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A review of techniques suitable for measuring position or strain in Civil Engineering structures

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ABSTRACT

This report identifies commercially available techniques that might be useful for measuring position or strain in Civil Engineering structures. These techniques are reviewed and then used in a SWOT analysis to ascertain the best techniques for studying typical Civil Engineering measurement scenarios.

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1. INTRODUCTION

Optical image measurements are a non-contact versatile technique that can be used for displacement and strain measurements for a wide variety of structures. These techniques are generally well established for laboratory measurements but are relatively undeveloped for use outside controlled laboratory conditions. In particular the use of these techniques for examining large civil engineering structures is highly innovative, but the practical measurement issues are formidable. A good understanding of the effects of environment, such as lighting variation, non-perpendicular imaging and vibration on the expected errors is essential for wide-scale acceptance of this technique for monitoring the built environment.

Many asset owners and contractors are looking for a simple system that will easily and quickly evaluate the heath of a structure and help develop potential maintenance and repair strategies. It is believed that optical based measurement technologies have the potential to effectively fulfil this application requirement. If this technology is going to be embraced by the private sector then benchmarking and validation exercises against existing measurement techniques are essential to give any proposed optical solution credibility.

An initial brainstorm was carried out at NPL with the project partners to try and identify techniques that might be useful for measuring position or strain in Civil Engineering structures. These are listed below.

Optical

- Imetrum (2D/3D)
- DIC (2D & 3D)
- Total stations
- Laser sensor / tracker (interferometer)
- Laser distance

Sensors on structure

- Displacement
  - LVDT
  - Potentiometer
  - Mechanical methods (tape measure / ruler / string lines etc)
  - Dial gauges
- Strain
  - FBG
  - Strain gauges
- Indirect
  - Accelerometers
  - Tilt meters
- Position
  - GPS

Other distance measurements

- InSar

These and other techniques will be technically reviewed against the measurement criteria listed in section 2.

2. MEASUREMENT CRITERIA

Long term monitoring versus test

Routine test measurement
24x7 fixed, defined period
24x7 permanent installation

Type of measurement Static / dynamic

Real time measurement

In plane or out of plane measurement

Strain vs shape

Full field versus discrete measurement

What are the numbers of points made by the measurement?

Quality of measurement

Accuracy / drift / resolution = quality of measurement (go/no-go indicator)
Reference points needed
Reproducibility
Direct measurement versus indirect
Data interpretation

Ruggedness

Environmental sensitivity
Lifespan of equipment: Moving parts in the sensor
Calibration and maintenance

Cost of measurement

Installation on structure Installation time / cost
Contact / non-contact
Cost of equipment
Health and safety considerations
Deployment ease / ease of use
Survey/continuous operation
Semi-skilled versus skilled operators for in-situ measurements
(excluding post processing requirements)
Data file size
System integration

Technology Readiness Level

Market acceptance / coverage

This list of criteria with their associated questions will be used to help assess the relative merits of the different techniques.

3. LITERATURE/INTERNET SURVEY

From this initial list of techniques as a basis an internet/literature survey was undertaken to identify other techniques that might be relevant. Typically these techniques will have a high technology readiness level (TRL) as they may be well established in a particular industry sector. The sectors chosen were selected by NPL business development experts for various sectors on the basis of similarity to the measurement issues involved with bridge measurement. This could include similarity of structure or type of measurement needed.

An Internet/literature search was then made within each of these sectors trying to identify solutions that might useful for bridge measurement.

Pipes and tunnels

Investigating service activities incidental to oil and gas extraction and also techniques used for pipeline inspection and for tunnels used for telecoms and utilities [1-3]. The techniques in these sectors are mainly based around fibre optic sensors for strain and corrosion and also ultrasonics for metallic pipe wall thickness inspection.

Mining and Quarrying

There are considerable uses of laser scanners for assessing shape and volume of enclosed spaces such as vertical mine shafts [4]. Commercial modules for laser scanning with a resolution of about 4 mm are manufactured by Sick [5] and scanners can even be used in very small bores [6]. Robotic total stations can be used but they can only measure 250 points per second [7], which is much slower than other 3D laser scanning of mines[8] but at a resolution of about 2mm.

Scanning large static objects for defects

Scanning and shape measurement is used for the manufacture of aircraft and spacecraft and has been used for the examination of wings and rotors [9]. BAe have used DIC for measuring wing shapes using a portable fringe projection system. For measuring the shape of hulls for ships [10] sub mm laser measurements with a resolution of about 0.25mm have been successfully made using coherent laser scanning. The shape of submarine hulls needs to be determined accurately for sonar sensing applications, both dynamic sub hull shape measurement [11] and by semi-manual measurement of shape during manufacture by a combination of shape measurement via laser tracker and hull integrity using ultrasonics, but needs human to move "mouse" around [12].

Surveying

There are many requirements for shape and dimension measurement in surveying applications. These include site preparation [13], where total stations with a resolution of 2mm and 2ppm are used. For large structures like dams there have been comparisons between laser scanning and SAR interferometry which has sub mm resolution [14].

Research and experimental development in natural sciences and engineering

This section covers many different techniques. Satellite imaging has been used for sea level and ice sheet measurement etc. When SAR interferometry has been used then 1-2m height resolution for topography and mm for relative displacements can be achieved [15]. If urban measurements are made by using plane mounted SAR then 0.1m resolution can be achieved and this has applications in land use, forestry, and farming [16]. For robotics LIDAR can be used with an accuracy of 10-50 mm [17]. In other applications in robotics systems using structured lights can achieve 0.1mm resolution [18].

In whole body measurement for medical imaging then volumes of about a 1m cubed 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 [19].

In archaeology a laser pantograph has been used to measure shape [20] and there are many examples of the creation of 3D laser scans of buildings [21].

Another device that has been developed is the time-of-flight camera [22] and this is very promising as a high speed/low accuracy shape measurement device and will be discussed in more detail later.

4. REVISED LIST OF TECHNIQUES

The techniques that measure in-plane local deformation are in italics.

Optical sensors
1 *Imetrum 2D*
2 *DIC 2D*
3 DIC 3D
4 Total stations
5 Laser sensor / tracker (interferometer)
6 Coherent laser scanning
7 Laser scanners
8 Structured light
9 Time-of-flight camera

Sensors on structure
10 Displacement
- LVDT
- Potentiometer
- *Mechanical methods (tape measure / ruler / string lines etc)*
- *Dial gauges*

11 Strain
- *FBG*
- *Strain gauges*
- *Optical crack gauges*

12 Indirect
- Accelerometers
- Tilt meters

13 Position
- GPS
- Pseudolites

Other distance measurements
14 InSAR

Optical sensors

4.1. IMETRUM 2D

Introduction

Imetrum [23] make a Video Gauge that typically measures displacement to a resolution of 1/100,000 of the field of view of the image. The technique involves tracking user-specified locations in a video image using pattern recognition software. Video can also be recorded for post processing. The system measures relative movement – strains, rotations and extensions are outputted in real time, whilst actual displacements can be obtained by simple post-processing.

The system is commercially available for materials testing applications, where it is typically used to measure in place of traditional strain gauges and extensometers. It is starting to be used for in-situ measurements of large structures, although bespoke solutions are not commercially available yet.

Hardware requirements are an industrial specification video camera and dedicated computer. Sampling rate is dependent on the camera used, but is usually either 5, 15 or 120Hz. Higher frequency and higher definition cameras can be used and data still processed in real time, although storing video becomes problematic at higher frequencies and resolutions due to large file sizes.

The system is designed to have multiple cameras attached easily to either generate a 3D understanding of movement, or cover a larger area of a structure.

Figure 1. The Imetrum Video gauge

Long term monitoring versus test

The Imetrum 2D system can be used for routine test measurement, 24x7 fixed and permanent installation, provided a stable base is used and a suitable environmental housing.

Type of measurement Static / dynamic

Real time, dynamic measurement is the most common application of the system to date, although static monitoring is also possible, either by averaging data over long periods of time, or by switching the system off and on.

