



MODERN SPATIAL MONITORING METHODS FOR GEOTECHNICAL STRUCTURES ALONG THE TRANSPORTATION NETWORKS

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Abstract

This paper provides an overview of the field observation methods used in the monitoring of geotechnical structures along the transportation networks. The focus is on modern field observation methods to evaluate the behaviour of structures relevant to transportation infrastructure. Various advanced remote sensing methods such as photogrammetry, LiDAR (Light Detection and Ranging) and SAR (Synthetic Aperture Radar) together with ground-based geodetic methods such as GNSS (Global Navigation Satellite System) will be investigated for their effectiveness in providing real-time and accurate displacement data. The integration of modern advanced methods aims to improve the data acquisition process and provides a holistic understanding and visualisation of asset behaviour and environmental conditions. By using the power of modern monitoring methods, transport authorities can improve their decision-making processes, prioritize maintenance, and ensure the long-term resilience and safety of infrastructure. As accurate information from inspection and monitoring is crucial to make the right decisions regarding maintenance and safety, the advantages and disadvantages of the above methods are discussed.

Keywords: geotechnical structures, photogrammetry, LiDAR, SAR, GNSS

1 Introduction

Spatial monitoring of geotechnical structures and materials, such as rock and soil is one of the most important steps in understanding geotechnical processes in general. Monitoring of all the values required for behaviour assessment is highly dependent on the used equipment and acquisition procedures. In general, geotechnical monitoring can be divided into two major groups, namely position sensing and displacement sensing [1]. Position sensing describes the measurement of distance between a reference point and the present location of the targeted location, while displacement is calculated as the change of the positions. Displacement sensing on the other hand describes the measurement of the distance between current location and the previously recorded location.

2 Spatial monitoring methods

2.1 Global navigation satellite system (GNSS)

In the past few decades, global navigation satellite system (GNSS) technology has been widely used as one of spatial monitoring methods. It uses satellite constellations which includes United States' Global Positioning System (GPS), Russia's Global Navigation Satellite System (GLONASS), China's BeiDou Navigation Satellite System (BDS) and the European Union's positioning system named Galileo, see Table 1. All systems consist of three segments: the space segment, the control segment, and the user segment. The space segment includes satellites circling the Earth and transmitting one-way signals that give current satellite position and time. Control segment includes worldwide monitor and control stations that maintain the satellites in their proper orbits, while the user segment includes all GNSS equipment which can receive signals from satellites and use that information to calculate three-dimensional position and time.

Table 1 GNSS Constellations (March 2024)

System	Satellites in operation	Orbital height	Civil signals
GPS	31	20,180 km	L1 C/A, L2C, L5, L1C
GLONASS	26	19,130 km	L1OF, L2OF, L3OC
BeiDou	44	21,528 and 35,786	B1I, B2I, B3I, B1C, B2a
Galileo	28	23,222 km	E1, E5a, E5b

GNSS based spatial monitoring compared to a traditional monitoring methods offers advantages such as no need for visibility between monitoring points, real-time monitoring, weather independence, high precision, and long-term deformation monitoring [2]. The basic principle of GNSS is that a receiver on earth can receive signals from satellites orbiting in precisely known patterns, and the distances (trilateration) between the receiver and these satellites can be calculated [3]. These measured distances with the corresponding satellites can form imaginary spheres which all intersect and indicate exact location of the receiver (Figure 1).

