echoes, however it is difficult firing enough projectiles and targeting may be difficult. However this would still be more consistent and faster than a human operator and it may be possible to analyse the acoustic signature ideally with an air coupled microphone rather than a rock phone in contact with the tunnel structure. This is a serial measurement and may be difficult to do in parallel; to detect delamination in one brick will need one tap per brick/block with temporal spacing to avoid echoes or cross talk.

6.7.3 Current state of development and Commercial Availability

Vibrometers are well developed for laboratory use but have been used for landmine detection [4] the issue with this technique may be to get sufficient vibrational energy coupled into the tunnel surface, but large track ballast settling vehicles may be suitable for this.

The processing and acoustic signature recognition has been incorporated into a commercial instrument from Golder RMT [105, 106]. The production of suitable projectiles and accurate launching may require considerable robot development. Although a modified paint-ball gun may suffice as a delivery mechanism.



Figure 13. The RNT Acoustic Energy Meter and geophone on-a-pole extension

6.7.4 Limitations

A vibrometer system has sufficient standoff from the tunnel wall to have no issues with clearance. After visiting Holme tunnel it would seem that any sensor that is needed to be close to the surface, i.e. within about 10 cm is unlikely to be very wide applicable. It would seem at least 50 cm stand-off is generally required. Using another method to couple sound into the tunnel wall like a rolling wheel is unlikely to be successful.

However the tunnel walls may not be sufficiently reflective to ensure a large enough reflection for an accurate measurement by the vibrometer.

Both techniques are unlikely to work if the surfaces are not perpendicular to the launch mechanism or vibrometer.

Any projectile delivery device might be too harsh if any other instrumentation is already in position, like tilt meters, crack gauges, or LVDT. The effect of substantial vibrational energy introduced locally or globally may be problematic on those instruments also.

6.7.5 Accuracy

From work carried out by Golder RMT it would seem that accuracy is better for impact echo than GPR. In [81-84] there are comparisons between GPR and impact echo and generally GPR can detect delamination and voids, not cracks and Impact echo is better for measuring lining thickness and defects.

However the huge increase in tunnel coverage over that practically achievable using human operators may improve the accuracy as local effects may be more clearly defined leading to a better understanding of the internal sub-surface defects.

6.7.6 Time to make measurement

A vibrometer can be used in a scanning mode and might make measurements of 1m x 1m per second in good conditions and at useful measurement spacings. It is unlikely that impact echo will be able to work as fast as this but it will still be much faster and more consistent than human operators.

6.7.7 Issues to be resolved in feasibility trials

- Can sufficient vibrational energy be introduced into the tunnel wall from a rail mounted "shaker" or track tamper for a vibrometer to be able to make a measurement?
- Are the tunnel walls reflective enough or would reflectors/markers need to be introduced?
- Can impact echo measurements be made using microphones rather than geophones
- Can suitable projectiles be used to produce large enough signals for impact echo measurements
- Is a tethered re-usable projectile more suitable for this task?

6.8 Techniques rejected as being unsuitable

Several techniques have been identified during the literature review and sectors survey that initially appeared to be promising for this tunnel examination application but have been rejected for various reasons.

Point sensors [1, 2, 52] have been rejected as the high infrastructural cost of mounting them within the tunnel means they are unlikely to be suitable, however variants where sensors are mounted on scheduled trains may be useful and were identified in the water detection chapter.

For sub-surface measurement ultrasonic and c-scan techniques have been identified [3] [19, 26] for concrete lined tunnels, however for the inhomogeneous tunnel lining it is unlikely to be useful as the signal attenuation may be too high.

There are several alternative techniques for measuring shape; Photogrammetry has sufficient accuracy but will require a large number of targets fixed to the tunnel wall, which will add to the cost of deployment and may mask other defects to be measured [107]. Ultrasonic rangefinders could be used instead of laser rangefinders, [108], but are relatively inaccurate and likely to be strongly affected by humidity fluctuations and the speed of sound is influenced by the humidity levels. ESPI also can be used to measure shape and displacements, but is very susceptible to vibration [43].

Crack identification has been investigated many times using optical imaging techniques [11, 24, 27, 30]. However the much more complex images that result from brickwork and masonry rather than smooth concrete mean this is quite hard to do. Digital video records have been made [109] which can provide images for image analysis [110, 111], but more promisingly linescan cameras mounted on anti-vibration devices [112-114] have been successfully used. These techniques can achieve crack resolutions of 2-5mm widths [115] or even sub-mm at 8 metres per second tunnel travel speed [116] but all these measurements have been made on smooth even concrete tunnel linings and are unlikely to be useful for brick or masonry-lined tunnels.

7 Positional and orientation requirements

There are similar positioning and alignment requirements for all sensors and measurement techniques since the main aim of this programme is to provide data sets that can be compared to previously made data sets. To do this in a fashion that will yield useful information about any potential changes means that the measurement must be taken in the same place on the tunnel surface for each measurement run. If the position is referenced from some trackside marker and measured along the length of the rails then the orientation of the sensor to the vehicle and hence the tunnel surface must be known so that the actual position on the surface can be calculated.

Measurements in tunnels using diverse vehicles such as ROV's [117] and semi-submersible sensor platforms [118] have been successfully deployed. High-resolution measurements have been made to sub-mm accuracy [116] using rail-mounted vehicles although custom electric options have also been explored [119]. A reliable accurate

platform will almost certainly not be a road/rail vehicle, but something like the Network Rail multi-purpose vehicle (MPV).

To make repeated measurements needs accurate positioning/repositioning to allow subsequent measurements to be accurately indexed. These can be supplemented by track measurements, like baseline and reference points. Instruments like a total station can be used to check the position of the measurement platform to help with uncertainties with measurement, probably to a few mm. Additional infrastructure, like targets on the tunnel surface, may help, but precision movement down tunnel along the track may be straightforward using laser range finding and servo alignment of the sensor platform [120], if the rails haven't moved too much.

Steadiness and vibration levels of the measurement vehicle could limit the vehicle speed and hence measurement speed, and may be mitigated by an anti-vibration device [112-114] or a gyro stabilised Steadicam device [121] to ensure orientation stability.

Many of these question can only be answered by trialling some solutions. Using DIC as an example, an independent assessment of the orientation and reproducibility of the measurement can be made by comparing this stitched images from multiple measurement passes in a typical tunnel scenario. It is likely that orientation control will be the main issue, if the track is not fixed in position in x, y, and z.

In these trial systems tight control will be needed between the movement of the vehicle and capture of data perhaps using a servo controlled stages with error signal from a quadrant detector and a laser line (for alignment); if the vehicle moves slowly enough perhaps with rubber rimmed wheels then vibration may not be a problem.

Obviously for a full system than any additional infrastructure that is needed for alignment of the sensors must not impede normal rail operations and should require minimal special setting up prior to a tunnel survey.

7.1 Issues to be resolved in feasibility trials

- Does the track really move that much, how could this be investigated?
- On a MPV how accurate is alignment and can vibration be minimized?
- Is it best that repeated measurements are done in same direction to help minimise instrumentation orientation errors?
- Can DIC or image stitching provide a good enough position on the tunnel wall to be used for most positional/orientation requirements?
- Will tunnel surface mounted targets help alignment?
- Can specific anti-vibration and Steadicam mounts help with alignment and sensor stability?

8. Software techniques for the high speed evaluation of data

8.1 Scope

The scope of this work was to develop a software requirement specification developed from the recommendations of techniques needed for WP1 and WP2. This needed an understanding of the requirements for data input and output, and a review of the current Network Rail decision algorithm being developed for manual tunnel condition surveying. Using this information available software has been reviewed and assessed for its applicability to this programme of work.

8.2 Data sources for investigation

To get familiarity with the challenges posed by processing tunnel examination data several trial datasets were obtained. These data sets were generated using laser scanning systems and were from Tytherington, Wivelscombe and Ffestiniog Tunnels. The two tunnels were scanned using different measurement setups.

8.2.1 Omnicom datasets

Omnicom Engineering [122] supplied datasets from laser scans carried out in the Tytherington and Wivelscombe Tunnels. These were quite large datasets with each scan typically about 2GBytes in size for a tunnel of about 300 metres.

The shape of the scan using this measurement technique is in the form of a spiral, like a corkscrew or "Slinky" with the axis of the spring down the length of the tunnel. The scan was made with an approximate step size of 2 mm in the circumferential direction, equivalent to an angular step of 0.05° , and 2cm along the tunnel length for each turn.



Figure 14. The measurement equipment used to make the Omnicom measurements.

Image from http://omnieng.co.uk/uploads/RTEmagicC_landrover_02.jpg.jpg

The scans were made in different directions but the scan spiral path was the same with the order of the data points reversed. The laser scanning equipment was a standard Z+F laser scanner that was mounted on the front of a road/rail vehicle, Figure 14. An inertial measurement system was used in conjunction with a rail-mounted odometer to measure the position within the tunnel.

The raw data was processed so it could be used with OmniSurveyor 3D.

8.2.2 ScanTech dataset

The ScanTech data [123] was collected in the Ffestiniog Tunnel. This was done using a fixed Leica HDS 3000 scanner (similar to the Z+F scanner used by Omnicom). For each fixed position a point cloud was generated by allowing the scanner to make a full spherical scan. Targets were used ahead and behind the scanner along the rail to allow registration of subsequent scans. By keeping the forward targets fixed and moving the scanner past them, they then became the rear targets and allowed each dataset to be accurately aligned.

Between each fixed position the scanner was moved by about 15 metres and it took about 3.5 minutes to make a full scan, with about 90 seconds to move the scanner. This results in a measurement speed of about 13 hours for 3500 metres, the length of the Ffestiniog Tunnel. The total data file size for these measurements was about 8Gbytes.

Considerable semi-manual processing was then required by ScanTech to align and stitch the point cloud data sets together to measure the whole tunnel. Pointools software was used to visualise the 3D dataset, this is a commercial package used in architectural surveying. Additionally the intensity information was used to generate equi-rectangular panoramas that could then be rotated to give an interactive 3D view.

8.3 Analysis software packages

Various different software packages were investigated to determine their suitability for use in processing and visualising the datasets. Additionally they were investigated to see if they were able to align and then show the differences between subsequent datasets.

The software packages included proprietary software packages used for surveying and open source solutions for manipulating structured and unstructured data, like meshes. Other software investigated included general-purpose visualisation packages, civil engineering design tools and custom programming software written in Java developed at NPL. This was generally used to reformat, align, subtract and unroll datasets.

8.3.1 Omnisurveyor 3D

This is a software system from Omnicom Engineering that uses the laser scan data to allow track gauging to take place. The system allows the user to scroll through the data along the length of the scan and to carry out various gauging tasks at different points. For the purposes of this work the system was used to output the point scan data in the form of a binary DXF file. This file contained the coordinates of the point scan data referenced to the Omnisurveyor internal data coordinate system that has been aligned with the track. An example of the operation of the system is shown in Figure 15.

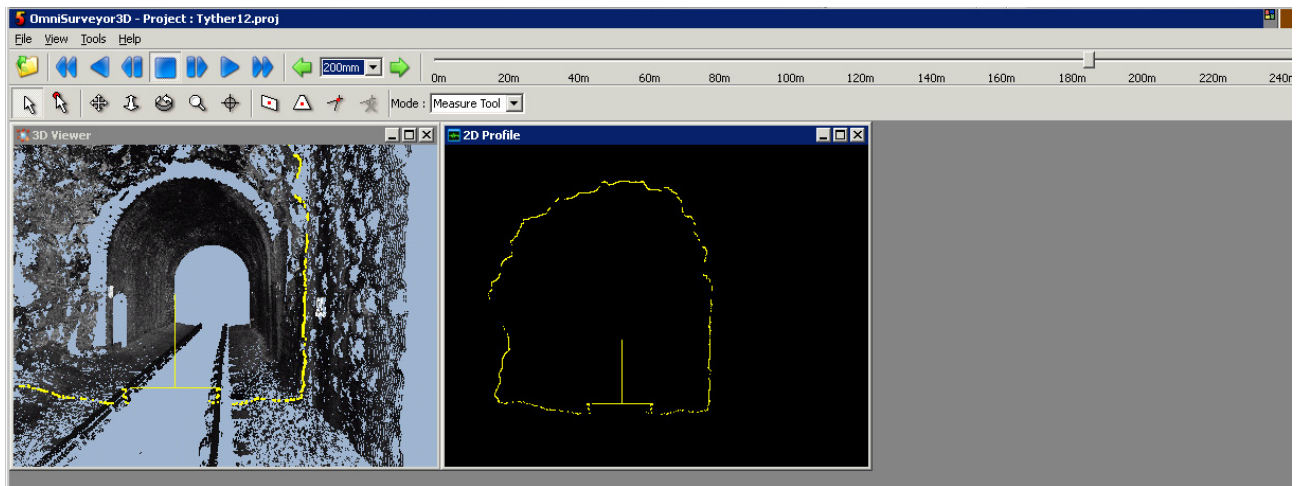


Figure 15. A screenshot from Omnisurveyor 3D showing a 2D slice from the Tytherington Tunnel (Tyther12) dataset.

8.3.2 Pointools

The ScanTech data sets were processed using Pointools [124] a general-purpose system for manipulation of point cloud data. This system allows export of point cloud coordinate data in DXF format. This software costs £900-£2500 per seat. A screenshot showing the system in operation can be seen in Figure 16.