In plane or out of plane measurement
In-plane measurement of displacement and strain can be made, although when a large field of view is selected (for example when monitoring a whole structure using a single camera), highly localised strain cannot be measured. Out-of-plane measurement can also be measured, with the resolution proportionate to the distance of the camera from the object, making it viable at close range (less than 10m) only. Using multiple cameras and integrating the data gathered off-line gives a full understanding of a structures' performance.

Full field versus discrete (numbers of points of measurement)

Full field data capture by video, which is then transferred to discrete points by system user. In reality this is, a discrete system for day-to-day use, but with video recording, can be full-field (a grid of points can be added to an image, with up to 100 points tracked in real time).

Quality of measurement

Dependent on the Field of View, more than distance (need to use different lenses for different distances from image). Typical resolution is 0.01 pixels, or 1/100,000 of field of view (in each axis) for the standard camera (higher definition cameras can be used). Measurement is not susceptible to drift over time. Movement of the camera can be corrected by using a reference point within the field of view. The measurements are direct measurements of image deformation, with strain and rotation derived from these measurements. The ability to easily re-examine the images if there are anomalous features is a strength.

Ruggedness

With a suitable housing then the cameras will have suitable environmental protection. Changes in lighting in particular have an impact on the measurements, but these can be mitigated in the software, by artificial lighting or by using targets.

The system does not have moving parts, and has no need for calibration.

Cost of measurement

Installation cost is minimal for the camera system, although with environmental housings and mountings will cost a few thousand pounds. A basic single camera system starts at around £5k for hardware, with a monthly software licence of around £1k. Multiple camera systems may be necessary for large structures, which will include added complexities to ensure data synchronization. Data storage and analysis will involve additional cost (if large video files are needed to be stored). Depending on lighting conditions and definition of the object being monitored, targets may or may not be required. If targets are required they can be painted, and so are cheap.
There are no health and safety considerations and the system can be easily deployed on a surveyors tripod, or purpose-built mount. Can be used by semi-skilled operators, using laptop interface, or can be plugged into existing data loggers.

Technology Readiness Level

Good market acceptance and coverage within materials testing (TRL of 9). A number of trials have been conducted with large structures that have produced good results, but for in-situ measurement, TRL is about 7.

4.2. DIC 2D

Introduction

Digital image correlation (DIC) is a technique used to measure deformation of a surface by comparing two images [24-27]. The images are essentially before and after something of interest has taken place. They can then be processed using DIC software such as [28, 29] 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.

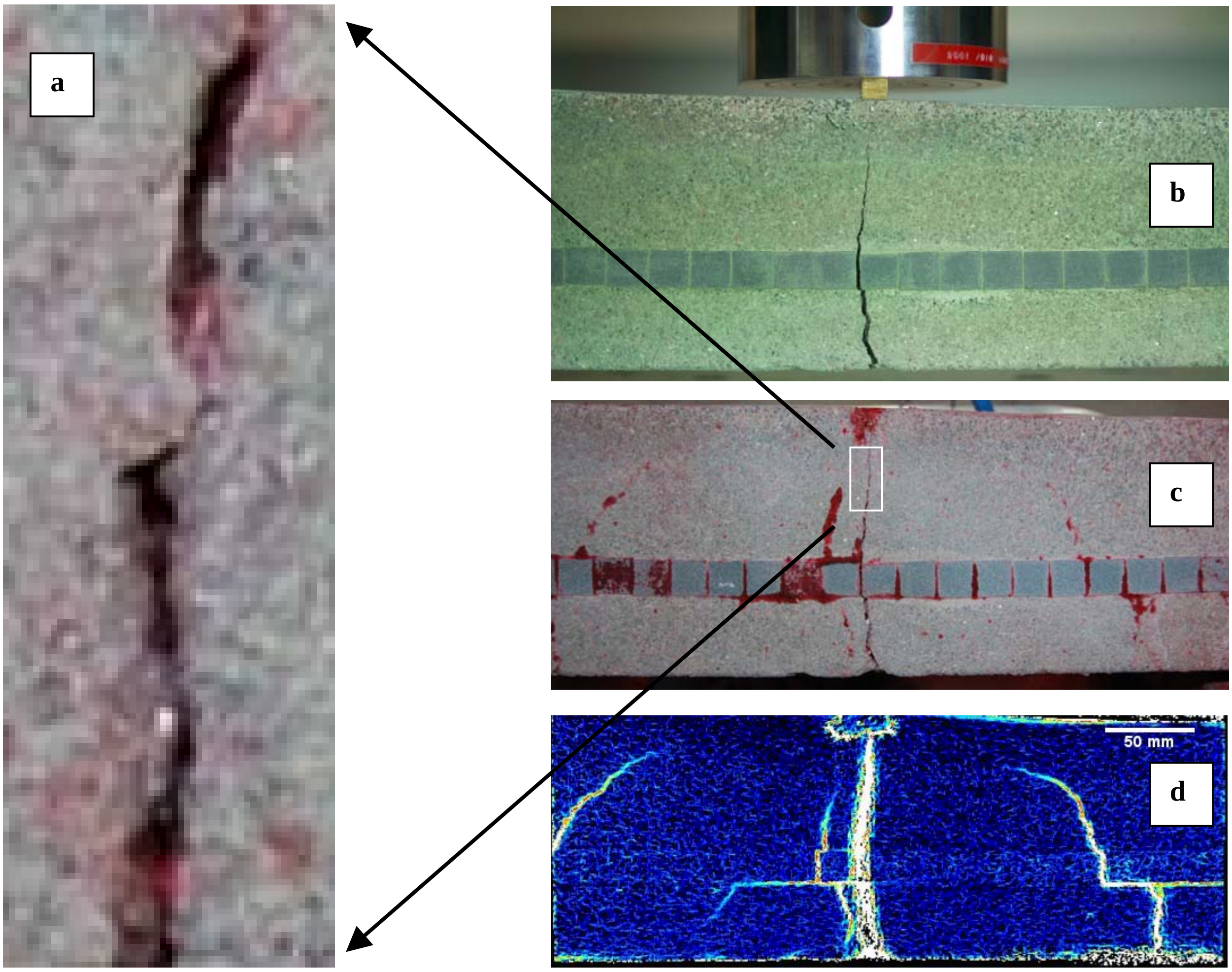

Figure 2. A cracked concrete specimen, Figure 2a shows a close up of the crack in Figure 2c. Figure 2b shows the concrete specimen during testing. Figure 2c shows the cracks identified using dye penetrant, Figure 2d shows a DIC image plotting "strain" or local deformation, light areas indicate where there is high "strain".

The technique is well developed for use in the laboratory but it has had limited trials for in-situ measurements of large-scale structures [25]. However recent developments have identified the ability of the technique for measuring crack opening [26-28] and detecting changes in images [24], Figure 2, which is ideal for structure examination when the images compared are those acquired months or years apart.

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 [29, 30] 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.

Long term monitoring versus test

DIC can be used for routine test method and for 24x7 fixed and permanent installation, however 24x7 installation will probably not be with such high resolution and expensive cameras.

Type of measurement Static / dynamic

Although real time image capture at the frame rate that uncompressed images can be captured/stored is possible, considerable post-processing will be required.

In plane or out of plane measurement

In-plane measurement of displacement and derived strain can be made. If the strain field is known then image matching can be made using higher-level strain pattern fitting.

Full field versus discrete (numbers of points of measurement)

Currently can be up to 160 million per field of view per image. Stitching images can increase this value.

Quality of measurement

Needs two images so a differential measurement is made, the reference image(s) needs to be similar to the final images. The typical resolution is 0.05-0.1 pixels or greater then 1 part in 100,000 of the field of view. Parameters calculated during processing give an estimate of the quality of the measurement on a pixel by pixel basis. Reproducibility is mainly determined by the quality of the repositioning/stability of the camera mount. The variations introduced by individual cameras can be easily measured and calibrated out using well established techniques. The measurements are direct measurements of image deformation, with strain derived generally from these measurements. The ability to easily re-examine the images if there are anomalous features is a strength.

Ruggedness

With a suitable housing then the cameras will have suitable environmental protection. However they will be susceptible to atmospheric conditions and changes int he structure due to rain, snow etc, However these changes will be easily detectable and hence their will be a low incidence of false positives?

The moving parts in conventional SLR cameras are mirror movements and shutter movements. However these types of cameras are generally of a high state of reliability as they are commodity/professional equipment.