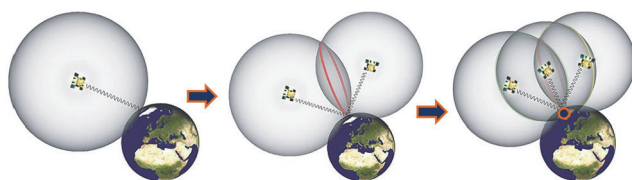


Figure 1 Basic principle of GNSS positioning, from [4]

For the purposes of GNSS spatial monitoring there are two categories of tested and most used data acquisition methods: Real-Time Kinematic (RTK) and Precise Point Position (PPP), and one called "Direct Displacement Measurements" [5], which is innovative application of GNSS technology. RTK positioning is a highly accurate sub-centimetre positioning method used in a wide range of applications. It works by using a base station located at a known position and a mobile receiver called "ROVER" located at an unknown position. The base station receives signals from GNSS and uses these signals to calculate its position. The mobile receiver also receives signals from the same satellites and uses them to calculate its position (Figure 2).

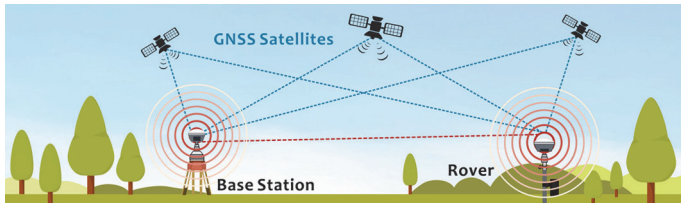


Figure 2 RTK positioning, from [6]

On the other hand, PPP positioning uses a single GNSS receiver. It uses a network of global reference stations to compute precise estimates of GNSS satellite orbits and clock errors. These calculations are then delivered to the end-user via satellite or over the internet. The PPP technique is more robust and accurate than RTK [7, 8].

2.2 Photogrammetry

Photogrammetry is the practice of determining the geometric properties of objects in general using digital photographic images. This involves estimating the three-dimensional coordinates of points on an object of interest. These are determined by measurements made in two or more photographic images taken from different positions. Common points are identified on each image. A line of sight (or ray) can be constructed from the camera position to a point on the object. The intersection of these rays (by triangulation) determines the three-dimensional position of the point [9, 10].

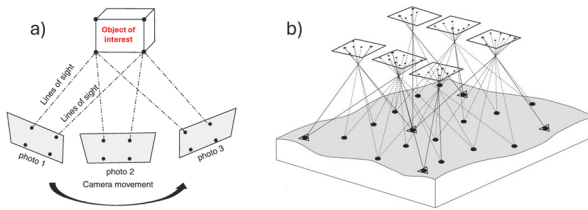


Figure 3 Principles of photogrammetry a) terrestrial, from [11] and b) aerial photogrammetry, from [12]

In the practice of photogrammetry there are two main methods for collecting photographs (Figure 3). Pictures can be taken on traditional tripods set, or by hand on the ground, and this is known as terrestrial photogrammetry. If pictures are taken from air, then aerial photogrammetry rules apply. Aerial photogrammetry is generally utilized on large or difficult to access sites and can cover large areas quickly, while terrestrial photogrammetry is more object focused. UAS (Unmanned Aerial System) development in past decades has greatly influenced photogrammetry data acquisition [13]. By attaching digital camera (or any other sensor e.g. thermal camera, multispectral camera) to an UAS, many overlapping photographs can be collected in a very short time and a final product of such photogrammetric survey is usually a colored 3D point cloud, or digital model in 1:1 scale. Based on those models or point clouds a lot of other outputs can be generated like Digital Surface Models (DSM), Digital Terrain Models (DTM), high resolution orthophoto maps and similar others [14], see Figure 4.

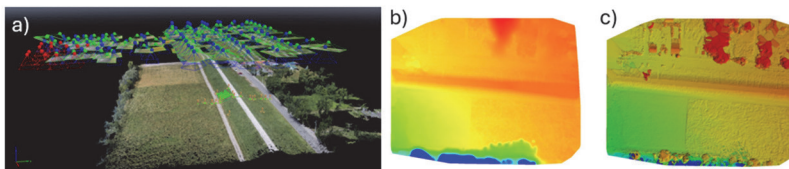


Figure 4 Different photogrammetry outputs: a) Point cloud, b) Digital Terrain Model (DTM) & c) Digital Surface Model (DSM), from [13]