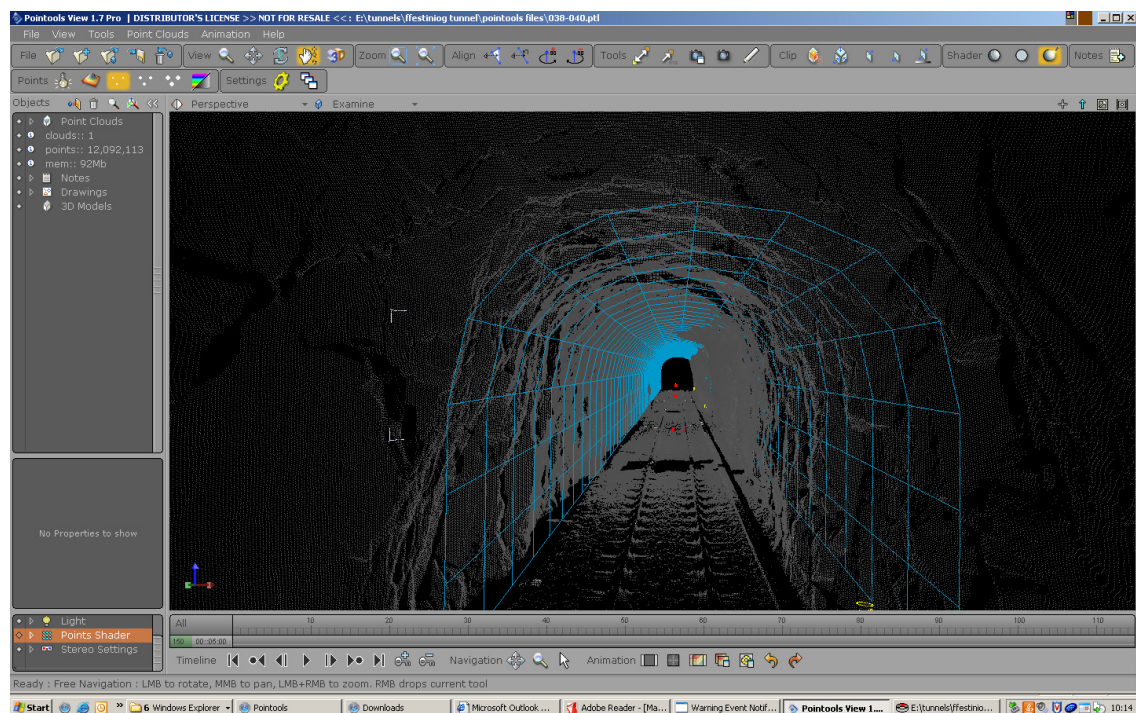


Figure 16. An example of the Pointools system, displaying the data set from ScanTech of the Ffestiniog Tunnel.

8.3.3 Panini/FSPviewer

An additional form of output generated from ScanTech survey data is in the form of 360° images that can be viewed with special viewers. Viewers such as Panini [125] and FPSViewer [126] are capable of dealing with very high resolution panoramic images



Figure 17. An equi-rectangular panorama produced by ScanTech and rendered using Panini, showing a forward view of the Ffestiniog Tunnel. The targets used for aligning each stationary scan can be clearly seen.



Figure 18. The rearward view corresponding to Figure 17.

and allow equi-rectangular views that can be interactively scrolled around and zoomed including viewing of the ceiling of the tunnel and the measurement equipment that hasn't been shielded by the imaging components. An example is shown in Figure 17, in this image the forward targets can clearly be seen, and in Figure 18 the rearward targets can be seen. These are the targets used to align each stationary scan with neighbouring scans.

8.3.4 Paraview

Paraview is an open source general purpose visualisation system primarily designed to image structured and unstructured meshes [127]. ParaView was developed to analyse extremely large datasets using distributed memory computing resources. It can be run on supercomputers to analyse very large datasets as well as on laptops for smaller data and was developed by various large national laboratories in the US.

It was used to visualise the point cloud data exported from Omnisurveyor 3D or Pointools and then processed using the NPL developed tools to generate a simple unstructured mesh to aid visualisation and post processing, Figure 19.

The system is very comprehensive and allows easy manipulation of 3D data and is currently the visualisation tool of choice for this project and is quite stable, although it is not very tolerant of mistakes in the formatting of its input data files.

Paraview is available on many different computing platforms.

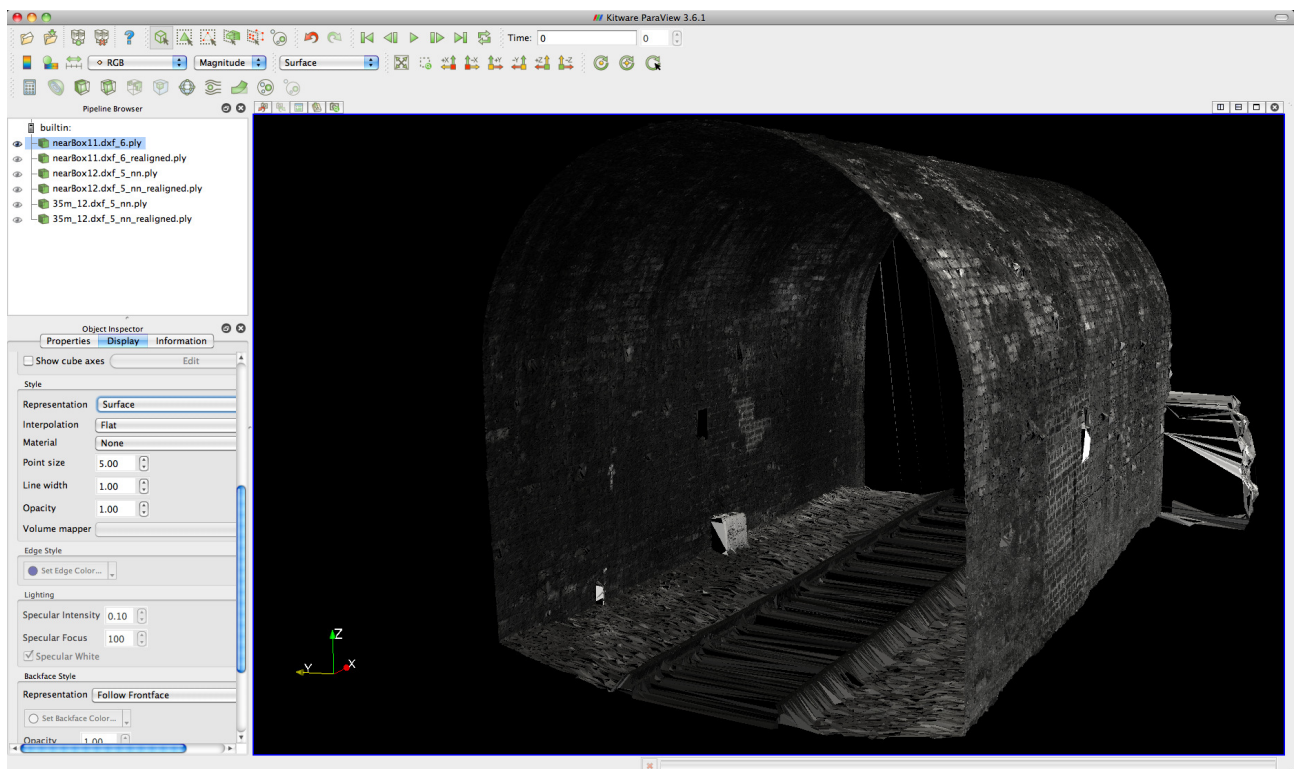


Figure 19. Omnicom data exported to Paraview after NPL software pre-processing. Many datasets can be loaded simultaneously and quickly displayed or overlaid to allow easy comparison.

8.3.4 Meshlab

Meshlab [128] is an open source, portable, and extensible system for the processing and editing of unstructured 3D triangular meshes. The system is designed to help in the processing of the typical not-so-small unstructured models arising in 3D scanning, providing a set of tools for editing, cleaning, healing, inspecting, rendering and converting these kind of meshes, Figure 20. The system is heavily based on the VCG library developed at the Visual Computing Lab of ISTI - CNR. It has many additional functions that allow reduction in size, smoothing of meshes, removal of holes and defects etc.

However it was found to be very unstable and even for small sections of tunnel data seemed to be unable to process meshes using any of the useful tools without crashing.

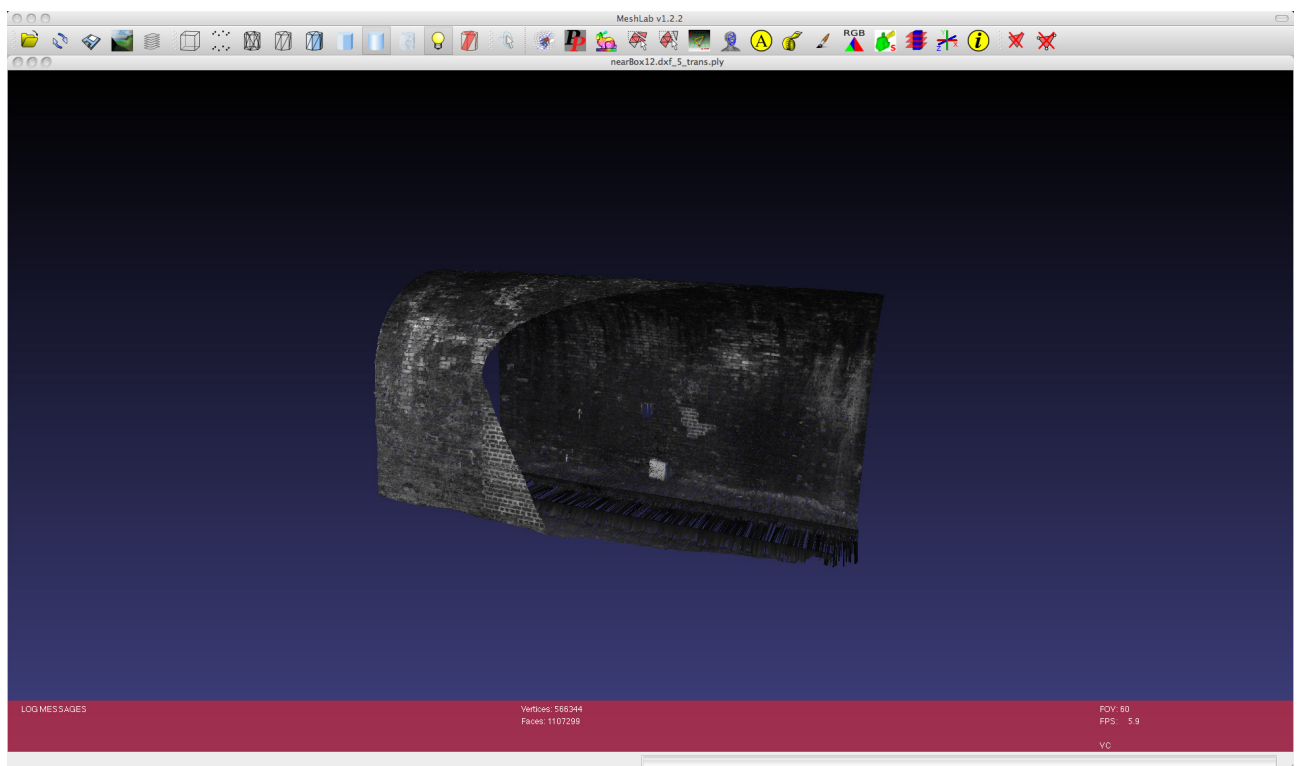


Figure 20. Omnicom data imported into Meshlab, the data has been clipped with a plane close to the eyepoint.

8.3.5 Avizo

Avizo is a commercial visualisation system [129] based on the Open Inventor visualisation toolkit and is very similar to the SGI (now NAG) Explorer data visualisation system. It has many of the features of Meshlab and Paraview combined, including mesh compression, mesh smoothing and mesh alignment. Although the mesh manipulation processes seems to be a very slow and could only be successfully carried out with very reduced size meshes.

The Avizo package is very comprehensive and comes in different flavours which have different tools depending on the expected use of the software. More research is needed to establish the full uses of this software for this task, but initial investigations indicates that most of the required functionality is present.

The system has very many functions and is extensible to allow user sub-routines to be added. The software company indicates that there is scope for consultancy to develop custom modules for specific algorithms that may be developed for this project. The system has been used in process control and can be configured to automatically process new data that is loaded into a database as it becomes available.

There is an additional module that can be used to allow custom filters to be developed to read in data formats that are not currently readable, but the simple PLY format used as an intermediary by the NPL meshing tools can be read in successfully, Figure 21. The rough surface near the crown of the tunnel to the right of Figure 21 is caused by the inability of the laser scanning to image re-entrant facets or shadowed facets of rough stonework present here.

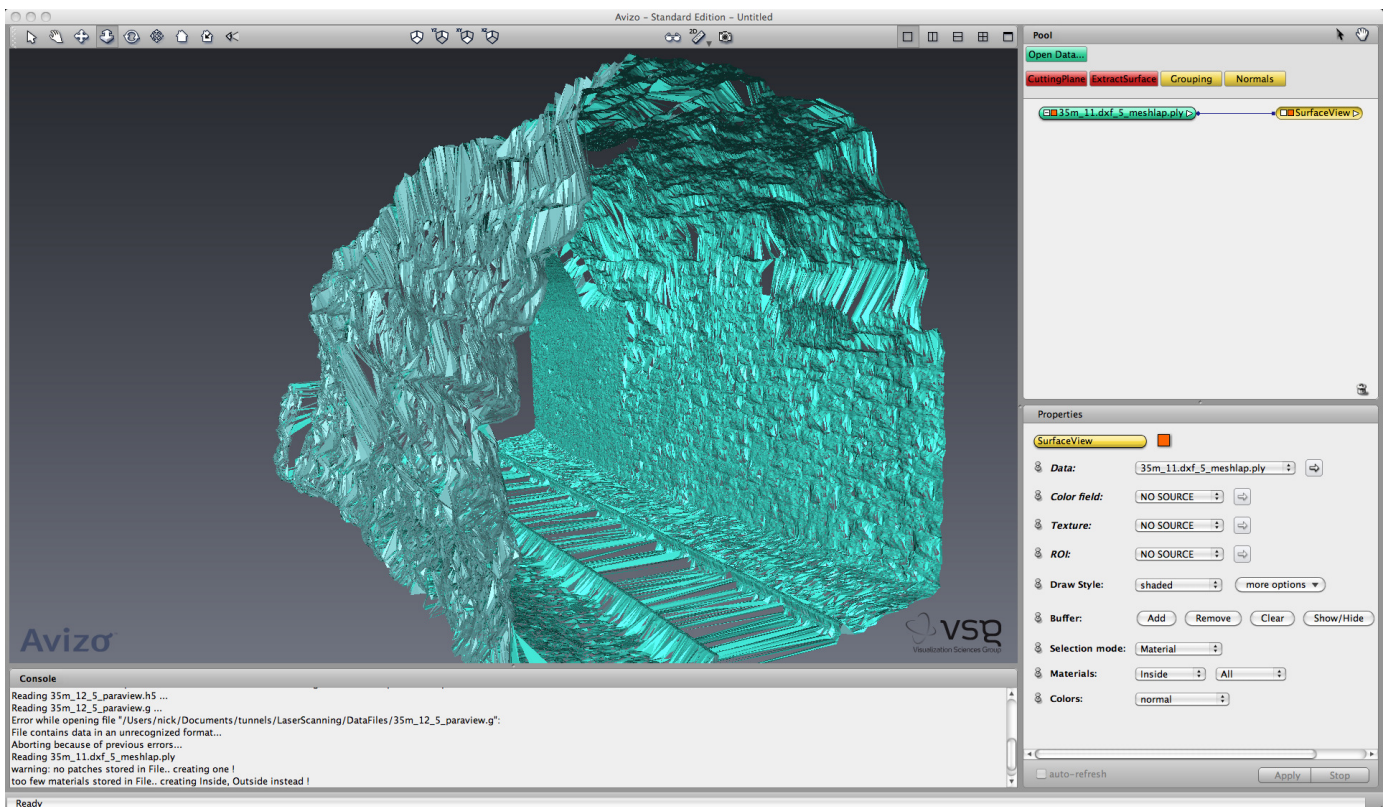


Figure 21. Data from the Tytherington Tunnel taken at 35 metres down the tunnel where it changes from lined to unlined, visualised using Avizo. The transition from brickwork to block work and to unlined tunnel crown can be clearly seen to the right of the image.