Calibration of the system can be performed by measuring fixed targets in the field of view or by introducing a pattern on to the area of interest periodically.

Cost of measurement

The system is non-contact and so there are no installations required on the structure. However a suitably robust and stable mount is required for the camera to ensure no unwanted movements. The very high-resolution cameras are expensive but the trickle down effect into more reasonably priced alternatives means that the cost of equipment is falling.

Deployment is very simple with few H&S issues. The measurement is better suited to survey operations since the complexity of a weatherproof housing and its effect on the image and measurement accuracy can be avoided.

Although care is required in setting up the equipment it can be done by semi-skilled operators with a degree of assurance that the images are suitable after casual examination.

The size of the data files, particularly for high-resolution images makes transfer by the internet problematic, however the size of hard disks etc. mean that storage isn't an issue. It can be harder to integrate image based measurements into a system unless the region of interest (ROI) is known in advance.

Technology Readiness Level

The TRL for the technique in a laboratory environment is 9 but for in-situ measurements it is probably about 5 although work at NPL is developing this technique towards 6-8.

4.3. DIC 3D

Introduction

3D DIC is very similar to 2D DIC except the two images to be compared are captured simultaneously or near simultaneously with a spatial separation between the positions of image capture to produced a stereo pair. The stereo pair is processed using DIC techniques and the relative lateral displacements between images from the two cameras can be converted to height differences or topography. The cameras can either capture images simultaneously on a fixed baseline or by capturing images from the same camera as it has been moved. It is important to know accurately the position and orientation of the camera during this process.

Long term monitoring versus test

3D DIC can be used for routine test method and for 24x7 fixed and permanent installation, however 24x7 installation will probably not be with such high resolution and expensive cameras. As the camera images are used in pairs then if two cameras are used then they must have a fixed base joining them that is stable with time. If one camera is used to synthesise two cameras then accurate orientation and positioning is needed.

Type of measurement Static / dynamic

Although real time image capture at the frame rate that uncompressed images can be captured/stored is possible, considerable post-processing will be required.

In plane or out of plane measurement

Out of plane measurement of shape is derived from this technique.

Full field versus discrete (numbers of points of measurement)

Can be up to 160 million per field of view per image. Stitching images can increase this value.

Quality of measurement

This technique needs a pair of stereo images captured simultaneously or within a short time. The typical resolution depends on the length of the base line between the two cameras and the accuracy that similar areas can be matched in the two images, which is typically 0.05-0.1 pixels or greater then 1 part in 100,000 of the field of view. So for a distance between cameras of 1m and a working distance of 10m and image width of 2m with 9000 pixels a range accuracy of 0.2 mm is possible.

Parameters calculated during processing give an estimate of the quality of the measurement on a pixel-by-pixel basis. Reproducibility is mainly determined by the quality of the repositioning/stability of the camera mounts and the ability to maintain a stable baseline between the cameras. The variations introduced by individual cameras can be easily measured and calibrated out using well-established techniques.

The measurements are direct measurements of shape referenced to a plane parallel to the baseline. The ability to easily re-examine the images if there are anomalous features is a strength.

Ruggedness

With a suitable housing then the cameras will have suitable environmental protection. However they will be susceptible to atmospheric conditions and changes in the structure due to rain, snow etc.

However these changes will be easily detectable and hence their will be a low incidence of false positives?

The moving parts in conventional SLR cameras are mirror movements and shutter movements. However these types of cameras are generally of a high state of reliability as they are commodity/professional equipment.

Calibration of the system can be performed by measuring fixed targets in the field of view or by introducing a pattern on to the area of interest periodically.

Cost of measurement

The system is non-contact and so there are no installations required on the structure. However a suitably robust and stable mount is required for the camera to ensure no unwanted movements. The very high-resolution cameras are expensive but the trickle down effect into more reasonably priced alternatives means that the cost of equipment is falling.

It is more expensive than 2D DIC as an apparatus for fixing the camera baseline is needed, and two cameras or more might be needed.

Deployment is very simple with few H&S issues. The measurement is better suited to survey operations since the complexity of a weatherproof housing and its effect on the image and measurement accuracy can be avoided.

Although care is required in setting up the equipment it can be done by semi-skilled operators with a degree of assurance that the images are suitable after casual examination.

The size of the data files, particularly for high-resolution images makes transfer by the internet problematic, however the size of hard disks etc. mean that storage isn't an issue. It can be harder to integrate image based measurements into a system unless the ROI is known in advance.

Technology Readiness Level

The TRL for the technique in a laboratory environment is 7 but for in-situ measurements it is probably about 5 although work at NPL is developing this technique towards 6-8.

4.4. TOTAL STATION

Introduction

A total station is a combination theodelite and laser electronic distance measurer (EDM). The vertical and horizontal angles are measured as a telescope with cross hair is used to sight the instrument on a target. By making a distance measurement then the relative position of the point to the instrument can be made. The vertical angle is measured relative to the direction of gravity angle and any slight misorientation of the instrument is compensated for by a floating mirror arrangement. The horizontal angle can be measured relative to magnetic north but it is more usual to use some additional reference targets on the structure to create a local coordinate system. A robotic variant uses a corner cube or patterned target to sight the system automatically if the target doesn't move too rapidly.

Figure 3. A total station

Long term monitoring versus test

A total station was originally designed for use in survey conditions such as routine test measurements. The more recent variants can now lock onto a target and also steer between a series of target positions making 24x7 measurements for a short term defined period or even as a 24x7 permanent installation, as on the Jubilee Line extension in London.

Type of measurement Static / dynamic

Real time measurement at a rate of about 1 measurement per second is possible with readily available equipment, depending on how much a robotic total station has to move between targets.

In plane or out of plane measurement

The measurement is a full shape measurement and includes in-plane and out of plane movement.

Full field versus discrete (numbers of points of measurement)

Realistically only 10's of points will be measured practically, at a measurement frequency of about one minute as the system is moved from one measurement point to the next.

Quality of measurement

The range accuracy of a typical total station is typically 2 mm at distances of up to about 100m. Total stations with different angular resolutions are available. The highest lateral resolutions obtainable are about 0.25mm at range of 100m although more common resolutions might be 2 mm. The distance measurement is effected by the humidity and temperature and typically after compensation for environmental factors the uncertainties are 2ppm for distance.

Total stations can use retro reflector targets and more recently simple white targets. If there is sufficient contrast suitable features might already exist on a structure that can be used as targets. Usually additional targets might be needed to determine the reference position of the total station but these would be similar to all techniques, which rely on accurate positioning of the measurement equipment. The stability of these instruments is very good and by using external targets the position of the total station can be eliminated from the measurement of structure shape.

The total station provides a direct measure of 3D position and requires little data interpretation.

Ruggedness

Modern total stations are robust equipment designed to be used on building sites and for surveying in arduous conditions. However they are susceptible to rain and inclement atmospheric conditions as they are an optical measurement.

They are complex precision pieces of equipment and may be expected to have a limited lifetime. They would have to be returned to the manufacturer for routine calibration and maintenance.

Cost of measurement

Minimal installation is required on a structure, in some cases targets might not be needed, although for most robotic tracking measurements with no human intervention a target is likely to be needed at the point of interest. Therefore the system is non-contact.

The cost of a total station may be £5k to £30k depending on the resolution and range of the equipment and the number of automatic tracking features present. The laser produces radiation, which is safe to use in a site environment. Modern total stations can be setup relatively quickly and have built in software to generate a resection to provide a local coordinate system, this lowers the skill level required to operate this type of equipment. Once the target points have been surveyed and mapped using the total station then the system can be programmed to track that series of targets automatically. The data produced is compact and describes the 3D position of the targets with respect to the local coordinate system and can be readily integrated with other systems.

Technology Readiness Level

This is a mature technology and has widespread usage in the civil engineering sector, incremental performance improvements are made to accuracy and speed of measurement regularly but the technique is unlikely to change radically in the near future.

4.5. LASER SENSOR / TRACKER (INTERFEROMETER)

Introduction

A laser tracker uses a laser interferometer combined with a pan and tilt mechanism to track the position of a retro reflector target as it moves[31]. It is different from a total station in that it can make range measurements to 0.05 mm over a much smaller total distance of up to 10's m, but with generally higher accuracy and usually with a greater number of measurements per second. They are generally designed for an indoor environment but can be used outside with weather protection in benign environments. They can track targets moving at up to 5 m/s.