2.3 Light detection and ranging (LiDAR)

Light Detection and Ranging (LiDAR) employs the method of sending laser light on to the target (area of interest) and measures the reflected light back to recognize the variation in wavelength and arrival time of the reflected light. The measurement is done by calculating the laser return times and their wavelengths. From these measurements, it can calculate the distance to draw the digital representation of the target. Since light travels at a very high speed, the calculation of the exact distance through LiDAR is very fast. The equation (1) is used to calculate the distance to a target:

$$D = c(\Delta T/2) \quad (1)$$

where, D = distance of the object, c = speed of light & ΔT = time required by the light to travel. It can generate precise, high quality, and three-dimensional map of the environment that it scans [15, 16]. The LiDAR system emits many laser lights on to the surface. The system's sensor measures the time it takes for the reflected light to reach the sensor and this process is repeated until a map of the surface is created. By recording the returning signals and measuring the time of flight, laser ranging is often carried out through two main methods: phase and pulse method [17]. Pulse method involves the emitting of a short but intense laser beam to the target of interest and measures the precise time duration until the echoed signals are received, while phase method provides more accurate distance detection but suffers from a more confined effective range. In phase method, the laser device generates a continuous laser radiation rather than a pulse. By comparing the wave patterns between the emitted and received versions and measuring the phase difference, the distance can be evaluated. When the laser device is mounted on an airborne platform, e.g. an UAS or airplane, the location and altitude of the moving platform should be determined in advance, see Figure 5. A global positioning system (GPS) aided by inertial measurement unit (IMU) is commonly used to provide such a pre-measurement, and then the coordinates of the targets on the ground are estimated correspondingly [18].

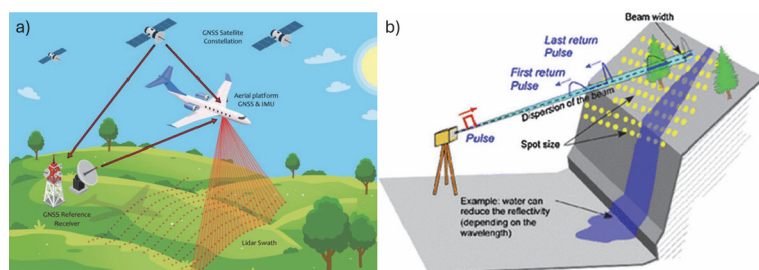


Figure 5 LiDAR platform: a) airborne, from [19] and b) terrestrial, from [20]

The main product of LiDAR survey, as well as in photogrammetry is a 3D point cloud. In ideal environmental conditions a typical LiDAR system can have a sub-centimetre accuracy with possibility of recording over 1 million points per second, or over 200 points per square meter. LiDAR technology can provide many different visualisations of surveyed areas, Figure 6. For example, LiDAR can provide visualisations of displacement fields of surface ground motions, such as landslides. This allows an easier evaluation of the landslide kinematics and failure mechanism compared to only using single-point measurements, such as GPS [21]. This kind of displacement is acquired by computing differences between sequential point clouds taken at different times.

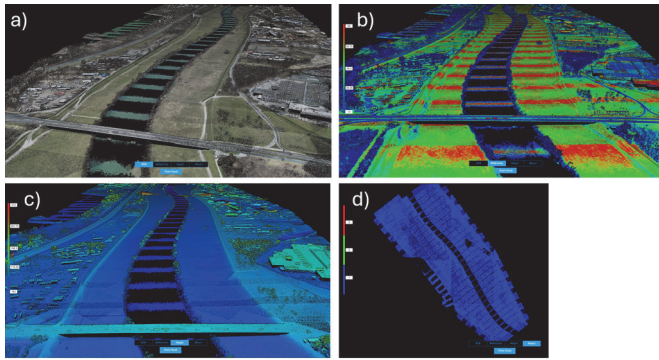


Figure 6 LiDAR visualisations: a) RGB, b) Point reflectivity, c) Height of terrain & d) Return