8.3.6 MicroStation and TerraSolids plug-ins

MicroStation[130] is a civil engineering design tool that can allow team collaboration for design and infrastructural surveying of typical civil engineering projects. It is heavily biased towards large projects and allows geographical data, CAD data and survey data to be combined. With the addition of the TerraSolids plugins [131] it is possible to add airborne LIDAR data and laser scan data to the system. The TerraSolids suite of programs has additional features including alignment and image rectification [132] that might be useful for tunnel examination. The main use for these modules is airborne mapping and some considerable effort might be needed to express the requirements for tunnel work in this context. However this would give a complete integration between CAD, survey and maintenance operations in one package plus plug-ins. It seems more biased towards display than calculation, but further more extensive research is really needed.

8.3.7 Java tools

To aid the translation of data from the Omnicom datasets to a form that could be visualised in the visualisation systems meant converting the point cloud data, which was exported as a binary DXF file containing point coordinates and colours, into an unstructured mesh that could be more readily visualised.

The NPL Java software loaded in a DXF file and reduced it in size by a factor in the circumferentially direction so that when a mesh was generated it had a more equal size in the x direction and radial direction, i.e. using every fifth data point means the generated mesh would be about 1cm by 2 cm. The software generated a triangular mesh by using two consecutive points and then looked for the closest point in the next part of the spiral using a kd-tree algorithm [133]. Preliminary work assumed a constant number of points that were needed per revolution, and so the nearest point was found on the next revolution of the spiral. However this was found to change too rapidly and unpredictably to work successfully as the number of points per revolution changed during the scan.

Once the mesh was generated it could be visualised as previously shown in the figures above. Subsequent analysis then included unrolling of the mesh to produce a flat map of the interior of the tunnel. In addition a technique was developed using an iterative closest point algorithm [134] to allow data sets to be aligned globally. This could then output the geometry with the original measured intensity replaced by a measure of the distance to the nearest closest point to help identify differences in shape.

8.4 Visualisation

The visualisation of the data is a vital part of the whole work programme and is essential to help identify the data output from the techniques for characterising the differences between subsequent data scans. Even when a system has been developed that automatically searches data sets for significant differences visualisation tools will still be needed to report the position of anomalous readings and to allow "drilling down" of the data sets to identify whether the anomalies are; real and important, real and caused by a easily identified but unimportant change (like a bird roosting) or caused by a measurement issue.

The data visualisation can be either done using a 3D or 2D technique. Each technique has its merits and probably a combination of both would be needed for full understanding of the data.

8.4.1 3D representation of tunnel data sets

A 3D visualisation is the most realistic way of presenting the data from a tunnel scanning measurement system. In these systems where only surface data is measured then the mesh produced shows the surface. However it has to be remembered that the exterior of this mesh surface is an artefact and wouldn't be seen in a real tunnel examination, Figure 22, only the interior surface would be seen. However it is found that if this feature is turned off during visualisation then it is harder to appreciate the structure.

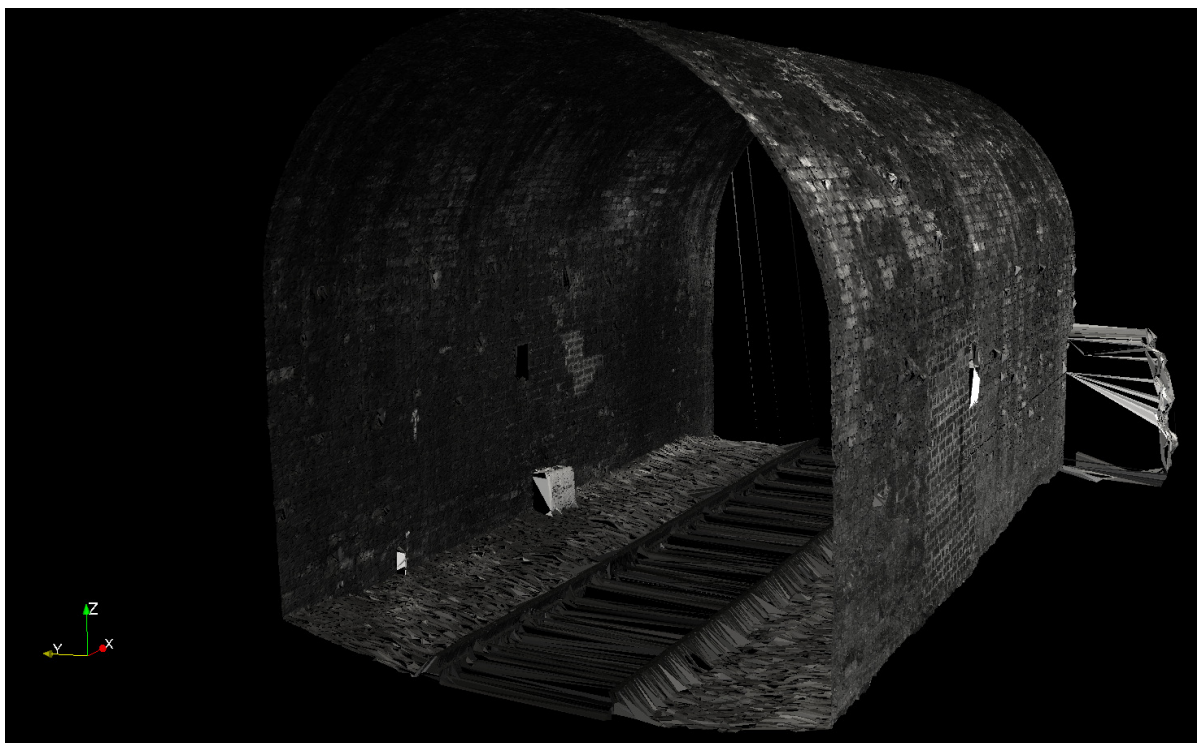


Figure 22. A 3D view of the laser scan data from Omnicom, meshed using NPL Java tools, visualised using Paraview, from Tytherington Tunnel dataset.

In Figure 22 extra lines can be seen, to the right of the picture, that are artefacts caused by the NPL meshing technique and are a side effect of the different number of points per revolution measured with the laser scanner. There are also small triangular holes in the mesh caused by this effect and as a by-product of a global thresholding that removes triangles that are longer than a pre-set length. This removes laser scan measurement noise where some points appear to be much further away because of multiple reflections. If the reflected signal from the laser scanner is very weak then there will be a missing data point also, which could lead to a missing triangular mesh element.

Figure 23 shows another part of Tytherington Tunnel and it can be seen that mapping the measured intensity of each scanned spot onto the mesh adds visual cues to the image compared to Figure 21 where only the shape is shown. There are similar artefacts to those in Figure 22 to the mid right of the image on the tunnel wall. Here the glancing

incidence of the laser scan to the facet rock face means the point cloud density is very low leading to the artificial appearance. The visualisation systems allow the data sets to be zoomed in, shifted and rotated to allow the user to interact with the data set and to make it easier to gain insight from the data.

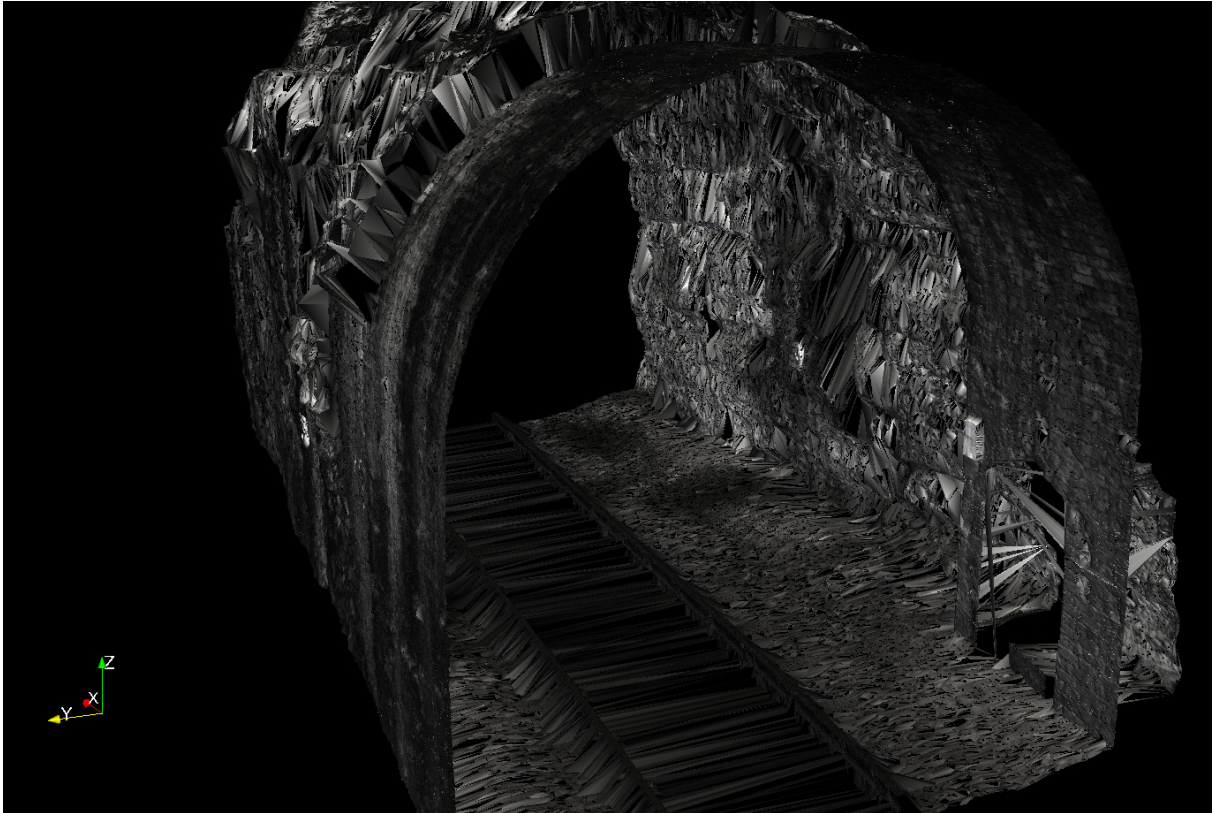


Figure 23. A 3D view of the laser scan data from Omnicom, meshed using NPL Java tools, visualised using Paraview, from Tytherington Tunnel dataset

Another example is shown in Figure 24, here just point data is shown as there is no mesh and it can be seen that it is much harder to make out the shape of the tunnel wall.



Figure 24. ScanTech point cloud data processed with Pointools of the Ffestiniog Tunnel.

8.4.2 2D Image representation of tunnel data sets

To try and replicate the current manual tunnel defect measurement practice then an unrolled tunnel is most useful. Also by unrolling the 3D data to produce a 2D surface the data can be easily archived and analysed using image based techniques, which may be more computer efficient and may make interpretation easier. Figure 25 shows some of the problems that occur when this is attempted. The data processing has all been done using NPL developed Java processing tools.

In Figure 25 the unrolling was done along a line parallel to the X axis and at the average midpoint of the tunnel data in the Y-Z plane, this was after manual realignment of the Omnicom data so that the direction of travelling along the tunnel section was locally parallel to the X axis. In this example it can be seen that the distance to the tunnel wall changes because the shape of the tunnel isn't a cylinder.

To compensate for this then a custom tunnel shape was developed for this tunnel section that only used cylindrical coordinate transformation for the tunnel crown and effectively cut the tunnel walls and base and laid them out flat, Figure 26. There is still some slight distortion caused by an imperfect alignment of the tunnel axis with the X axis (or alternatively the tunnel section may not be straight).