Figure 4. An example of some laser trackers

Long term monitoring versus test

A laser tracker can be used for routine survey type test measurements and also for 24x7 fixed, defined period and permanent measurements, although atmospheric variability may cause problems.

Type of measurement Static / dynamic

Real time measurement

In plane or out of plane measurement

This is a 3D shape measurement

Full field versus discrete (numbers of points of measurement)

Discrete measurement, just one point at a time, although could have lots of targets.

Quality of measurement

Accuracy of this measurement is likely to be about 50 micrometres referenced to the base of the laser tracker, although a local coordinate system like that used for total stations can be set up so reference points will be needed for orientation and alignment. This system is likely to be very reproducible and is the basis of transfer standards for coordinate measurement machines.

It is a direct measurement of 3D position and needs little data interpretation.

Ruggedness

Current systems are more suitable for indoor use and as precision machines they need good temperature stability, which might limit their use outside to very benign conditions. They have few moving parts but are of great precision and would need substantial maintenance and calibration regularly.

Cost of measurement

A laser tracker is portable and would require little installation. Control of temperature might be an issue in extreme circumstances. The technique is non-contact only requiring a small retro-reflector target.

A full 3D laser tracker would give full coordinates of a target, but is likely to be expensive >£15000 such as [http://www.faro.com/lasertracker/whats-new/]. There are minimal health and safety considerations and once locked onto a target and a reference coordinate system set-up they are automatic and suitable for a survey or with a well-designed enclosure long-term operation although temperature and humidity changes will effect the measurements. They can be used by semi-skilled operators and provide an easy to integrate digital signal of retro reflector position.

Technology Readiness Level

Laser trackers are regularly used in high precision metrology and calibration scenarios but are not commonly used outside the laboratory because of environmental considerations.

4.6. COHERENT LASER SCANNING

Introduction

By using a heterodyned frequency approach such as a coherent laser scan then the accuracy of the laser range measurement may approach 0.25 mm even for quite large surfaces [10-11]. 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 5. The Metris Coherent laser radar. The only commercial coherent laser scanner currently available.

Long term monitoring versus test

A coherent laser scanner can be used for routine test measurements for survey type applications.

Type of measurement Static / dynamic

Real time dynamic measurement for each pixel, but typical scans make take seconds to minutes depending on number of points measured.

In plane or out of plane measurement

This is a 3D shape measurement

Full field versus discrete (numbers of points of measurement)

The measurement is generally full field although smaller areas of interest can be scanned in shorter time periods.

Quality of measurement

The typical accuracy might be expected to be about 0.25mm with no reference points needed. By fitting surfaces to the point cloud generated accuracy may be improved. It would be expected that the measurement would be highly reproducible as long as the atmospheric conditions were measured. It is a direct measurement of shape and the data interpretation would be aided by having a full field measurement.

Ruggedness

Although the technique has been used to monitor large structures these have generally been in shipyards or in enclosed areas. It is expected that the measurements would be susceptible to environmental conditions through the influence on the speed of light. The equipment is from a very limited range of manufacturers and has precision moving parts.

Cost of measurement

No installation costs beside a stable base are required. It is a non-contact measurement technique with minimal health and safety considerations. A system would be easy to deploy and use and suitable for skilled operators. The data size would be quite large as a point cloud is generated and integration into systems would require considerable processing and interpretation.

Technology Readiness Level

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. Coherent laser scanners are only available from Metris, Figure 2, although well developed it is not widely used.

4.7. LASER SCANNERS

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 [32], security scanner [33] and is used in surveying instruments such as total stations [13]. When it is combined with a scanning head then full field 3D measurements [34] are possible and the system has been widely used for many applications including nuclear fuel processing [35] and more commonly surveying and measurement in mining and quarrying [4-8] and archaeology and architecture [21].

The scale of scanners and objects scanned can vary considerably with scanners mounted on aircraft for large-scale structure and city measurement [36][17]. There are even examples of miniature scanners being used in endoscopy within the human body [37].

Figure 6. A commercial laser scanner

Long term monitoring versus test

Laser scanners are generally used for routine test measurement in a survey type application.

Type of measurement Static / dynamic

Although this is real time measurement as each point in the point cloud may be acquired at 10,000~100,000 points every second it might take seconds to minutes to generate a 3D point cloud and so it is a static measurement.

In plane or out of plane measurement

This technique measures 3D shape.

Full field versus discrete (numbers of points of measurement)

This is a full field measurement capable of producing full 360-degree point clouds.

Quality of measurement

In these systems the typical error in the range measurement (radial direction) is probably about 2-5 mm, (depending on the scan speed) [38]. Although no reference points are needed, as surfaces may be fitted to observed structures within the point cloud, it is more normal to use a few well-positioned targets to aid alignment. Generally these are reproducible direct measurements and are easy to interpret since full field data is produced. Errors caused by unwanted reflections of water and shiny surfaces can produce anomalous data.

Ruggedness

Laser scans are increasingly being carried out in the field and the instruments are suited for use in a building or maintenance type environment. They do rely on precision movement of rapidly moving mirrors but can be easily calibrated on site.

Cost of measurement

Equipment setup is quite quick for a survey and they require no installation of targets on the structure, although additional targets may help with alignment of data sets subsequently. The equipment is typically £60k with no health and safety implications as the laser is eye safe. They are suited to survey operations by skilled operators. They can produce extremely large data files and system integration is not trivial.

Technology Readiness Level

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. Many types of scanners exist and they are a mature technology for many types of civil engineering surveys.

4.8. STRUCTURED LIGHT

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 determine 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.

There are some optical systems, which use minimal triangulation, or none at all, to image the surface [39-44].

Systems using portable fringe projection have been tried [9]. Systems using structured light in the form of grids or stripes [18, 19, 45] 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 x2 metres [46]. Such systems have been used to create realtime video rate 3D data acquisition for Radiohead videos [47].

Figure 7. A point cloud captured in real time using a structured light scanner

Long term monitoring versus test

Structured light systems are more generally used in survey scenarios for routine test measurement. They can be used for 24x7 measurements and the light pattern will need to be moved over the surface perhaps with a projector or mechanical scanner. Additionally high levels of light and uneven lighting like strong shadows means measurement might be harder during the day, although infra-red illumination can be used.

Type of measurement Static / dynamic

Real time measurement is possible, at over 60Hz, Figure 7.

In plane or out of plane measurement

This is a 3D shape measurement that produces a point cloud.

Full field versus discrete (numbers of points of measurement)

This produces a full field measurement with potentially many points.

Quality of measurement

The techniques using structured light and optical triangulation are well developed. The increasing resolutions 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.

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).

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.

No reference points are required and a direct measurement is made of shape. The usual issues with interpretation of point cloud data exist.

Ruggedness

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. In some situations shadowing may take place too. Some versions of this system for surveying from a moving platform mean that there are no moving parts although generally the light pattern will need to be scanned over the surface.

Calibration would generally take place in situ perhaps using reference points.

Cost of measurement

No installation is required on the structure for this non-contact method. A Konica Minolta range 7 scanner costs typically $80,000, although simpler large scale scanners can be constructed using COTS.

There are no health and safety considerations and the system can easily be deployed. It can be used for survey or more unusually continuous operation and can be used by semi-skilled operators for in-situ measurements. The data will generally be 3D point cloud data but in a structured grid which reduces processing requirements. System integration will only be by semi-manual selection of a ROI.

Technology Readiness Level

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.

Balfour Beatty recently acquired LaserRail and now has the LaserFleX [48] system that is commercially available and capable of tunnel examination. The Mermec T-Sight 5000 [49] is a similar system also designed to use the triangulation method to measure rail tunnel geometry.

4.9. TIME-OF-FLIGHT CAMERA

Introduction

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 [22]. 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 [50].

Figure 8. The Mesa time-of-flight camera

Long term monitoring versus test

This type of system can be used for all types of measurement, including routine test measurement and 24x7 measurements.