2.4 Synthetic aperture radar (SAR)

Synthetic aperture radar (SAR) has been widely used for Earth remote sensing for more than 30 years. It provides high-resolution, day and night and weather-independent images for a wide range of applications from geoscience and climate change research, environmental and Earth system monitoring, 2D and 3D mapping, change detection, 4D mapping (space and time), security-related applications up to planetary exploration [22]. Simplified, it works in a way that radar antenna, which is mounted on a moving platform, such as aircraft or satellite, transmits sequential electromagnetic waves, and is also used to collect the back-scattered echoes. Surface characteristics can be determined by measuring the properties of those echoes, including the round-trip time of the pulse signal, the strength of the backscatter and the phase of the return wave, Figure 7. SAR uses the motion of the radar antenna over a target region to provide finer spatial resolution than conventional stationary beam-scanning radars. Images created by SAR include a range dimension and an azimuth dimension, in which many individual pulses are combined to produce a long image swathe. Imaging radars are usually side-looking because down-looking radars are not able to differentiate two targets having the same distance from the sensor but located on the opposite sides. In order not to only create images of landscapes, but also capture motions of the ground surface, SAR interferometry, making use of the phase information of the echoes, is developed. For a given scene, by comparing the phase information of multiple radar images derived at different times, it is possible to measure very subtle ground surface changes [23].

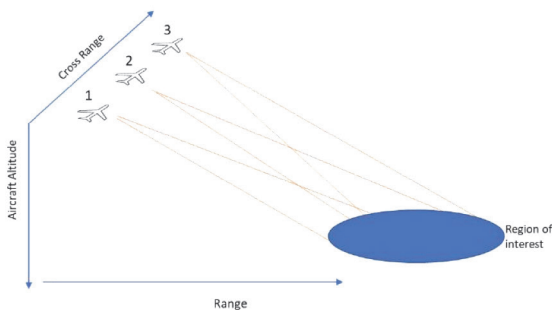


Figure 7 Synthetic aperture radar (SAR) image formation, from [24]

3 Conclusions

Objective of this paper is to highlight modern spatial methods and technology which can be used for monitoring of geotechnical structures along the transportation networks. Using GNSS technology and monitoring methods like RTK and PPP can both provide sub centimetre accuracy and thus provide data only along certain number of points, which must be well marked and stabilized on the field. Advantage regarding this method is independence of weather conditions and can be observed no matter day or night. Observed points don't have to be in visual line of sight, but a downside of this method is a location of surveyed points, which must be located on a position not near high buildings or trees.

Photogrammetry as modern monitoring method is perhaps one of the most optimal technique for spatial data acquisition. Considering development and prices of sensors which are used, time needed on the field to map certain area of interest, UAS accessibility, accuracy, image processing to generate various outputs makes this method highly popular among remote sensing methods. The biggest disadvantage is dependence on the weather conditions, since it requires good visibility and daylight, and not being able to penetrate vegetation. Also, legislation for flying over, or near transportation network while traffic is moving is something that must be taken into a consideration.

LiDAR mapping and monitoring is very similar to photogrammetry, but with one big exception. Regardless that both provide 3D point clouds, data collected by LiDAR is not prone to a time-consuming computer processing and is available almost right after acquisition. LiDAR data also provides additional information like reflectivity and intensity, which can be used for further analysis for monitoring purposes. LiDAR sensors are also much more expensive than sensors used in photogrammetry.

SAR technique, which has been around for 30 years is maybe one of the most promising future methods for conducting spatial monitoring along transportation networks. Availability of SAR data for almost every corner of the Earth is making this technology highly popular and appreciated. Once the workflow with this kind of data is established, which can be very time consuming, it can become highly powerful tool for infrastructure managers for management of their resources and assets.

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