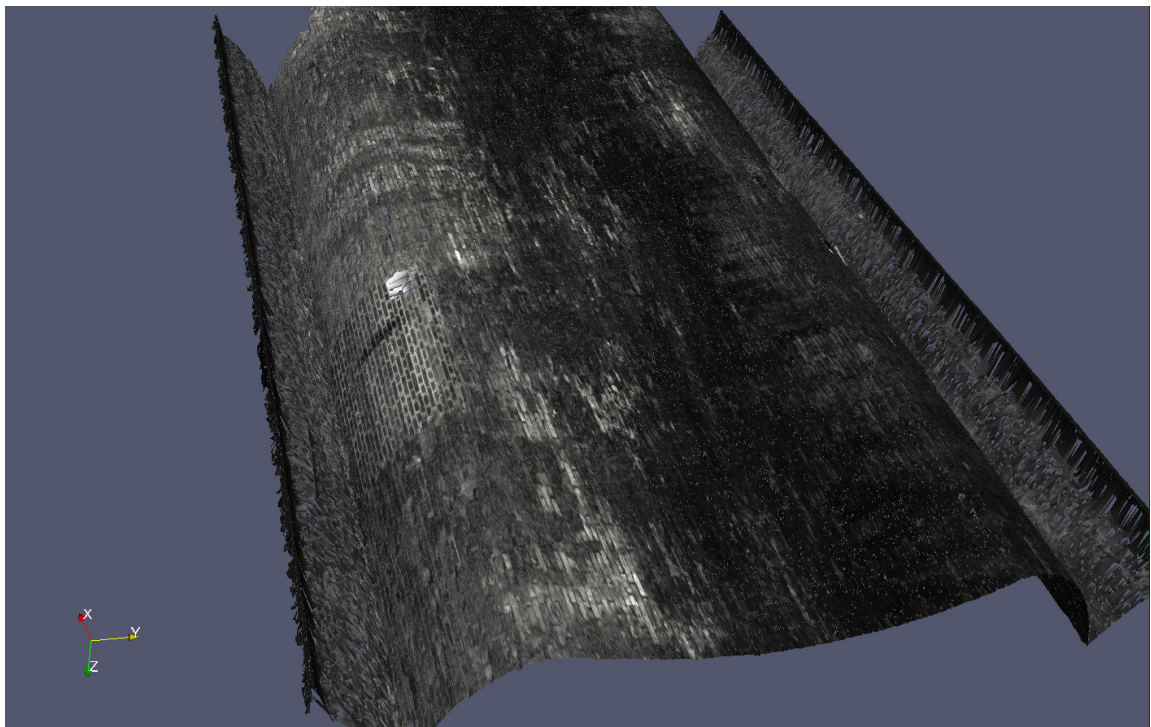


Figure 25. An early attempt at unrolling a tunnel section using a cylindrical polar coordinate unwrapping by mapping circumferential length in the y direction. The z direction is the distance to the face measured from an average midpoint in the undeformed Y-Z plane perpendicular to the X axis.

Another example of this type of mapping is from the Golder RMT impact echo map [106], Figure 27.

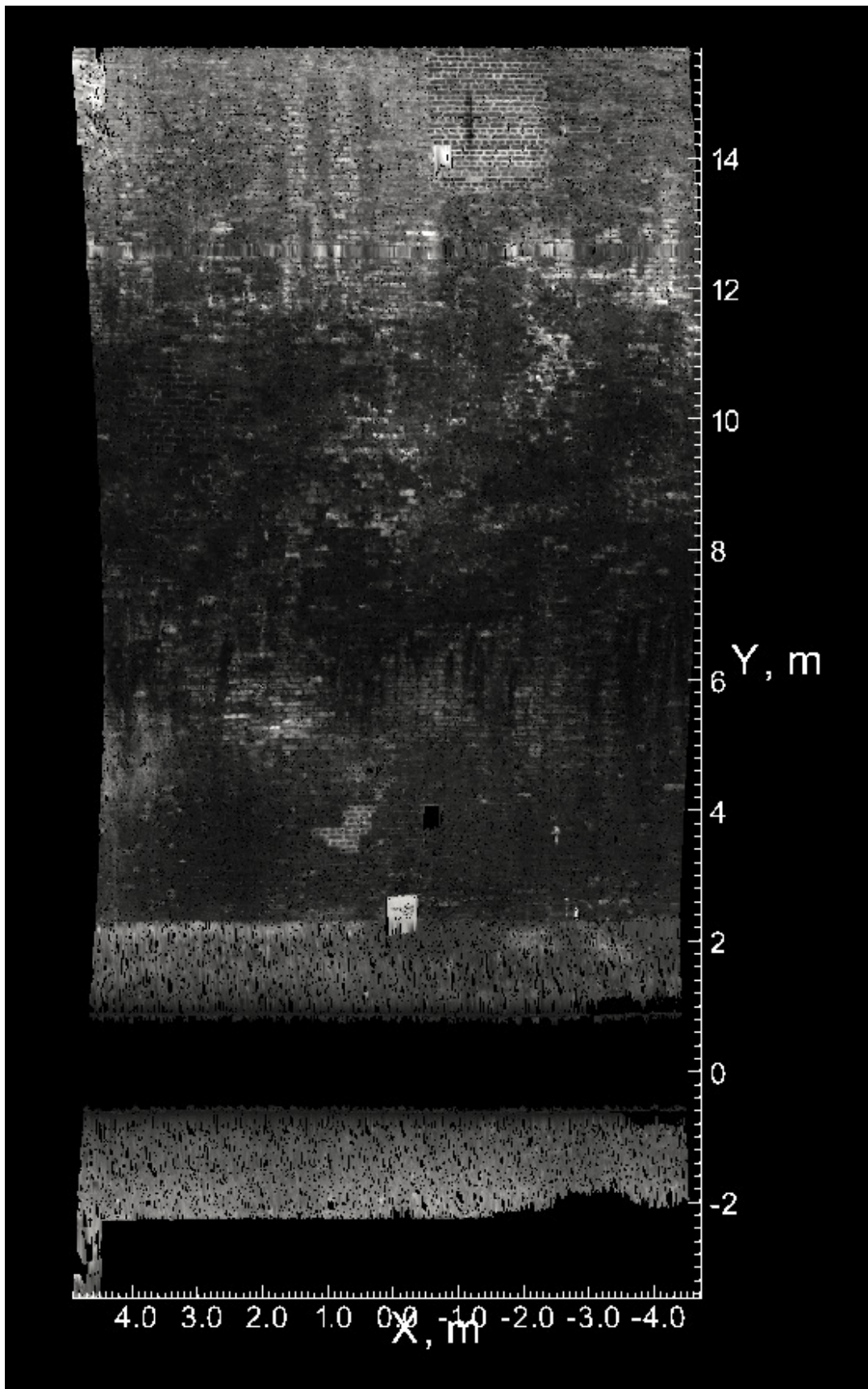


Figure 26. The data from Figure 22 is unrolled, the track base is at the bottom of the image, and there is frequent evidence of missing triangles in the mesh, particularly in the ballast around the track at the bottom of the picture.

An advantage of the 2D image representation of the data is the ease of examining the data scan, i.e. how easy it is to interact with the image data by simply sliding it horizontally so that different sections of the tunnel come into view. An alternative is to use a stack of images to show different areas of the tunnel, although it may be that damage might span two images in a stack necessitating lots of moving back and forth between images to examine its extent.

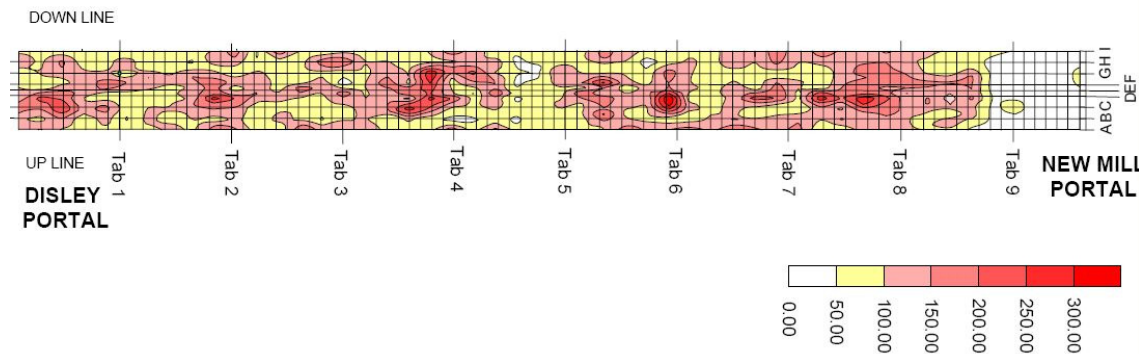


Figure 27. Golder RMT data from [106, Figure 12] showing impact echo measurements on a grid comprising the whole internal surface, excluding the track bed, within the Disley Tunnel.

8.5 Methods for data analysis

To remove a large amount of manual manipulation of datasets a technique needs to be developed to allow data sets to be aligned and then compared. The technique that has been well developed for this work, when using point cloud data, is the iterative closest point (ICP) method. The reference [135] gives a good review on the current state of development for various techniques that were implemented in the NPL software tools. One of the problems with these techniques is the inability to accurately align structures, that don't have many features or markers and are very similar in shape along their length, as in the data used for Figure 22.

Figure 28 shows a result of aligning data sets, one set is the data shown in Figure 22 and the next is after traversing the tunnel again but from the opposite direction. Figure 28 shows a map of closest point distance between these scans shown in arbitrary units with the maximum nearest neighbour distance corresponding to 10 cm. For this comparison the data sets (Tyther11 and Tyther12) were measured with the scanner travelling different directions along the track and this may have added additional differences due to angular differences as the data was subsequently scanned. This effect could be explored by examining data from tunnel measurements when the laser scan vehicle travelled the same direction.

More work is really needed to identify the cause of these apparent differences, but they are closely related to the way the data is measured and that needs to be examined too. The effect in Figure 29, seems more confined to the rocky areas and this may be that relatively small amounts of laser scanner "wobble" mean that small angular variations across the faceted rock face, on the left of the image, gives greater apparent differences than for the smoother brickwork on the right of the image. The effect of the laser scanner "wobble" on the measured data can be seen in Figures 30, 31. In Figure 30 the

laser scanner “wobble” may be responsible for the uneven horizontal position of the mesh lines and the differing spacing seen between vertical mesh lines. In Figure 31 wide dark lines are apparent where the spacing between vertical scans is uneven.

Alignment of the data sets and the repeatability of the measurements are vital precursors to data analysis; as it is best to start with a near perfect aligned data and then do minimal realignment if the highest reliability of measurement is required. However other types of realignment may be more successful depending on the way the data is captured and it may be that local rather than global realignment is more successful if there is large uncertainty in the position and orientation of the measured data.

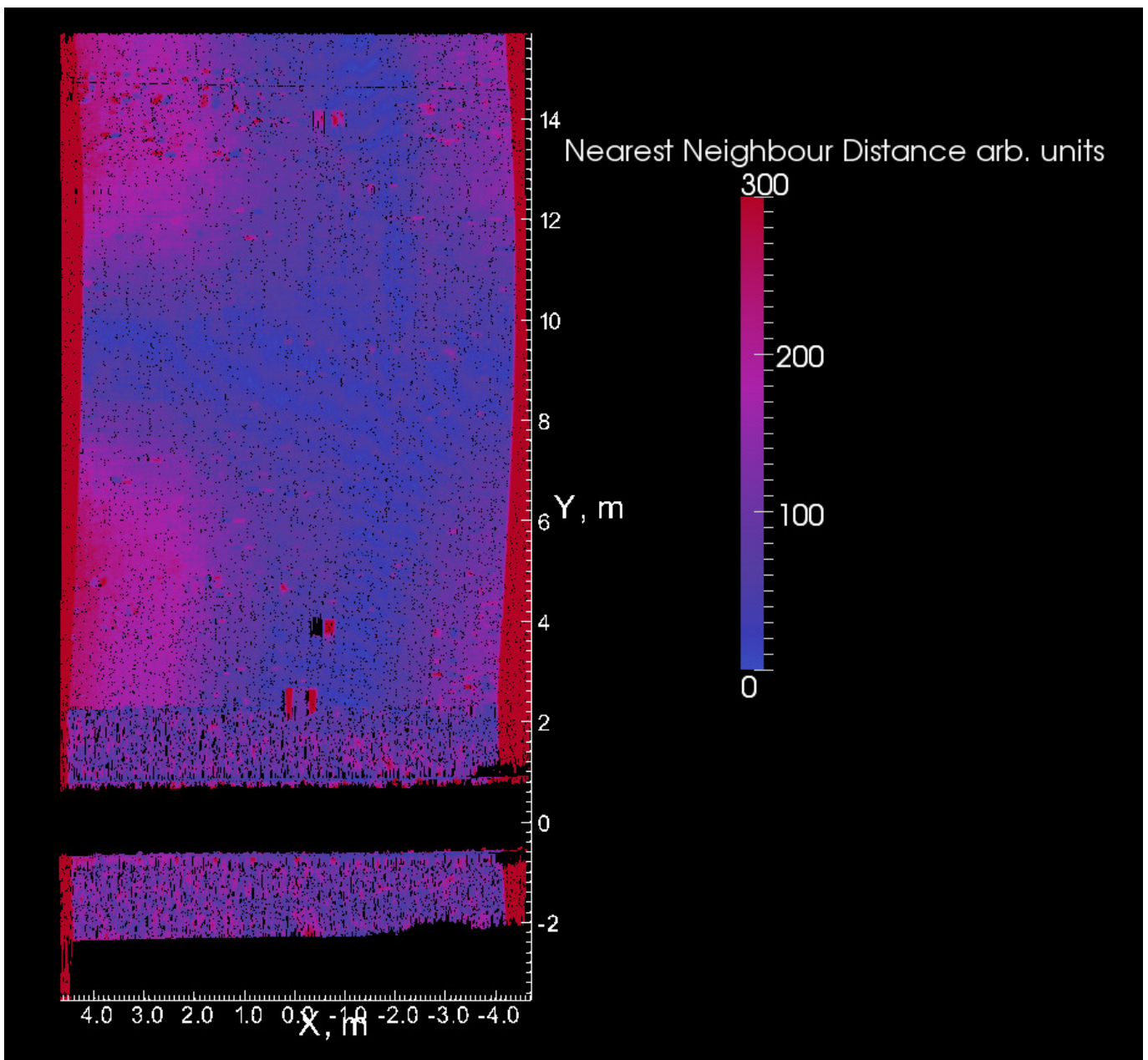


Figure 28. The differences between subsequent laser scans, Tyther11 and Tyther12, in the area shown in Figure 22 after unrolling the data. The maximum range is about 10 cm and the absolute value of the difference is plotted.