Type of measurement Static / dynamic

The TOF camera can be used for real time measurement. The TOF camera can capture 176 x 144 pixels at 54 fps (although there are higher performance devices available).

In plane or out of plane measurement

This system measures 3D shape in a structured grid.

Full field versus discrete (numbers of points of measurement)

The system can make a full field measurement at a relative low resolution although the high frame rate means that mechanical dithering can be used to increase the spatial resolution whilst still making realtime measurements.

Quality of measurement

The current accuracy of the system is likely to be about 5mm but 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.

No reference points are needed and the system should be quite reproducible as it is solid state. It is a direct shape measurement and requires minimal data interpretation.

Ruggedness

There is similar environmental sensitivity to the other optical measurement techniques. However there are no moving parts in the sensor, which should make the system reliable and stable. Calibration would need to be done in-situ.

Cost of measurement

No installation on the structure is required for this non-contact technique. TOF cameras are commercially available from Mesa Imaging and PMD amongst others and may cost £6000. There are no health and safety considerations and deployment is easy. The system can be used for survey or continuous measurement and can be used in an automated system or by semi-skilled operators. The 3D surface grid produced will require semi-manual system integration.

Technology Readiness Level

These devices are new to the market but are commercially available, it is expected that there may be relative rapid improvement in device performance as they are used for commodity products like game motion input devices, for Microsoft (although this technology may not be in this type of controller after all! [51]).

Sensors on structure

4.10. DISPLACEMENT

Introduction

Displacement can be measured on a civil engineering structure using a variety of point sensors these can be in a wired or wireless network although for the latter suitable sources of power are required for long term measurement. There are many sensors that can be used for this but the most common are linear variable differential transformers (LVDT)[52], potentiometers and various manual mechanical measurement techniques, like tape measures / ruler / string lines and dial gauges.

Figure 9. A selection of LVDT's

Long term monitoring versus test

Manual measurement techniques are used for routine test measurement and survey work, the electrical sensors like LVDT's can be used for 24x7 measurements.

Type of measurement Static / dynamic

Manual measurements are generally confined to static situations whilst real time measurement can be made using electrical sensors like LVDT's.

In plane or out of plane measurement

All the displacement measurement techniques have the potential to make in-plane or out of plane measurements as they are generally two ended measurement techniques and make a relative measurement between a reference point and the point of interest. For measurements made out of plane for a flat-faced structure then an additional reference point would need to be constructed.

Full field versus discrete (numbers of points of measurement)

These measurement techniques are restricted to discrete measurements with one measured displacement per fixed sensor. Manual techniques can make multiple measurements with each instrument but generally not enough to produce a full field measurement.

Quality of measurement

LVDT's are capable of very high accuracies limited only by the resolution of the logging device and the stability of the temperature. Issues with drift of measurement for LVDT's and potentiometers is generally insignificant. Manual measurement methods are limited in accuracy by the device used and the skill of the operator. Reproducibility for manual measurements may be low. It is possible to get some differences between different operators using the same equipment to measure the same structure or even the same operator measuring the same structure with an extended interval.

Reference points are inherent in these direct measurements which are generally easy to interpret.

Ruggedness

Automated measurement can be effected by temperature but it is possible to measure this independently and make suitable corrections. Manual measurements can also be similarly corrected.
LVDT's can be designed to have no moving parts in contact which greatly increases their lifespan, but generally these types of sensors are very well developed and robust. However they arte not well able to withstand out of measurement plane loadings like bending etc. which can occur in some extreme circumstances.

Calibration is usually done by removing sensors and returning to base for calibration.

Cost of measurement

The main cost of implementing a wired sensor array is the cost of installation and wiring. The capital cost of the sensors is usually quite low. For a wireless sensor array there are reduced costs for wring but additional costs for the equipment. Wireless sensor networks may not give the availability of measurement data a wired system can give.

For a manual inspection the main costs are operator time although in some environments access and safety may add considerable extra costs.

The measurements are usually contact measurements. There are considerable health and safety considerations particularly when measurements are needed to be made in hazardous situations like nuclear installations or at height. Generally a skilled operator or installer is required. Data size is generally minimal and with sensor arrays system integration is generally trivial.

Technology Readiness Level

These techniques have widespread industrial acceptance and are well developed.

4.11. STRAIN MEASUREMENT

Introduction

Many of the techniques developed in section 4.10 can be used for strain measurement. However often direct measurement of strain or measurements are needed with a small gauge length that requires specific sensors including fibre Bragg gratings in optical fibres (FBG), electrical foil strain gauges, vibrating wire strain gauges and optical crack gauges.

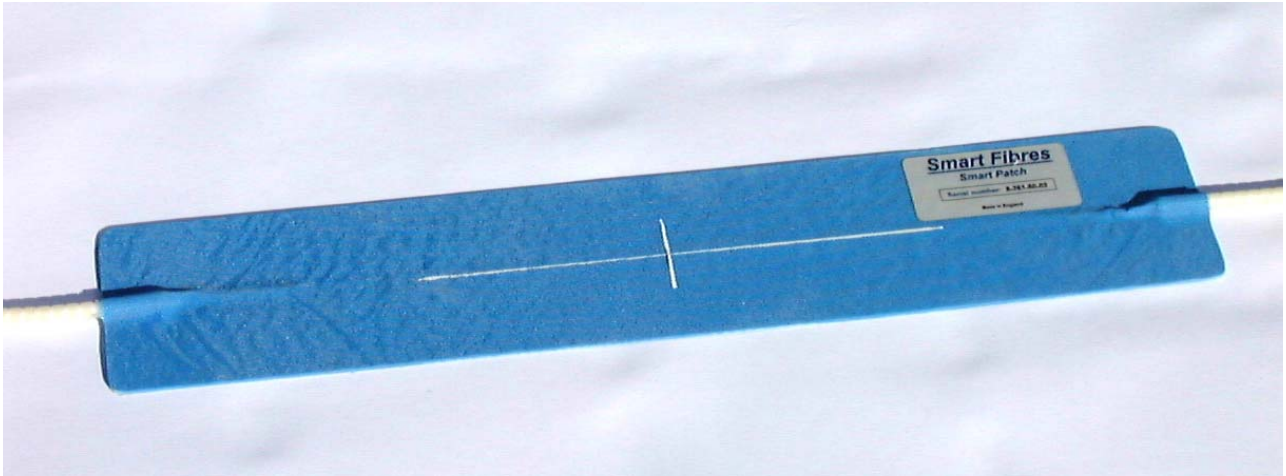

Figure 10. A FBG SmartPatch manufactured by SmartFibres Ltd

Full field versus discrete (numbers of points of measurement)

These techniques provide discrete measurements, although it is possible to have a hundred FBG sensors on one fibre optic measured simultaneously.

Quality of measurement

Strain gauges generally have an accuracy of about 1 microstrain, however this assumes that they are properly thermally compensated for the material they are measuring. No reference points are required. For a well applied strain gauge then they are very reproducible and they provide a direct easy to interpret measurement.

Vibrating wire sensors can take measurements at about 1 Hz other strain sensors can make measurements at 100's Hz.

Ruggedness

Strain gauges can be affected by temperature, foil strain gauges can be made to compensate for thermal expansion within the target structure if it is made of a uniform material. However if there are thermal transients, perhaps caused by sunshine moving across the sensor ,then there can be anomalous effects. FBG's need thermal compensation, usually done by using a second FBG in a PTFE shroud so it sees the same temperature but no strain. Optical crack gauges need temperature compensation for movement of the plastic or glass targets.

There are no moving parts to foil strain gauges, FBG's and crack opening gauges and they tend to have a long lifetime. Vibrating wire sensors are a tried and tested long term civil engineering measurement technique. However all strain sensors can de-bond from their substrate particularly in damp and moist conditions. In trials most foil strain gauges have been found to fail within about 1 year when embedded in structures, FBG's are more long lasting.

Most strain gauges are calibrated according to manufacturers gauges factors and usually cannot be calibrated in situ. No maintenance is generally needed or required for these sensors.

Cost of measurement

The main cost of foil strain gauges is installation, which is a skilled job. FBG's may cost £100's pounds, optical crack gauges are only £10’s each but need to be mounted accurately. All these techniques are contact point sensors and for electrical sensors will need a wired or wireless network which adds additional costs. FBG's can use an optical network in a ring topology and require expensive optical measurement devices to measure strain in the FBG.