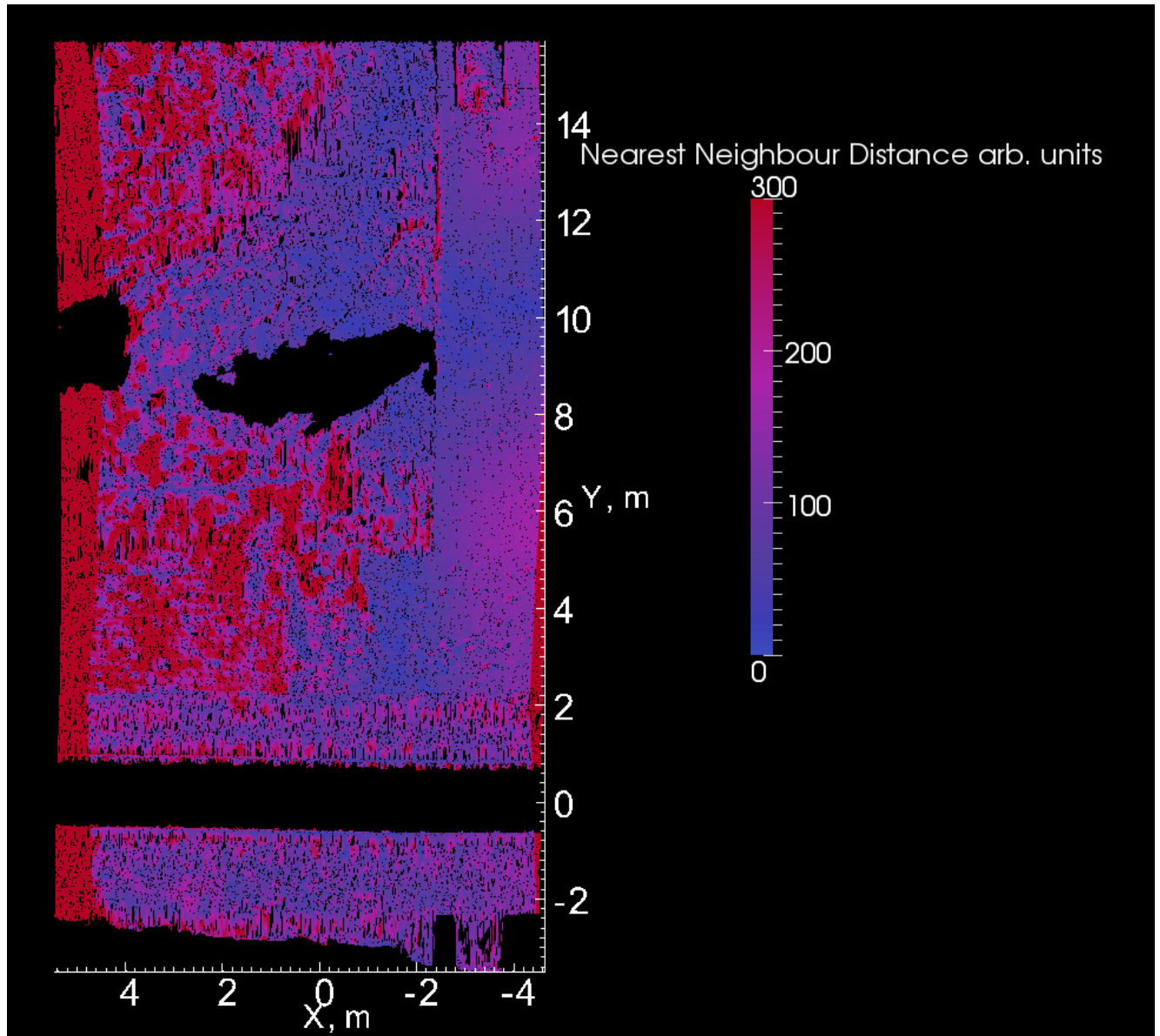


Figure 29. The differences between subsequent laser scans, Tyther11 and Tyther12, in the area shown in Figure 23 after unrolling the data. The maximum range is about 10 cm and the absolute value of the difference is plotted.

There may be advantages in converting the point cloud data to an unstructured grid that is common between scans and used as the master coordinate system. This coordinate system may benefit from robust ways of adding targets to the tunnel wall, or using DIC techniques for image alignment to aid absolute positioning.

Using a grid has obvious advantages when comparing to Defect Record Sheets, Figure 32, from [136] that are being developed for manual examinations. If these record sheets can be filled in automatically using automatic methods then it will be easier to integrate manual and automatic methods of tunnel examination.

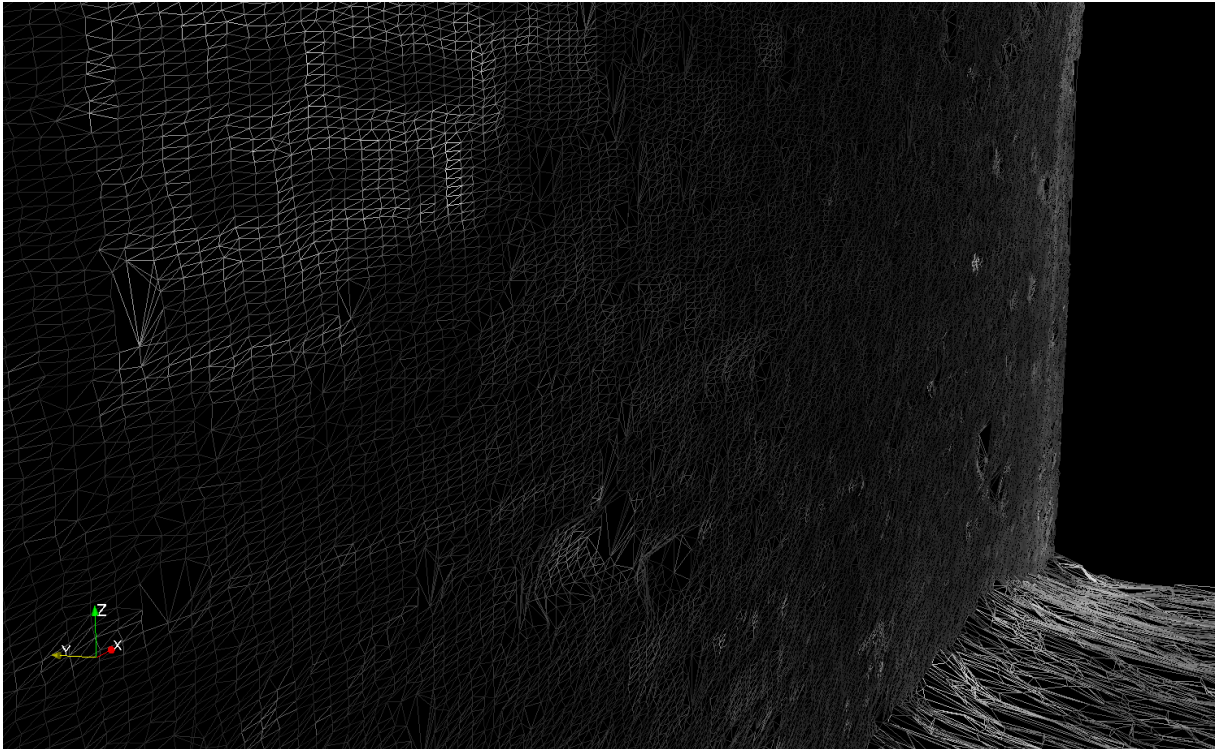


Figure 30. A detail of the data from Figure 22 showing the details of the mesh and the unevenness of the scanned data points.

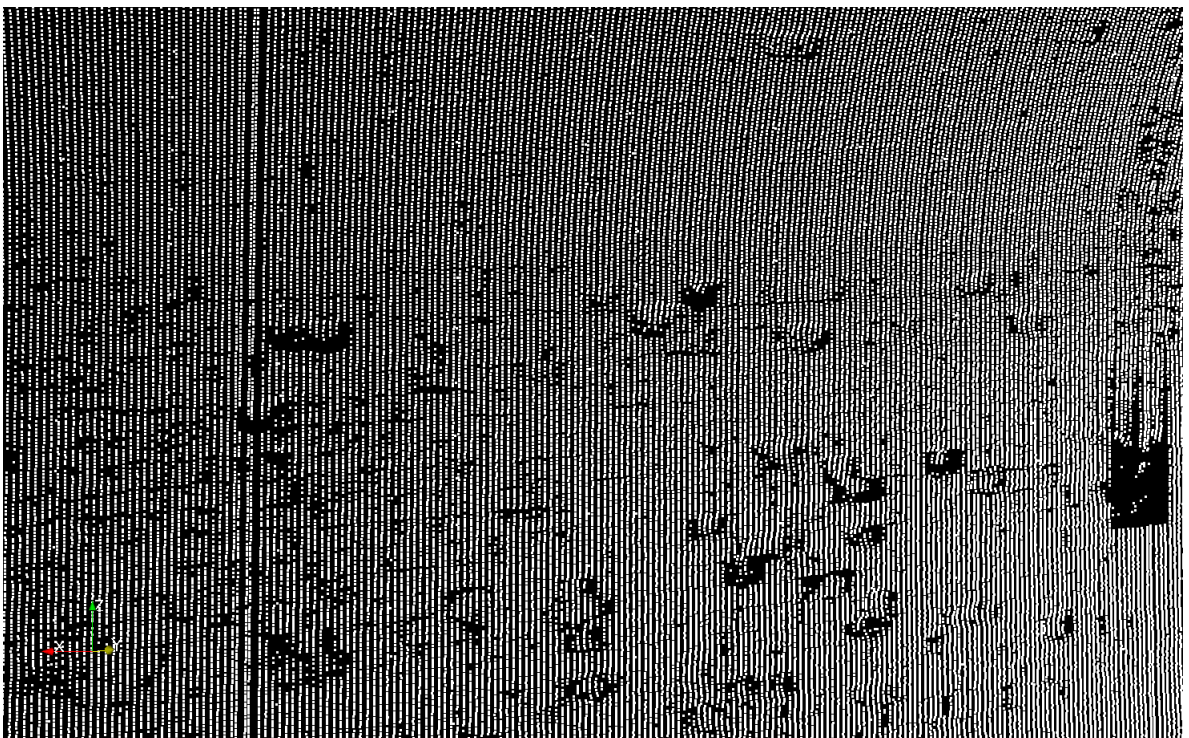


Figure 31. Missed vertical scan lines in point data from Figure 22.

A.4 Defect record sheet - tunnel sections (single crown)

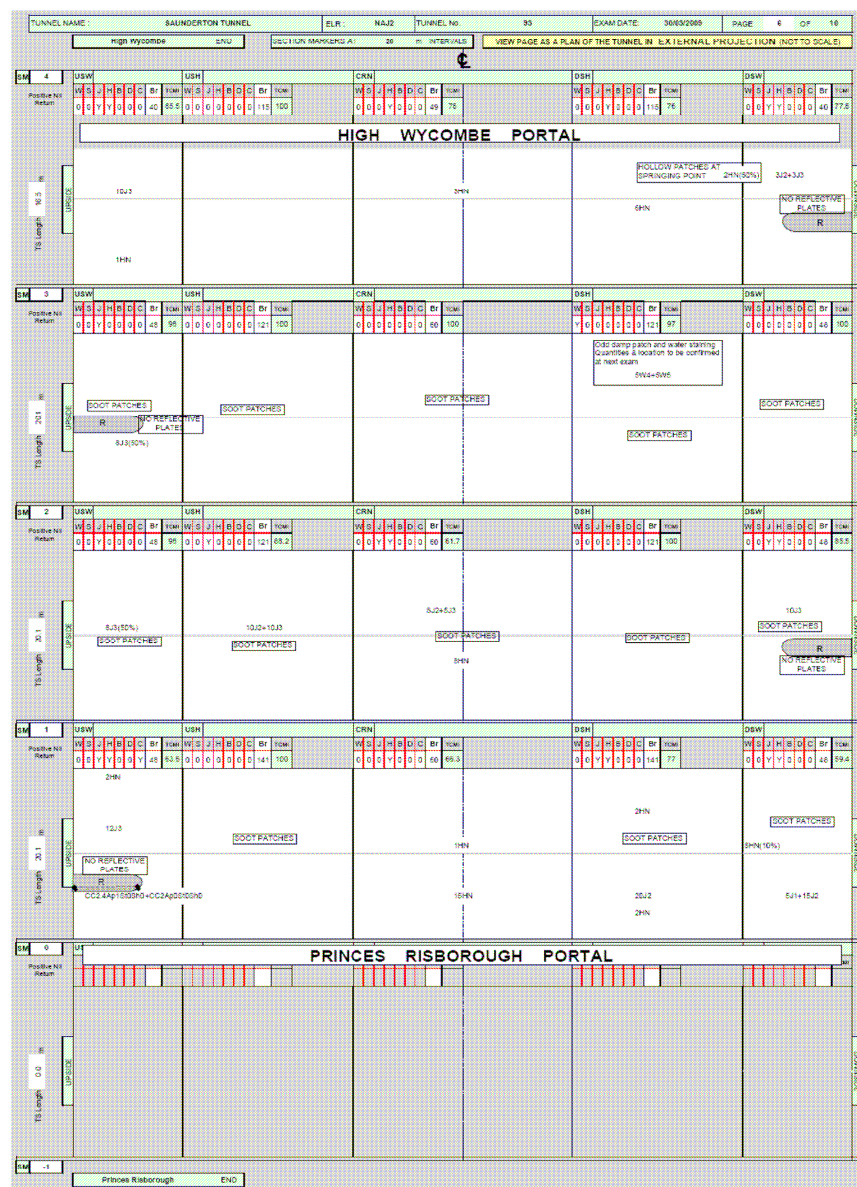


Figure 32. A defect record sheet from [135]

8.6 Summary of data analysis and visualisation techniques

Data can be analysed and subsequent measurement runs can be compared either using point cloud data or data represented in a mesh. The advantages of transforming the data sets to regular meshes means that subsequent comparisons would be much faster and less storage would be required. In addition comparison to manual surveys would be easier. There are benefits in visualising the data in both 2D and 3D form as different features will be emphasized and interpretation will be easier when trying to identify defects by combining different measurement types.

Techniques for assessing and visualising measurement quality need to be developed.

There are various packages available to visualize point data and unstructured mesh data although it seems that larger data files may cause problems with some of the packages.

Paraview seems to be the best general-purpose package and although limited to mesh data the majority of measured data is likely to be in a meshed form rather than point form. Paraview promises the capability to be scalable with computing resource more easily, although this has not been tested.

Specific features that might be needed such as mesh creation, mesh unrolling and mesh alignment will probably need to be custom programmed, Paraview has facilities to add user written plug-ins.

8.7 Issues to be resolved in feasibility trials

- The effect of the stability of scanning the tunnels on the accuracy and repeatability of the final measurement grid.
- Investigating the size of the data files and techniques for reducing their size/resolution to enable faster processing.
- Developing a suitable format to store all the different data types including uncertainties/confidence in the measured data.
- Try to find ways to extract data from proprietary programs.
- Evaluating 2D and 3D techniques for data visualisation
- Testing integration with defect record sheets.

9 Conclusions

An investigation into alternative methods suitable for tunnel examination has been made. This investigation has identified techniques based on physical principles after a brainstorm with NPL staff. It has also identified techniques used in other industrial sectors that might also be relevant to this measurement problem. The techniques were ranked according to various relevant selection criteria and a more detailed examination was made into each technique that was likely to be suitable for this task.

After additional interactions with industry experts and visits to see plant and structures then a series of recommendations have been made into which techniques should be investigated further and are most likely to be successful, economic, efficient and suitably accurate for the task of tunnel examination for each of the classes of structurally relevant defects.

Preliminary investigations using trial data files has helped identify data acquisition issues and techniques that might be used for visualisation. Comparison techniques have been identified for comparing subsequent scans. It is expected that the data storage requirements for each technique will be similar if a similar scanning resolution is used for assessing a tunnel. The amount of data to be stored and processed may be very large so efficient ways of managing and comparing subsequent scans will be needed.

10 Recommendations

The aim is to make repeated measurement runs and to see the differences between runs over time, since relating the current shape/state of the tunnel to some fixed ideal is generally difficult. In making these recommendations the questions in section 4 have been used to guide the detailed investigations for the different techniques.

Shape of Tunnel

For this category image triangulation methods are the current best choice for high-speed measurements, when combined with imaging then interpretation will be much easier. 3D DIC can also be used for high-speed measurement, but will need more post-processing. TOF camera has borderline accuracy, but offers the real possibility of low cost high-speed measurement, with certain benefits of capturing full fields of data.

TOF cameras, DIC, and triangulation systems essentially have no moving parts and maybe more robust and reliable, although optical lenses will need to be kept clean. Laser scanning is probably a less robust solution but maybe combined with total station measurements for accurate surveying.

TOF cameras and other techniques that capture a full field image allow image stitching which can improve measurement reliability, but at the cost of more processing.

These methods have been considered and are not recommended:

Laser scanning, when fixed will be very slow to measure a tunnel, if vehicle mounted then it will be faster but additional ways of stabilizing the process may be required. However it is a well-developed technique in many civil engineering applications and would be a useful technique for comparison.

SAR probably has a pixel size that is too large, for high resolution measurements targets are also required.

Crack opening measurements

The only viable techniques for this are DIC to measure crack opening and shear, and 3D-DIC to measure crack step. Additionally image stitching may improve positioning

These methods have been considered and are not recommended:

GPR techniques are unlikely to work for the inhomogeneous material in the tunnel lining. Most shape measurement techniques will not have the required spatial or range resolution for this.

Optical imaging techniques on there own, whilst being successfully developed for looking at concrete tunnels are unlikely to be able to work in the multi-patched tunnel environment with the variety of building materials, unless used in conjunction with DIC.

Delamination

This is unlikely to be done at high speed unless the damage leads to a shape or crack opening change, but the techniques most likely to be successful are impact echo and GPR.

These types of measurements are likely to be able to scan a whole tunnel in one possession (5-10 hours).

GPR has been extensively investigated for concrete and there are commercial services available for this, but results for brick structures were very difficult to interpret, but useful measurements may be possible for large ring separations. It has the potential to be done at high speed.

Impact echo may be the most reliable for typical Network Rail tunnels and is the most similar to current manual examination techniques, but will be slow even when automated with a robot.

Thermography is unlikely to be useful unless the tunnels are very dry or the amount of water is closely correlated with areas of damage.

Water ingress

Water ingress measurements will require a multi-sensor approach, using imaging for dry to moist conditions, shape measurement and imaging for visible water flows and sound measurement for substantial water ingress.

Humidity sensors on scheduled trains may give qualitative data that can be used to investigate tunnel water ingress much more frequently and develop statistical ways of determining water ingress.

Data analysis and visualisation

It is recommended that the development of algorithms and software tools proceeds in parallel with the development of the measurement sensor systems, as the combination of both are required for an efficient, easy to understand measurement system.

Data can be analysed and subsequent measurement runs can be compared either using point cloud data or data represented in a mesh. The advantages of transforming the data sets to regular meshes means that subsequent comparisons would be much faster and less storage would be required. In addition comparison to manual surveys would be easier. There are benefits in visualising the data in both 2D and 3D form as different features will be emphasized and interpretation will be easier when trying to identify defects by combining different measurement types.

Techniques for assessing and visualising measurement quality need to be developed.

A combination of measurement techniques that will satisfy the measurement requirements.

- DIC and imaging for crack opening measurements and sensor location.
- 3D-DIC or triangulation for shape measurement.
- Sound measurement to determine high levels of water ingress

Traveling at a few metres per second or higher.

Delamination should be possible at slow speeds ~ 0.1 metres per second with better resolution, smaller measurement spacing, and much better consistency than human operators at present.

High-speed measurements may be possible using a TOF camera, high-resolution digital camera and a humidity sensor array. The limiting factor on speed is probably the stability of the measurement platform, although this system may be able to use the shape measurement to locate sensor platform and correct for some twisting.

11. Overall programme plan for future development and implementation

Introduction

The measurement solution for alternative methods for railway tunnel examination will include a combination of measurement technologies and a sub-frame on which the sensing technologies will be mounted. In addition there will be a data analysis and visualisation software subsystem developed to allow easy interpretation of the measurement data and easy integration with current Network Rail IT systems. The development of this plan has been aided by the research and conclusions described in the previous chapters of this report.

The plan has been divided into three work streams:

- Work stream 1 – Quick wins – short term deployment
- Work stream 2 – Medium term deployment
- Work stream 3 – Longer term deployment

Each work stream contains the development of particular sensing technologies as well as the development of software and a sub-frame necessary to deploy those sensing technologies in the appropriate time frame.

It is also expected that two additional tasks will take place during the lifetime of the research programme; the first task will involve project management and technical steer using a group of immediate Network Rail stakeholders and technical experts, and will involve regular technical progress meetings. The second additional task will run annual technical progress workshops where the larger group of stakeholders, technical experts, potential collaborators and service providers will have an opportunity for project updates and strategic steer. It is expected that publications will also be produced to enable peer-review and engagement with a wider community.

The full plan is provided in Microsoft Project format, and is summarised below with supporting information. The summary below includes:

- A description of the task and the key activities
- Identifies potential collaborators
- Identifies likely timescales and costs
- Identifies any risks

Assumptions and Dependencies

The timescales are estimates to provide an indication of likely man-months and time periods needed for each activity. These are based upon NPL experience and knowledge gained in WP1,2 and 3. The estimates do not represent a quotation or budgetary estimate of work from NPL, nor any sub-contractors that are likely to be required. It is expected that Network Rail will use these estimates and their experience of previous R&D projects to form a view on the budget required for the work.

The estimated cost for each activity has been provided as if they were to be carried out independently of each other. This is based on the principle that different contractors may be used. They may be opportunities for cost reduction if the same contractor carries out complementary activities.

Generic Risks

Risk	Mitigation
Ability to find suitable partners for each activity area	Conduct workshop event(s) to identify suitable partners
Ability to achieve required specification for each sensing technology	Laboratory based trials used to assess suitability. Quality stage gates required to assess if technology should be taken forward to next level of development
Ability to achieve technical co-ordination across activity areas	Technical advisory / steering committee required to oversee all technical programmes of work
Ability to develop and deploy large scale research project in rail sector	A contractor familiar with managing, carrying out and sub-contracting large scale technology projects in the rail sector needs to be engaged early in the project
Availability of test structures	Use of mock tunnel in early stages to overcome need for extended possession. Later stages require possession of active or inactive tunnels. These tunnels need to be identified early in the ext stages of the programme
Solution does not meet specification because of unanticipated limitation	Developing several techniques per measurement area means the chances of meeting specification are much improved

Costs

Activities have been given an estimated man-month cost. An estimate of any significant in-direct cost, such as the purchase of equipment or facilities, has also been provided. These are shown in the four tables below.

In addition to these primary costs it is expected some smaller in-direct costs, such as travel and subsistence, consumable items and low value equipment may be needed. These additional costs should be factored into the overall cost of the programme.

No estimate for the cost of hardware development, field trials or deployment have been provided. The next year of the programme focuses on conducting feasibility trials. Hardware development, field trials and deployment fall beyond the next year of the project. Once the feasibility trials have commenced it will be possible to estimate these costs.

Programme Management	Effort (man-months)	Elapsed time (months)	Significant indirect costs (£K)
Project management	2	12	0
Technical management	3	12	0
Stakeholder engagement, knowledge transfer & publicity	0.5	12	5
<i>Sub-total</i>	<i>5.5</i>		<i>5</i>

Work stream 1 'Quick wins'	Effort (man-months)	Elapsed time (months)	Significant indirect costs (£K)
2D-DIC			
Lab based measurements	1	4	
Prototype development using mock tunnel	1	4	10
Empty tunnel and comparison against reference tunnel	2	4	20
Time of flight			
Lab based measurements	2	6	
Prototype development using mock tunnel	1	4	10
Empty tunnel and comparison against reference tunnel	2	4	15
Triangulation			
Lab based measurements	0	0	0
Prototype development using mock tunnel	1	8	10
Empty tunnel and comparison against reference tunnel	2	4	0
Sub-frame development (passive system for low mass, low speed)			
Prototype development using mock tunnel	5	12	55
Software development (2D mapping, 3D shape, low speed DAQ)	6	12	15
Exploratory activities			
GPR	2	4	25
Impact Echo	3	5	15
Multi-sensor	2	6	10
Vibrometer	2	6	10
<i>Sub-total</i>	<i>32</i>		<i>195</i>

Work Stream 2: Medium Term Deployment	Effort (man-months)	Elapsed time (months)	Significant indirect costs (£K)
Shape & Crack opening			
3D-DIC			
Lab based measurements	3	9	30
Prototype development using mock tunnel	2	6	15
Empty tunnel and comparison against reference tunnel	2	6	10
Delamination			
GPR			
Lab based measurements	3	6	25
Prototype development using mock tunnel	3	6	5
Empty tunnel and comparison against reference tunnel	4	8	5
Impact Echo			
Lab based measurements	4	9	25
Prototype development using mock tunnel	8	18	45
Empty tunnel and comparison against reference tunnel	8	18	50
Sub-frame development (active system for medium speed)			
Empty tunnel and comparison against reference tunnel	12	24	100
Data analysis and visualisation	6	12	15
<i>Sub-total</i>	<i>55</i>		<i>325</i>

Work Stream 3: Long Term Deployment	Effort (man-months)	Elapsed time (months)	Significant indirect costs (£K)
Water ingress	4	9	5
Software development and system integration	6	12	15
<i>Sub-total</i>	<i>10</i>		<i>20</i>

Work Stream 1, Quick Wins– short term deployment.

This work stream looks at developing measurement techniques that are likely to be easily deployed in a short (12 month) time period and are either well developed or show exceptional potential as a part of the potential measurement solution.

Key activities in WS1 are;

1. 2D-DIC
2. Time of flight camera
3. Triangulation range sensor
4. Sub-frame development (passive system for low mass, low speed)
5. Data analysis and visualisation (2D mapping, 3D shape, low speed DAQ)
6. Exploratory activities

WS 1.1 2D-DIC

This measurement technique will develop 2D DIC as a crack opening measurement technique for in –plane crack opening and shearing. As an additional by-product it will allow the construction of panoramic images that can be used as a master map for the other tunnel survey techniques and may be useful in aiding sub-frame alignment

The target accuracy for this technique is detection of crack opening of 1mm and crack shearing of 1mm this can be achieved by using a sufficiently stable and reproducible repositioning system and then capturing images with sufficient numbers of pixels, probably with about 1 pixel per mm.

The following issues are to be addressed with *laboratory based measurements*;

- Can DIC work in problematic conditions, like water on the surface or fog etc. so at least a quality of the measurement is reported?
- How many pixels per mm are really needed for sufficient crack opening detection?
- If images are captured that overlap can large panoramas be constructed that will that help in accurate positioning?

The following issues are to be addressed with *prototype development using mock tunnel*

- Can measurements be made at high speed; are there effects that cause image blurring?

The following issues are to be addressed with *Empty tunnel and comparison against reference tunnel*

- What effect is there if the tunnel wall is painted to identify the cracks, is too much detail lost for accurate image registration?
- What effect if the tunnel is changed, say with extra instrumentation?

Potential collaborators

During this work stream external collaborators will not be needed. However during this work stream and after presentations at the end of year 1 workshop, potential partners for this measurement technique will be identified as required.

Technical risks

- The choice of lenses may make imaging the curved tunnel wall difficult:
 - **Mitigated by:** Multiple cameras may be needed to ensure sufficient coverage whilst limiting distortion.
- Dirt or condensation on lenses:
 - **Mitigated by:** There are well-developed techniques that allows imaging to take place from aircraft and other moving vehicles in adverse conditions.
- There may be unanticipated environmental conditions:
 - **Mitigated by:** In this work stream tests will take place in relatively benign conditions. Later work on trials and hardware development will address protection for the more extreme environmental conditions.

WS 1.2 Time of flight camera

Although this instrumentation has only been recently developed it does have the potential to make high-speed measurements of surface shape with a 5-10 mm accuracy. As it captures an image then there are certain advantages with automatic alignment that might mean that the stability requirements from the sub-frame are reduced and the potential to make very high-speed measurements is more likely.

The target accuracy for this technique is 5mm in range. This is at the limit of current systems, but is stated to be achievable by some manufacturers. Future developments may have a higher range resolution.

The following issues are to be addressed with *laboratory based measurements*;

- Identification of suitable device
- Investigate manufacturers claims on accuracies
- Can the image-based output be used to address mis-orientation.

The following issues are to be addressed with *prototype development using mock tunnel*

- Stability of measurement with slow speed
- Maximum speed of measurement
- The effect of variably wet surfaces for tunnel measurement

The following issues are to be addressed with *Empty tunnel and comparison against reference tunnel*

- Stability of measurement with medium speed
- Steadicam style devices to ensure alignment.