There are no health and safety considerations unless the area of application is hazardous or difficult to access. Installation is a skilled job but the monitoring can be carried out by semi-skilled operators. System integration is generally very easy for the sensors. Optical crack gauges need manual reading and are unsuitable for system integration.

Technology Readiness Level

Foil and vibrating wire strain gauges are a mature well established product. FBG's are increasingly being used in civil engineering applications but their high price means that their applications are limited.

4.12. INDIRECT DISPLACEMENT MEASUREMENT

Introduction

These techniques use indirect methods to measure displacement. This includes using accelerometers to measure vibration and hence deduce displacement by integrating the acceleration signal twice versus time. Tilt can be measured using sensitive tilt sensors to calculate relative displacement against some known fixed point and assuming the structure behaves in a known way.

Figure 11. A wireless tilt sensor

Long term monitoring versus test

These sensors can be used for routine test measurement during a survey as the sensors can be easily temporarily fixed to the test structure. They are also suitable for 24x7 fixed long term testing in a wired or wireless network. The advent of MEMS based accelerometer sensors, which can be used for measuring tilt as well as acceleration, whilst not as accurate as high precision sensors, are very compact and need very little power and are ideally suited to wireless networks.

Type of measurement Static / dynamic

These sensors are used for real time measurement.

In plane or out of plane measurement

These sensors measure shape by inference of its effect on local tilt or vibration.

Full field versus discrete (numbers of points of measurement)

These sensors make discrete measurements

Quality of measurement

Using acceleration from vibration to determine displacement will only work for short time periods because of drift in the sensors and the inability to pick up very long time period fluctuations caused by thermal expansion and seasonal changes. So generally only vibrational amplitude would be measured.

Tilt measurements when made using MEMS devices are also subject to long term drift, although electrolytic tilt sensors are more stable over time.

These devices are mass produced and are generally very reproducible but offer an indirect measure of displacement and are more prone to errors caused by other measurements in the dimensions of the structure and the quality of the model used to describe the movement of the structure.

Ruggedness

These devices are very rugged and have effectively no moving parts. As they sense only gravity they can be completely sealed. Calibration is generally not possible due to the solid state nature of the devices and maintenance is not needed and not possible.

Cost of measurement

These sensors generally cost £'s to a few £100. Their main cost is the installation time and cost of wiring or wireless nodes. The positions that they are generally required to measure are relatively inaccessible so their are health and safety considerations in installation. Once installed, by semi-skilled personnel they produce compact data streams that can readily integrated into systems.

Technology Readiness Level

These are well developed sensors and their is already market acceptance. Wireless options are becoming available but still need to be fully trialled.

4.13. GPS

Introduction

GPS

GPS works by triangulating signals from satellites in orbit, which have precisely known position. For consumer products this allows accuracies of 5-10 metres. By implementing additional country scale base stations that radio communicate data about the atmospheric conditions to receivers the accuracy can be increased to 5 metres with 95% probability. By measuring the carrier wave phase measurements can be of the order of a few mm but these measurements need clear views of the sky and are generally for static or slow moving structures. Various hybrid solutions are available which offer lower cost and time to make a measurement at the expense of accuracy.

Pseudolites

In some circumstances because of urban canyons or measurements made in tunnels etc. a view of the sky isn't available therefore measurements can only be made by the creation of a constellation of pseudolites, advanced ground-based devices that simulate a GPS satellite.

They could be placed in strategic locations around a site to provide additional satellite signals for receivers. Pseudolites face numerous hurdles to commercial viability, including the fact that they might clash with the Wide Area Augmentation Service (WAAS), currently under development by the U.S. Department of Transportation. WAAS is intended to support civil aviation and, combined with GPS, allow precision approaches to airports. Because part of the proposed system uses pseudolites, obtaining a license to broadcast on a GPS frequency as a pseudolite may be perceived as a potential source of interference for aerial navigation.

There has been work is studying the feasibility of this and a Swedish PhD project estimates the cost at 80,000 Swedish Crowns or about £7000.

Long term monitoring versus test

These types of measurements can be used for routine test measurement in a survey environment or for 24x7 long term measurements.

Type of measurement Static / dynamic

These techniques allow real time measurement of position at several Hz.

In plane or out of plane measurement

These techniques measure shape.

Full field versus discrete (numbers of points of measurement)

The measurements are discrete.

Quality of measurement

Racelogic do several systems for monitoring race car performance on test tracks. The high-end system needs a base station £8k, and a Vbox for £12k [53]. This system can make measurements at 100Hz and with an accuracy of 2cm. They also make lower spec system which measure at 5 Hz and has a relative resolution of 20cm This is about £7-8k for a basestation and mobile unit. Both systems are very sensitive to multi-path reflections and so are designed only for open race tracks in fields, but only take two minutes for initial setup.

There are research projects which may be able to provide high accuracy for a minute or so which would be adequate for this application, they might only use one low cost receiver, but they also require specific realtime data from satellite measurements which isn't provided in realtime but after eight days currently. However this may be practical and low-cost in the future [54].

Carrier wave systems like NovAtel FlexPak-G2 can make measurements to 1 cm accuracy and the EuroPak claims 3mm when the Galileo system comes on-line.

GPS measurements are very reproducible and are a direct measurement of 3D position.

Practically measurements can only be made with a clear view of the sky and minimal structures close to the monitored structures that might cause multi-path reflections.

Ruggedness

These measurements are very rugged and show good environmental sensitivity, however they are more sensitive to the environment in the upper atmosphere and near earth space and so may be adversely effected by space weather like coronal mass ejections etc. They need no calibration or maintenance and the equipment is all solid state so likely to be very reliable.

Cost of measurement

Installation needs a base station with aerial but these are relatively compact. No other installation is required. The cost of the equipment is quite high and may be many £10k's for high accuracy equipment. Setup can be fairly quick. There are no health and safety considerations apart from sensor placement. The systems a re automatic and need semi-skilled operators and allow easy system integration.

Technology Readiness Level

This is a mature technology, new advances such as Galileo will increase resolution but less than an order of magnitude.

Other distance measurements

4.14. INSAR

Introduction

This section will concentrate on InSAR or interferometric synthetic aperture radar measurements. The use of ultrasonic distance measurement is fraught with problems concerning the speed of sound variation with temperature and humidity and this type of measurement is more easily done using a laser measurement device.

SAR is a radar technique that uses the travel time of an electromagnetic wave, in the radio or microwave range, reflected off an object to measure its position. By using multiple transmitter/receivers a synthetic aperture can be simulated. By looking at phase measurements from multiple measurements then high resolution topographic information can be obtained [55].

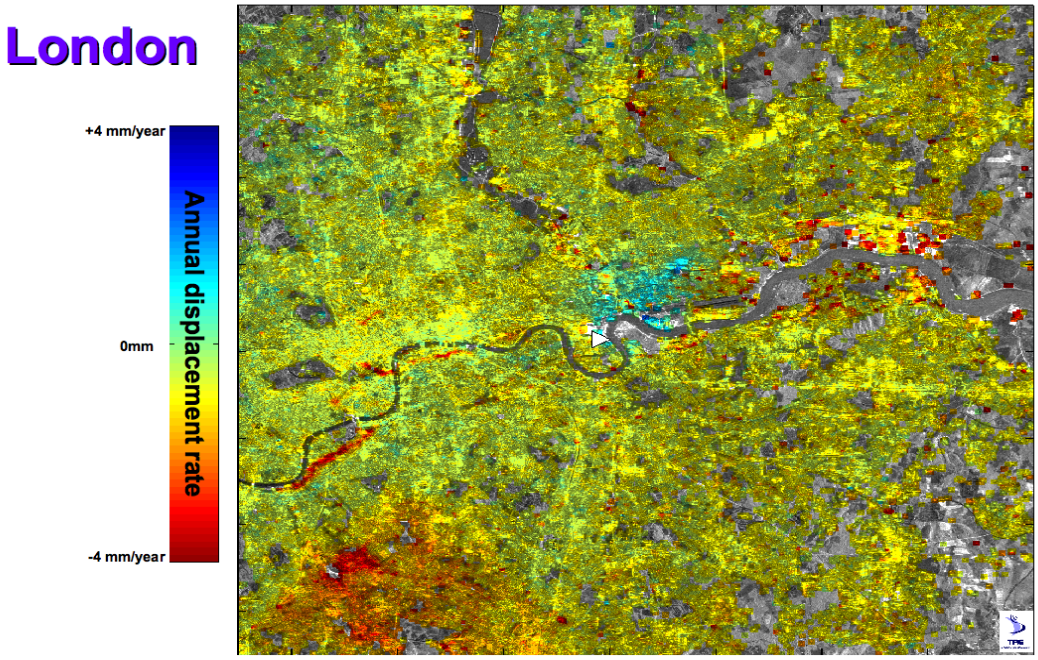

Figure 12. An example of satellite based INSAR measurement from [56]

SAR has been used for satellite measurements of terrain [57] 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 [16], 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 [36, 58-59].