Potential collaborators

During this work stream external collaborators will not be needed although a dialogue will be set up with the TOF camera manufacturers to determine their product roadmap and to feedback information on potential camera improvements. However during this work stream and after presentations at the end of year 1 workshop, potential partners for this measurement technique will be identified as required.

Technical Risks

- Camera does not meet manufacturers specifications
 - **Mitigated by:** Several cameras are available and will be evaluated prior to deciding on what device to investigate further.
- High-speed image based data stream is difficult to handle
 - **Mitigated by:** There are well developed systems already in use by Network Rail for handling high-definition data streams

WS 1.3 Triangulation range sensor

These sensors are relatively well developed and have been used by Network Rail for general gauging duties. They should be easily transferable to tunnel shape measurement. As they only make measurements on one line they are susceptible to vibration affecting position and orientation.

The target accuracy for this technique is 5 mm; according to manufacturers this should be achievable. If it is not sufficient then a higher resolution camera may be needed to resolve the projected laser line. The resolution may be adversely affected by the stability of the sub-frame.

As the equipment is well developed it is not expected that there will be any *laboratory based measurements*;

The following issues are to be addressed with *prototype development using mock tunnel* in this case it is anticipated that these experiments might take place at Network Rail Derby in collaboration with the operators of the equipment. The mock tunnel may be a temporary construction used adjacent to the sensor whilst it is in a convenient place.

- Manufacturers accuracy claims
- Effect of sunlight
- How well does it work on flowing water on surfaces

The following issues are to be addressed with *Empty tunnel and comparison against reference tunnel*

- Steadiness of system during measurement

- Whether extra targets could improve positional accuracy at speed

Potential collaborators

Balfour Beatty LaserFleX, Serco, current owners of gauging service for Network Rail. ScanTech or Omnicom to produce a reference measurement of the empty tunnel for intercomparison.

Technical Risks

- Accuracy of measurement
 - **Mitigated by:** The well developed nature of this measurement system reduces the risk of this, an alternative system is also available
- Availability of sensor for testing
 - **Mitigated by:** Starting negotiations for access to system at start of WS1, investment in a dedicated system.

WS 1.4 Sub-frame development

This activity is to deliver a measurement sub-frame that has a functionality and specification complementary to the sensing technologies being developed in this work stream. This functionality of the platform is likely to initially be a passive system capable of providing a level and stable frame for low mass sensing devices operating at low speed.

The stability of this platform is crucial to the performance of the other measurement techniques and their ability to achieve their target accuracies.

It is not expected that there will be any *laboratory based measurements*; as the issues only really occur with realistic movement of the measurement sensors.

The following issues are to be addressed with *prototype development using mock tunnel*

- Does the track really move that much, how could this be investigated?
- Is it best that repeated measurements are done in same direction to help minimise instrumentation orientation errors?
- Can DIC or image stitching provide a good enough position on the tunnel wall to be used for most positional/orientation requirements?
- Will tunnel surface mounted targets help alignment?
- Can specific anti-vibration and Steadicam mounts help with alignment and sensor stability?

The following issues are to be addressed with *prototype development using an empty unused tunnel*

- Does the track really move that much?
- How much movement occurs at the sub-frame?

- On a MPV how accurate is alignment and can vibration be minimized?
- Will tunnel surface mounted targets help alignment?

Potential collaborators

In the early stages of WS1 the main requirements will be measuring the actual position and orientation vibrations. Initial work will identify if a simple passive solution is adequate for this. However during this work stream and after presentations at the end of year 1 workshop, potential partners for manufacturing a suitable sub-frame will be identified.

Technical Risks

- Orientation misalignment is difficult to control
 - **Mitigated by:** Other measurement system may be used to measure the apparent orientation and hence be used to correct all measurement systems for angle.
- An active system for position and orientation control is needed
 - **Mitigated by:** If this is identified early in WS1 then a suitable solution and contractor can be sourced for WS2. This requirement is not uncommon and has been addressed for video, targeting and other measurement systems.

WS 1.5 Data analysis and visualisation

This work will look at techniques for 2D mapping and analysis, alignment and visualisation of 3D shape and will be developed in parallel with the measurement sensing techniques. Research into these techniques are necessary as a pre-cursor to the development of comparative analysis software for the automatic identification of tunnel defects needing further investigation.

The development of comparative analysis software will depend on some initial measurement issues listed below and is expected to develop hand-in-hand with the development of the best techniques for each of the defect classes. It is expected that such a software system will need to be able to process large quantities of data either in a 3D or 2D surface form generated from appropriate measurement techniques and then make a comparison between subsequent measurement runs to identify differences between the data sets.

The issues to be addressed will include;

- The effect of the stability of scanning the tunnels on the accuracy and repeatability of the final measurement grid.
- Investigating the size of the data files and techniques for reducing their size/resolution to enable faster processing.
- Developing a suitable format to store all the different data types including uncertainties/confidence in the measured data.
- Try to find ways to extract data from proprietary programs.
- Evaluating 2D and 3D techniques for data visualisation

- Testing integration with defect record sheets.

A detailed specification for the software will be developed during this workstream, however a preliminary outline specification for this software might be expected to include the following;

- Ability to import data sets produced by appropriate measurement techniques.
- Storage of data sets in a readily accessible database system.
- Ability to compare stored data sets along the length of the tunnel and compute differences
- Ability to threshold differences against multiple thresholds as damage change markers
- Ability to combine multiple damage change markers from different measurement techniques and generate a damage report
- Ability to generate damage reports in an appropriate format, compatible with current practice, with an appropriate measurement of uncertainty on the results

Such a software system would need to be compatible with Network Rail computing resources and working practices. The data sets are likely to be large and would also be needed to be archived, although an intermediate data format may be developed to allow faster analysis that sacrifices some spatial resolution to aid processing speed.

Potential collaborators

Some potential collaborators have already been identified and their software has been trialled. Further evaluation of suitable software packages from VSG (Avizo package). Open Source ParaView and software support from Tessella will be made. At this stage general purpose packages are preferred as the variety of data input is potentially so large.

Technical Risks

- Required features may be unavailable in a software package
 - **Mitigated by:** Packages for consideration have been identified that can be easily extended with user subroutines developed within the project or with consultancy support from the software producers.
- Computing resource requirement may be too great
 - **Mitigated by:** Packages have been identified that are easily scaleable with increased computing power.

WS 1.6 Exploratory activities

This work stream will carry out preliminary research to determine the feasibility of the following techniques and to provide information for the later work streams.

- GPR
 - Can GPR be used with sufficient stand-off?
 - Can GPR be used to detect delamination in brickwork, [78] is not clear.
 - How is GPR data interpreted or can the changes between subsequent scans be used?
- Impact Echo
 - Can impact echo measurements be made using microphones rather than geophones
 - Can suitable projectiles be used to produce large enough signals for impact echo measurements
 - Is a tethered re-usable projectile more suitable for this task?
- Vibrometer
 - Can sufficient vibrational energy be introduced into the tunnel wall from a rail mounted "shaker" or track tamper for a vibrometer to be able to make a measurement?
 - Are the tunnel walls reflective enough or would reflectors/markers need to be introduced?
- Multi-sensor water sensing
 - Do the appropriate techniques work in typical tunnel conditions?
 - Is there sufficient overlap between techniques?
 - Can the measurements be made less qualitative?
 - Could a humidity sensor array be a simple low-cost alternative and be easily mounted to a vehicle?

Potential collaborators

For these feasibility studies then collaborators will not be required, however contractors may be required to help with GPR and Impact Echo measurements. The vibrometer may be able to make suitable measurements but this initial work will concentrate on determining the sensitivity of the equipment before an experiment is made using a track tamping machine.

Technical Risks

This is not required as these are feasibility studies.

Work Stream 2 – Medium term deployment

This work stream looks at developing measurement techniques that are likely to be easily deployed in a medium (24 month) time period and will rely on developments within WS1.

Key activities in WS2 are;

1. **3D-DIC**
2. **GPR**
3. **Impact Echo**
4. **Sub-frame development (active system for low mass, medium speed)**
5. **Data analysis and visualisation (2D mapping, 3D shape, medium speed DAQ)**

WS 2.1 3D-DIC

This measurement technique will develop 3D DIC as a crack opening measurement technique for out-of-plane crack opening and shape measurement. It requires two cameras or accurately known images from the same camera in two positions.

The target accuracy for this technique is 1mm in measuring out of plane movement for crack step measurement. This is achievable if the sub-frame is sufficiently stable and the repositioning is sufficiently reproducible and images with sufficient pixels can be captured.

It is envisaged that a similar development path to that used for 2D DIC is used involving *laboratory based measurements; prototype development using mock tunnel and Empty tunnel and comparison against reference tunnel.*

The experience gained from carrying out the 2D DIC measurements will be very useful in developing this aspect of measurement, as this is a different version of DIC.

Potential collaborators

Similar collaborators will be needed as for 2D DIC measurements.

Technical risks

In addition to the risks for 2D DIC

- Using the same camera for measurements after it has moved further along the tunnel may impose impossible to meet realignment criteria:
 - **Mitigated by:** Pairs of cameras may be needed to ensure sufficient accuracy of the baseline between images.

WS 2.2 GPR

Depending on the outcome of the feasibility study in WS1.6 this measurement system may need to be developed. It is expected that the *laboratory based measurements* would largely be determining the accuracy and selectivity of the system for various types and sizes of defects within brick work. The *prototype development using mock tunnel* would be the development of a system for accurately positioning and controlling the GPR antenna suitably close to the tunnel wall. The phase *Empty tunnel and comparison against reference tunnel* would be a practical trial within a real tunnel environment.

The target accuracy for this technique is to measure delamination with a face separation of greater than 5 mm. This may be complicated if there is water filling the void of the delamination.

Potential collaborators

These will be identified depending on the outcome of WS 1.6

Technical risks

These are largely mitigated by WS 1.6

WS 2.3 Impact Echo

Depending on the outcome of the feasibility study in WS1.6 this measurement system may need to be developed.

The target accuracy for this technique is to measure delamination with a face separation of greater than 5 mm. This may be complicated if there is water filling the void of the delamination.

It is expected that the *laboratory based measurements* would largely be determining the accuracy and selectivity of the system for various types and sizes of defects within brick work in a test system. The *prototype development using mock tunnel* would be the development of a system for accurately positioning and controlling the microphone and/or mechanical excitation system suitably close to the tunnel wall. The phase *Empty tunnel and comparison against reference tunnel* would be a practical trial within a real tunnel environment.

Potential collaborators

Golder RMT would collaborate on this if the impact echo feasibility study in WS 1.6 indicated that further development was merited.

Technical risks

These are largely mitigated by WS 1.6, but the largest risk will be the design and construction of a robot with sufficient control to provide mechanical excitation of the tunnel wall or to hold a microphone sufficiently close to the tunnel wall.

WS 2.4 Sub-frame development

This would continue the development work from WS1.4 to extend the speed range that the sub-frame could allow reduction of position and orientation vibration for. It is expected that this would require a close-control active system using orientation and position sensors combined with an active sub-frame to provide real-time correction to unwanted movement.

Potential collaborators

The collaborators identified in WS 1.4 would be used for this.

Technical risks

These will be largely mitigated in WS 1.4

WS 2.5 Data analysis and visualisation

This is an on-going development of WS 1.5. It is an extension, as the measurements may need to be made and processed at higher speeds as it is expected that by this work stream substantial quantities of measurement data will need to be processed and visualised.

The software specification developed during WS 1.5 will be used to develop custom software to evaluate the potential data comparison techniques and to help with the processing of the trial data for the different measurement techniques.

It is expected that there will be a requirement for techniques for increasing data throughput and these will be investigated.

The collaborators identified in 1.5 will be increasingly important in this stage as custom software needs to be developed, evaluated and trialled. Investigations into usability by Network Rail stakeholders and integration to Network Rail IT systems will be carried out.

Work Stream 3 – Longer term deployment

At this stage there should be enough measurement systems to provide data that the multi-sensor approach to measurement of water ingress can be trialled successfully with real structures. The development of the system software should now be focussed on usability and system integration.

Appendix 1 - Remit for Research Project Into Alternative Methods of Railway Tunnel Examination: Stakeholder Engagement Document

Purpose

This is intended as a briefing document for contributors and stakeholders in this project and to aid the process of further investigation.

Title

Alternative Methods for Railway Tunnel Examination – A Review and Recommendations for Network Rail

A desk based evaluation of existing practices using alternative technologies for railway tunnel examinations

Introduction

It is necessary to develop alternative techniques for tunnel examination that will meet future demands of reduced track access and increasing train operations.

Currently examinations are of a tactile nature whereby examiners traverse the internal length of the tunnel closely inspecting the lining from H level access equipment

Network rail is responsible for 703 operational tunnels throughout the network; this equates to 335 Km of tunnel structures.

Normally large proportions of this tunnel length remains unchanged between examinations and the examining resources, under current practice conduct time consuming tactile examinations to situations where there is little detectable change over the years.

The number and corresponding length of tunnels within those figures that give rise to concern where engineers regularly need to conduct manual special inspections is 63 which equates to 51 km of tunnel.

There is therefore a need to investigate the value of utilising alternative techniques to confirm the stability of the large proportions of the tunnels that remain unchanged, allowing the examination resources to be targeted to the areas of concern.

Objective

- The project will develop to detailed specification, new tunnel examination techniques and technologies that will replace the majority of manual examinations currently undertaken achieving a similar or better level of examination that that currently obtained.

Developed techniques, technologies and supporting data management:

- will have a frequency of evaluation of one year
- must be demonstrably faster than manual tactile examinations
- will include data evaluation techniques to allow comparison of tunnel examinations made at different times
- be able to support a whole life cost reduction compared to current examination techniques

Constraints

Examination techniques and technologies will need to ensure that the following degrading trends in common tunnel lining condition defects are monitored:-

- Cross sectional deformation including bulging.
- Lining face loss or lining thickness loss.
- De-lamination, honeycombing or voiding within the lining.
- Mortar loss in joints in brick linings.
- Water ingress.
- Fractures and cold joints.
- Missing brick or masonry units.