Long term monitoring versus test

The techniques have generally been used for routine test measurement or surveys but they can be used for 24x7 long term measurements.

Type of measurement Static / dynamic

Generally full field measurements re static, but single point measurements of range can be made dynamically.

In plane or out of plane measurement

These techniques measure shape on the scan grid, i.e. topography.

Full field versus discrete (numbers of points of measurement)

Both are possible

Quality of measurement

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 [56].

There are commercial INSAR solution providers who have developed the IBIS system [58]. 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.

The accuracy can approach mm's and no reference points are required. As the measurements use phase they may not be so susceptible to environmental effects in the atmosphere. These systems provide a direct measure of range to the target

Ruggedness

There is some environmental sensitivity due to changes in the speed of light but as the systems depend on phase measurements then this may be limited. There are no moving parts, calibration would be by measuring the range to known targets.

Cost of measurement

For point measurements reflective targets/antennae will be required. The measurement is non-contact and the cost of the equipment is potentially of medium cost. There are no health and safety considerations and the equipment could be used ny semi-skilled operators. System integration might be easy for point measurements.

Technology Readiness Level

For satellite mapping the techniques are well developed. There are university spin-off companies now engaged in making units for widespread commercial use.

5. POSSIBLE APPLICATIONS: SWOT ANALYSIS

Static load test: Highway bridge

Application characteristics

Short term static measurement	
Material type	Concrete
Environmental challenges	Low
Importance of ease of use	High
This is done "To validate a design or assessment model".	

Measurement requirements for this application

Requirement Type	Requirement	Importance to this application
Range/Accuracy	Maximum displacement: 10mm/ 0.1mm	High
Measurement frequency	Low	High
Immediacy of measurement	Real time indication/full data processed off-line	High
Measurement required	Primarily deflection (1D) spatially discrete measurement over 20 points	High
Secondary measurement	Strain	Low
Contact/ non-contact	Contact or non-contact	Medium
Cost of equipment	Generally not an issue	Low
Ease of equipment deployment	Needs to be quick and easy	High
Reposition equipment	As above	Medium
Equipment environmental protection	Minimal- weatherproof for duration of test	High
H&S issues	No possession required during test	Low
Equipment reliability	Reliability not an issue, possibilities for redundant equipment	Low

Suitable techniques

Technique	Strengths	Weaknesses
Imetrum 2D	Low cost of deployment, no access to base of bridge required. Can produce an archival image record of the structural area under test.	Resolution is a function of field of view
DIC 2D	Low cost of deployment, no access to base of bridge required. Can produce an archival image record of the structural area under test.	Resolution is a function of field of view, time to process full field data
Total station	Low cost of deployment, no access to base of bridge required	Will probably need retro reflectors fitted for most accurate measurements, at limits of accuracy.

Technique	Strengths	Weaknesses
		Resolution is a function of distance.
Laser tracker / Coherent Laser Scanner	Very accurate	Will require access to underside of bridge, Needs benign conditions, needs retro reflectors fitted
Automated Displacement	Traditional easy to deploy, very immune to environment	Problem if over water / rail / road, will need possession of area below bridge for tests. May be time consuming to deploy for multiple measurement points
Manual Displacement	No specialist equipment required	H&S issues mean operator is uncomfortably close to loading. Will require access to underside of bridge
InSAR	Very immune to environment	Needs retro reflectors and access to underside of bridge as range measurement.

Conclusions

If access to the underside of the structure is easy and there are no possession or accessibility issues then automated displacement using LVDT's on a tower for modest height of span above the ground or InSAR have great environmental immunity.

Imetrum 2D system or DIC 2D are good techniques and are suitable for this application especially when there are access issues to the underside of the bridge or very rapid deployment is required with no need for any fixed targets.

Laser trackers can only be used in very benign conditions and need access to the underside of the bridge.

Dynamic test: Railway bridge

Application characteristics

Short term dynamic measurement	
Material type	Steel
Environmental challenges	Low
Importance of ease of use	High
This is done "To validate a design or assessment model and to measure structure stiffness and damping characteristics"	

Measurement requirements for this application

Requirement Type	Requirement	Importance to this application
Range/Accuracy	5-10mm (for a 50-60m span)/ 0.1mm	High
Measurement frequency	100Hz	High
Immediacy of measurement	Real time indication	High
Measurement required	Primarily deflection (1D) spatially discrete measurement over 20 points	High
Contact/ non-contact	Contact or non-contact	Low
Cost of equipment	Generally not an issue	Low
Ease of equipment deployment	Needs to be quick and easy	High
Reposition equipment	As above	Medium
Equipment environmental protection	Minimal- weatherproof for duration of test	High
H&S issues	No possession required during test	Medium
Equipment reliability	Reliability not an issue, possibilities for redundant equipment	Low

Suitable techniques

Technique	Strengths	Weaknesses
Imetrum 2D	Low cost of deployment, no access to base of bridge required. Can produce an archival image record of the structural area under test.	Resolution is a function of field of view. High performance hardware will be required.
Automated Displacement	Traditional, easy to deploy, very immune to environment	Problem if over water / rail / road, will need possession of area below bridge for tests. May be time consuming to deploy for multiple measurement points
Accelerometer	Traditional, very immune to environment	Problem if over water / rail / road, will need possession of bridge for installation, displacement subject to drift

Technique	Strengths	Weaknesses
Vibrometer	Relatively immune to environment, needs no targets. Measure velocity change	Single point, expensive

Conclusions

If access to the underside of the bridge is limited then the Imetrum 2D system or vibrometer are the only techniques, which gives the speed of measurement. Multipoint measurements will need multiple vibrometers but only one Imetrum system, vibrometer measurements are only out of plane limiting the setup locations.

If the underside of the bridge is accessible and of modest height of span above the ground the LVDT or accelerometer on a tower technique can be used.

Accelerometers can also be used if a possession is available.

Static/dynamic monitoring: Suspension bridge

Application characteristics

Long Term Static/dynamic measurement	
Material type	Steel and concrete
Environmental challenges	High, Needs little susceptibility to environment (fog & pollution) and wind/rain
Importance of ease of use	Low
This is done to "Validate a model for future lifespan of structure and to integrate with traffic control for real time load management".	

Measurement requirements for this application

Requirement Type	Requirement	Importance to this application
Range/Accuracy	2000mm (1.5 km structure), /10mm	High
Measurement frequency	0.01/10Hz	High
Immediacy of measurement	Real time indication + system integration	High
Measurement required	(2D/3D) plus hanger strain if possible (this will require higher resolution), spatially discrete measurement over many points	High
Contact/ non-contact	Non-contact	High
Cost of equipment	Accurate equipment in place for a long period	Medium
Ease of equipment deployment	Fixed at start of monitoring	Low
Reposition equipment	For recalibration/ replacement	High
Equipment environmental protection	Long term reliable weatherproofing	High
H&S issues	Fitting of reference targets	Low
Equipment reliability	Long term equipment reliability	High

Suitable techniques

Technique	Strengths	Weaknesses
Imetrum 2D	Ease of setup. Can produce an archival image record of the structural area under test.	Resolution is a function of field of view, will require more than one camera
Accelerometers	For dynamic motion	Not for long term movement
Tilt Sensors	Maybe if the structures motion is very simple or well understood	Needs a well understood structure
GPS	Very suited for this application, effectively weatherproof	May require fitting of GPS receivers in hazardous positions, resolution changes as availability of satellites change Requires reference receiver installed at nearby fixed location. Sample rate may be too low in

Technique	Strengths	Weaknesses
		some circumstances Multi-path reflections are unlikely to be an issue on a bridge structure

Conclusions

GPS is the technique of choice for this application as large bridges generally have a good view of the sky and thus can use GPS and its carrier wave measurement variants to achieve the required resolution and measurement frequency, whilst exhibiting good environmental immunity.