Alternative techniques and technologies must be capable of monitoring the following lining types:-

- Brickwork.
- Masonry block.
- Cast and sprayed concrete.

Only the linings of the tunnel bore will be within the scope of the project. Portals, shafts, invert, refuges, cross passages and adits will be outside the scope of this project.

The following resolution will be required to monitor common defects:-

1. Cross sectional deformation – transverse +/- 5mm and longitudinally of 1m
2. Lining face loss or lining thickness loss of greater than 20mm
3. De-lamination within brick lining or voiding within the lining of greater than 5mm and the presence of honeycombing within concrete linings.
4. Mortar loss greater than 20mm within brick lining joints or 40mm within masonry lining joints.
5. Changes in quantities of water ingress and extent of area must be detectable in such ranges as damp patches increasing to running water and running water increasing to spouting water.

6. Fractures or cold joints will need to be detected with measurements greater than 1mm in the three cardinal measurement directions of step, aperture and shear. Increase in lengths of fractures from the base measurement will need to be detected of greater than 5mm.
7. Missing brick and masonry

Examples of defects



Figure A1.1 Examples of cracking in tunnel surfaces.



Figure A1.2 Lining deformation (Shape measurement)



Figure A1.3 Ring separation as an example of delamination



Figure A1.4 Water ingress

Appendix 2 – Laboratory Based Techniques: Definitions and Terminology

Potential solutions	Description of technique
Robotics	The use of an autonomous device to move instrumentation around a tunnel independent of a rail mounted survey system. This could be deployed on a tunnel-by-tunnel basis, make measurements and cause no disruption to normal rail services.
Laser scan	Techniques using continuous laser range finding, like Omnicom, producing 3D point cloud data
Radar	Ground penetrating radar to measure voids, moisture, cracks and general integrity
Microwave reflectometry	Similar to radar, but different frequencies. L frequency penetrates more deeply, more sensitive to water, but with less resolution
Acoustic range finder (surface only)	Measures form of surface using speed of sound
Template + interferometer	For regular shaped tunnels, template is close to the form of the tunnel, interferometry measures relative to template over small range
Impact echo/ fired balls	Mechanical interaction with tunnel wall, balls of ice, CO2 etc. To produce acoustic energy in tunnel wall
Thermal pulse + interferometry	Technique used to measure mechanical properties by heating the surface with a laser spot and causing an acoustic signal then picking up local deflection close by with interferometer
Airborne ultrasonics (sub-surface)	Powerful speaker or directed acoustic energy into tunnel wall and then pick up return signal. Can use vibrometer to measure vibration.
3D-DIC	Two camera for stereo DIC measurement of depth rather than approx in plane
Stereo Photogrammetry	Two camera measurements to fixed markers of surface
Triangulation optical	Projection of laser disc of light onto wall of tunnel, camera mounted off axis and sees laser disc distortion which depends of surface form.
Projected images/structured light	Project pattern onto wall and image from different points, like 3D body scanners for digitising peoples bodies
Shearography	Interferometric speckle technique, tunnel is deformed and then interference pattern. Other alternative is to make a hologram of the tunnel and then project hologram back onto tunnel and see the interference patterns.
Fluorescence, IR spectroscopy	UV or IR light spectroscopy to try and highlight aspects of water seepage, calcite crystals etc.
Water sensitive paint	Paint inside of tunnel, if water is present paint turns red
Correlation techniques (DIC)	Two images before and after, process to find differences between images, independent of features, can detect cracking, in-plane deformation, water , plant growth etc.
Visual SLAM	visual Simultaneous Localisation and Mapping. So like DIC but identify features and create map. Bleeding edge robotic vision research!
Humidity sensor array/train mounted	Lots of humidity sensors to monitor local change in water ingress mounted on train so scans as travels through tunnel.
Wireless array of point sensors	Mechanism for allowing lots of point sensors to intercommunicate, could measure strain , moisture etc.
Fibre optics	Fibre optic sensing array, single fibre multiple sensors,

Potential solutions	Description of technique
	temperature, moisture, strain
Leaching of chemical tracer	Add something to the water or on the walls measure in the soil or in a gutter.
Presence of organisms / calcites	Techniques for identifying algae or moss or bacteria or deposits associated with water, maybe spectroscopic or evolved gases.
Gas analysis	A chemical nose or sniffer to detect change in local gas environment, associated with water ingress, cracks (Radon)
IR thermography, gas detection using	As gas analysis
Vibrational analysis of whole structure	Acoustic resonance of whole structure complex spectral information but may give a signature that indicates major or minor changes.
Surface Rayleigh wave	Create surface travelling wave, very sensitive to cracks and discontinuities, use special acoustic lenses coupled with water to tunnel wall
Localised resonance	As vibrational resonance but maybe with train as baffle, like Swanee whistle
Pressure pulse response	Make a bang see the signature for the whole tunnel
Thermography	Heat up the tunnel wall with heat lamps, then use IR camera to measure surface temp with time or at a fixed time.
Flash thermography	Use a flash heat source, maybe H power laser to create heat pulse in tunnel wall, use subsequent IR temp measurement to assess surface thermal properties
Microwave induced thermography	Use a microwave heat source to create heat pulse in tunnel wall, use subsequent IR temp measurement to assess surface thermal properties
Wave guide	Microwave/ radio frequency resonance of whole structure complex spectral information but may give a signature that indicates major or minor changes.
RF conductivity	Use GPR to measure tunnel wall properties
Resistance	Use contact probes to measure tunnel wall resistance to assess material properties and moisture
SAR	Synthetic aperture radar, high resolution radar measurements for shape measurement
Coherent laser	Laser ranging but now with .25mm resolution in range
TOF camera	Time-of-flight camera, each of 100's x 100's elements can measure distance to sub-cm resolution.

Appendix 3 –Results of brainstorm of laboratory based techniques

A more detailed description of each potential solution can be found in Appendix 2.

Cost of Equipment: H >£150k, M £20k-£150k, L <£20k

Time of measurement: L - seconds, M - minutes, H -hours
(in terms of possession time so a continuous or automatic solution will score L)

TRL (See Appendix 4): H>TRL 8, M TRL 4-8, L <TRL 4

Likely Accuracy: + Meets Specification, - Doesn't meet Specification

Potential solutions	Cost of equipment	Time of measurement	TRL	when measurement problems does this solve	Likely accuracy	Notes
Laser scan	M	M	H	1 2 4 6 7	+	6 is borderline
3D-DIC	M	M	M	1 2 4 6 7	+	
Stereo photogrammetry	M	H	M	1 2 4 7	+	
Triangulation optical	M	M	H	1-7 exc 5	+	
Projected images	M	M	M	1 2 4 7	+	
Radar	M	M	M	1-7	+	
Thermography	M	L	H	5	+	Evaporative cooling for water ingress
Flash thermography	H	H	M	3 5	+	
Impact echo	H	H	L	3	+	
Thermal pulse interferometry +	H	H	L	3	-	Could be destructive
Microwave reflectometry	M	M	M	1-7	+	
Microwave induced thermography	H	M	L	3 5	-	
Shearography	H	H	L	n/a	-	
Wave guide	L	L	M	5	-	For moisture measurement using train as baffle
Fluorescence	M	M	M	5	-	Chemical identification
Resistance	L	H	M	5	+	Contact technique
Robotics	H	L	L	1-7	+	Exceptionally high measurement cost
Vibrational analysis of whole structure	L	H	L	all or none	-	Of whole tunnel
Airborne ultrasonics *(sub-surface)	M	M	L	3	+	What frequency, depth of penetration
Acoustic range finder (surface only)	M	M	M	1 2 4 7	-	Variable humidity will effect accuracy
Surface Rayleigh wave	H	H	L	3 6	-	

Potential solutions	Cost of equipment	Time of measurement	TRL	which measurement problems does this solve	Likely accuracy	Notes
Template + interferometer	H	M	L	all or none	-	
Water sensitive paint	L	L	L	5	-	Change in colour of paint
Humidity sensor array/train mounted	L	L	H	5	+	With forced convection
Leaching of chemical tracer	L	L	L	5	-	
Presence of organisms / calcites	L	L	L	5	-	
Correlation techniques (DIC)	M	M	M	6 7 2 4	+	
Visual SLAM	L	L	M	2 7 4	-	Spontaneous location and mapping
Wireless of point sensors	M	L	M	1-7	+	Exceptionally high measurement cost
Fibre optics	M	L	M	1-7	+	Exceptionally high measurement cost. Temperature & humidity
Gas analysis	M	H	L	5 6	-	
IR thermography, gas Detection using	H	L	H	5 6	-	To see gases
Localised resonance	L	H	M	5	-	
Pressure pulse response	L	L	L	all or none	-	

Appendix 4 – Technology Readiness Levels

Programme Phase	TRL	Summary Description	Key Aspects
System Validation	9	Technology “qualified” through successful service operations	Actual application of technology in its final form under service operation conditions
	8	Actual technology completed and qualified through test & demonstration	Technology proven to work in its final form and under expected conditions
	7	Technology prototype demonstration in an operational environment	Prototype near to, or at, planned operational system. A major step forward from TRL6
Technology Validation	6	Technology model or prototype demonstration in a relevant environment	Representative model or prototype which is well beyond TRL5 tested in a relevant environment
	5	Technology validation in relevant environment	The basic technological components are integrated with reasonably realistic supporting elements and tested in a simulated environment
	4	Technology validation in a laboratory environment	Basic technological components are integrated to establish they will work together. Low fidelity compared with the eventual system
Concept Validation	3	Analytical & experimental critical function and/or characteristic proof of concept	Active research and development is initiated. Includes analytical & laboratory studies to physically validate analytical predictions of separate elements
	2	Technology concept formulated	Invention begins. Application is speculative, with no proof or detailed analysis to support the assumption
	1	Basic principles observed & reported	Scientific research begins to be translated into applied research & development

Appendix 5 – Standard Industry Codes (SIC's)

After selection the following codes were identified that might be useful to this project these were from the *UK Standard Industrial Classification of Economic Activities 2003* from the Office of National Statistics.

SIC Code	Activity
02.01	Forestry and logging
10.1	Mining and agglomeration of hard coal
11	Extraction of Crude Petroleum and Natural Gas; Service Activities Incidental to Oil and Gas Extraction Excluding Surveying
14	Other Mining and Quarrying
15.61/2	Manufacture of breakfast cereals and cereals-based foods
17.2	Textile weaving
17.51	Manufacture of carpets and rugs
20.1	Saw milling and planing of wood, impregnation of wood
21.24	Manufacture of wallpaper
23.3	Processing of nuclear fuel
26.11	Manufacture of flat glass
27.1	Manufacture of basic iron and steel and of ferro-alloys
27.32	Cold rolling of narrow strip
28.11	Manufacture of metal structures and parts of structures
28.4	Forging, pressing, stamping and roll forming of metal; powder metallurgy
28.5	Treatment and coating of metals; general mechanical engineering
34.2	Manufacture of bodies (coachwork) for motor vehicles; manufacture of trailers and semi-trailers
35.2	Manufacture of railway and tramway locomotives and rolling stock
35.3	Manufacture of aircraft and spacecraft
40.1	Production and distribution of electricity
40.11	Production of electricity
40.12	Transmission of electricity
45.1	Site preparation
45.21	General construction of buildings and civil engineering works
45.23	Construction of motorways, roads, railways, airfields and sports facilities
60.1	Transport via railways
60.21/3	Urban and suburban passenger transportation by underground, metro and similar systems
62.3	Space transport
73.1	Research and experimental development on natural sciences and engineering
74.2	Architectural and engineering activities and related technical consultancy
74.20/1	Architectural activities
74.20/3	Quantity surveying activities

SIC Code	Activity
74.20/4	Engineering consultative and design activities
74.20/6	Engineering related scientific and technical consulting activities
74.20/9	Other engineering activities
74.3	Technical testing and analysis
74.60/1	Investigation activities
74.60/2	Security and related activities
92.11	Motion picture and video production
92.6	Sporting activities
Additional	Maintenance
Additional	Surveying
Additional	Satellite Imaging
Additional	Gauging
Additional	Manufacture of optical sensors
Additional	Aircraft manufacture
Additional	Bridge construction
Additional	Tunnel boring
Additional	Motorway construction
Additional	Body scanning
Additional	Motion capture
Additional	Military use
Additional	Robotics
Additional	Medical imaging

Appendix 6 - Sectors and application areas, which might have technology solutions applicable to tunnel measurement

Pipes and tunnels

- Service Activities Incidental to Oil and Gas Extraction
- Pipeline inspection
- Tunnels for telecoms
- Utilities

Surveying enclosed areas

- Mining and Quarrying

Scanning moving objects for defects

- Textile weaving, Manufacture of carpets and rugs,
- Machining wood
- Manufacture of wallpaper
- Manufacture of flat glass
- Cold rolling of narrow strip, treatment and coating of metals

Scanning large static objects for defects

- Manufacture of aircraft and spacecraft
- Examination of wings and rotors
- Ships
- Submarines
- Civil engineering structures like underpasses, subways
- Transmission of electricity, cables, pylons
- Wind turbines

Surveying

- Site preparation,
- General construction of buildings and civil engineering works, Construction of motorways, roads, railways
- Bridge construction, tunnel boring,
- Dams
- Spillways
- Architectural and engineering activities and related technical consultancy

Transport via railways

- Urban and suburban passenger transportation by underground, metro and similar systems

Research and experimental development on natural sciences and engineering

Satellite Imaging:

- Sea level measurement etc.
- Land use
- Forestry
- Farming

- Robotics
- Medical imaging

Engineering related scientific and technical consulting activities

- Technical testing and analysis
 - NDE
- Security and related activities
 - Anti-counterfeiting
 - CCTV
- Motion picture and video production
 - Motion capture
- Sporting activities
 - Motion capture, Hawkeye, body scanning
- Maintenance of civil engineering structures
- Manufacture of optical sensors and gauges
- Nuclear
 - Processing of nuclear fuel
 - New build
 - Storage
 - Deep geological disposal: integrity
 - Internal components

Medical

- Stents
- Endoscopes/Borescopes

Military use

- Range finding
- Radar technologies
- Satellite Imaging
- Assessing damage

Environmental monitoring

- Sea wall defence

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