If the motion is effectively in one plane or multiple synchronized cameras can be used then Imetrum 2D measurements is a cost effective alternative.

Accelerometer and tilt sensor measurements are well-established environmentally robust techniques, but need an array of sensors and a good understanding of how the structure behaves under varying loads.

Static monitoring: Dam

Application characteristics

Long Term Static measurement	
Material type	Rock and/or soil
Environmental challenges	High, needs little susceptibility to environment (fog and pollution) and wind/rain/snow, there may be no illumination during the night.
Importance of ease of use	Low
This is done to "Monitor the long term behaviour of a structure".	

Measurement requirements for this application

Requirement Type	Requirement	Importance to this application
Range/Accuracy	10mm/ 0.1mm	High
Measurement frequency	Low	High
Immediacy of measurement	Post processing of data Real-time indication & alarm is requirement in regions of high seismic activity.	Medium
Measurement required	(2D vertical/out of plane) multi-point measurement	High
Contact/ non-contact	Non-contact	High
Cost of equipment	Importance low if can reposition easily	Low
Ease of equipment deployment	May need to move equipment for monitoring different structures	Medium
Reposition equipment	Make long term measurements on different structures	High
Equipment environmental protection	High- long term reliable weatherproofing	High
H&S issues	Fitting of reference targets	Low
Equipment reliability	Need high reliability of equipment	High

Suitable techniques

Technique	Strengths	Weaknesses
DIC 2D	Full field measurement. Can produce an archival image record of the structural area under test.	Really need out of plane measurement too, only daytime measurements, long term change in vegetation may be problematic
Imetrum 2D	Multiple point measurements. Can produce an archival image record of the structural area under test.	Need multiple cameras, only daytime measurements, long term change in vegetation may be problematic
DIC 3D	Shape, out of plane full field measurement. Can produce an	Need large & stable baseline for accurate measurements.

Technique	Strengths	Weaknesses
	archival image record of the structural area under test.	Only daytime measurements, long term change in vegetation may be problematic
GPS	Environmentally robust absolute measurement	Not full field
InSAR	Has been demonstrated for this type of application, environmentally very robust, appropriate spatial resolution	Needs to use synthetic aperture to scan area, moderate spatial resolution
Tilt Sensors Total Station	Environmentally robust and well established Well-established technique.	Point measurements only, need infrastructure for power and logging data Marginal accuracy, needs retro reflectors, susceptible to environment

Conclusions

Most modern dams are instrumented at key points to monitor the structure during construction and subsequent operation. For point measurements GPS is sufficiently robust, but at the limits of accuracy.

For full field measurement then InSAR has been demonstrated successfully for this type of application (IBIS) and has the advantage of sufficient accuracy with adequate spatial resolution. DIC 3D can be used to measure the shape with a sufficiently long baseline, but vegetation may be problematic.

Imetrum 2D can measure settlement & bulge by looking along internal galleys within the dam structure. This gives 24/7 real-time monitoring of multiple points. Most of the other approaches are measuring on the down-stream face, which is quite far from where the load of the upstream reservoir is applied to the structure.

Many of the traditional sensors (tilt meters, extensometers, strain gauges) that are installed during construction will fail either during construction or within a few years. Imetrum 2D can be retro-fitted.

Crack opening measurement: Nuclear application

Application characteristics

Long Term Static measurement	
Material type	Concrete
Environmental challenges	Low unless high radiation
Importance of ease of use	Medium
This is done to "Monitor the state of a crack to determine if there is any acceleration in crack opening".	

Measurement requirements for this application

Requirement Type	Requirement	Importance to this application
Range/Accuracy	2mm/ 0.01mm	High
Measurement frequency	Low	High
Immediacy of measurement	Post processing of data	High
Measurement required	2D full field	High
Contact/ non-contact	Non-contact	Medium
Cost of equipment	As will be deployed periodically can be used on multiple crack measurements	Low
Ease of equipment deployment	Needs to be easy to deploy	Medium
Reposition equipment	Needs to make measurements separated by long time periods	High
Equipment environmental protection	Low- minimal weatherproofing/may be indoors or make measurements in good weather	High
H&S issues	No access	Low
Equipment reliability	Reliability not an issue	Low

Suitable techniques

Technique	Strengths	Weaknesses
Imetrum 2D	Quick setup, non-contact. Can produce an archival image record of the structural area under test.	Resolution is a function of field of view, will only be suitable if a crack at a known position is measured
DIC 2D	Full field measurement, non-contact, may detect crack growth in unexpected areas. Can produce an archival image record of the area under test.	Resolution is a function of field of view
Automated Displacement	Accurate	Severe H&S issues with fitting targets of point measurement equipment if radiation present.
Manual Displacement	Accurate	Overwhelmingly severe H&S issues with fitting targets of point measurement equipment if radiation present.

Technique	Strengths	Weaknesses
Strain Gauge/ FBG	Accurate	Severe H&S issues with fitting targets of point measurement equipment if radiation present.

Conclusions

If the position of a crack is unknown then DIC is the preferred technique for this application, as it can identify crack opening if it is in the field of view. Once the position of a crack has been identified then Imetrum 2D can be used for monitoring an existing crack. These techniques need no access to the structure under investigation, which means minimal H & S issues if there is radiation present.

Building monitoring: Whilst excavating or tunnelling nearby

Application characteristics

Long Term Static measurement	
Material type	Concrete, brickwork, stone, steel, glass
Environmental challenges	Medium, in urban environment.
Importance of ease of use	Low
This is done to "Monitor the state of a structure and to detect when significant changes occur"	

Measurement requirements for this application

Requirement Type	Requirement	Importance to this application
Range/Accuracy	5mm/ 0.1-1mm	High
Measurement frequency	0.01Hz	High
Immediacy of measurement	Real time indication linked to alarm	High
Measurement required	3D spatially discrete measurement over >10 points, preferably full field	High
Contact/ non-contact	Non-contact	Low
Cost of equipment	This work is generally very price sensitive	High
Ease of equipment deployment	It is important to have easy deployment, additional targets on adjacent buildings may be problematic	High
Reposition equipment	The equipment is fixed for this	Low
Equipment environmental protection	Long term reliable weatherproofing	High
H&S issues	Fitting of reference targets need access and possession generally of many structures	High
Equipment reliability	Need high reliability of equipment	High

Suitable techniques

Technique	Strengths	Weaknesses
DIC 3D/ Photogrammetry	No targets needed. Can produce an archival image record of the structural area under test.	Will need multiple cameras in a precise configuration. Entire measurement area will need to be illuminated for night-time operation
Total station	One total station can measure many positions at widely different positions	Will need retro reflectors for high accuracy work, need to swap instruments for routine calibration
Structured Light	Can provide high speed full field measurements	Difficult to provide illumination, problematic on very shiny surfaces

Technique	Strengths	Weaknesses
GPS	Absolute measurements, easily integrated into a network	Difficult seeing sky in urban canyons so accuracy very reduced
Imetrum 2D	No additional frequent calibrations required, targets not needed .Can provide a useful visual record of structure.	Target area needs to be illuminated for night-time operation, unproven long term reliability

Conclusions

For this application a total station is a cost effective way of measuring multiple 3D positions of many targets within the field of view**.** Imaging applications like DIC 3D, photogrammetery and Imetrum using multiple cameras can allow 3D point measurements to be made and may have the advantage of not needing targets. Structured light techniques need very powerful light generation (could be IR) to provide suitable measurements but have the advantages of full field rapid measurements.

GPS almost has the required accuracy but is likely to be constrained by needing a clear view of a large part of the sky.

APPENDIX 1 - LITERATURE REVIEW

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