

Opportunities and Impediments to the Use of Three-dimensional Laser Scanning for Adjacent Excavations

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Abstract

Although three-dimensional laser (3DLS) scanning has been used to document and monitor individual excavation walls and structures on a limited basis, impediments remain to its use for major infrastructure projects. This paper outlines current technological opportunities and obstacles for using 3DLS to predict excavation-induced, damage prediction. Specifics are provided as to limitations regarding cost, optical resolution, processing time, data set convergence, data conversion, and data mining. Specific solutions are proposed to advance the state-of-the-art.

Introduction

The logistics for adequate planning and monitoring of large, subsurface construction projects are substantial, particularly with respect to protection of existing, adjacent structures. This paper offers a brief overview of the viability of using three-dimensional laser scanning (3DLS) to assist in protecting buildings from adjacent excavations. Although 3DLS is applicable to condition assessments and real-time monitoring, the main technical challenges relate to damage prediction, thus, this paper describes how to use 3DLS for this purpose.

Broadly speaking, the underlying problem to be addressed is that excavation for foundations of a new building or as open cut tunneling can undermine and damage adjacent buildings, particularly older, unreinforced masonry buildings with shallow foundations. To avoid property damage and/or legal liability requires documenting the existing condition of adjacent buildings, predicting damage due to construction, and taking preventative steps to avoid the damage, including regular monitoring during the excavation. For individual buildings, the cost of this work may exceed \$10,000 depending upon the building's size and condition and the excavation period. Since the majority of this cost is the labor related to painstaking, manual surveying and modeling, suitable automatic methods have the potential to reduce the costs dramatically.

A recent innovation is the use of 3DLS to automate surveying and photographing individual buildings. This is possible because 3D laser scanners measure range from the scanner to individual points on the building, simultaneously acquiring a full-color image of the building from the viewpoint of the scanner. Thus, both survey models and photographs may be acquired automatically. The output of the laser scanner, however, is not suitable for Finite Element Modeling (FEM) with current methods, since laser scanners produce a cloud of points rather than a structural model of the building. In this paper, therefore, a method is presented to convert the point cloud output of a laser scanner into a FEM mesh for modeling of above-ground structures.

Building Condition Assessment and Damage Prediction

Preventing damage to adjacent buildings in a cost-effective fashion depends on being able to predict the damage that the new construction would cause. This requires an adequate theoretical model of how vulnerable a building is to damage, which in turn requires some quantitative description of the building and/or site in question. It is clear, therefore, that damage prediction has two stages: (1) documentation/surveying and (2) modeling/prediction. These stages may be performed though a wide variety of analog and digital techniques. At present, prediction is sometimes performed automatically using FEM, but with generation of the model performed manually, which can be prohibitively

expensive, when many buildings are at risk, unless digital documentation of the relevant buildings already exists. As a result, prediction is commonly performed entirely manually, often with a very rough rule of thumb by first estimating the excavation's zone of influence (e.g. Peck 1969, Clough and O'Rourke, 1984) and then comparing the estimated angular distortion and differential settlement against empirically derived damage charts (e.g. Burland and Wroth 1974, and Skempton and McDonald 1956). This paper proposes that automating the entire process can significantly reduce the cost of the assessment by developing an end-to-end process that employs 3DLS data to automate FEM mesh generation.

Three-dimensional Laser Scanning (3DLS)

Three-dimensional laser scanning is the terrestrial form of Light Detection And Ranging (LiDAR). Like radar, LiDAR reflects pulses of energy from objects and measures time-of-flight to determine the distance from the scanner to individual objects. By sending pulses at a large number of distinct angles, the scanner acquires a set of points whose position is known relative to the scanner, by which a three-dimensional model can be generated. Since the pulses are sent out at different angles, the spatial resolution of the resulting data is dependent on a combination of the angular resolution of the scanner, the distance from the scanner to the objects in the environment, and the angle of individual surfaces with respect to the pulse.

Both airborne and terrestrial scanners exist, but the main focus of this paper is the terrestrial version, because although the airborne version can scan hundreds of buildings in only a few hours, it is not yet of sufficient resolution to provide reliable details of building structures due to the obliquity of the scan with respect to building facades. At a minimum viable flyover height of 75 m, current airborne LiDAR achieves ground plane resolution of approximately .10 m, as shown in Figure 1, but the narrow field of view of 7° on either side of the plane's track, degrades resolution of vertical façade elements to 80 cm or worse. Although substantially improved over the preceding generation of technology, this sample density is insufficient for building feature extraction or damage identification (Figure 1). Future generations of aerial LiDAR will presumably improve this resolution, but for now, high-quality building facade data is only available through terrestrial laser scanners.

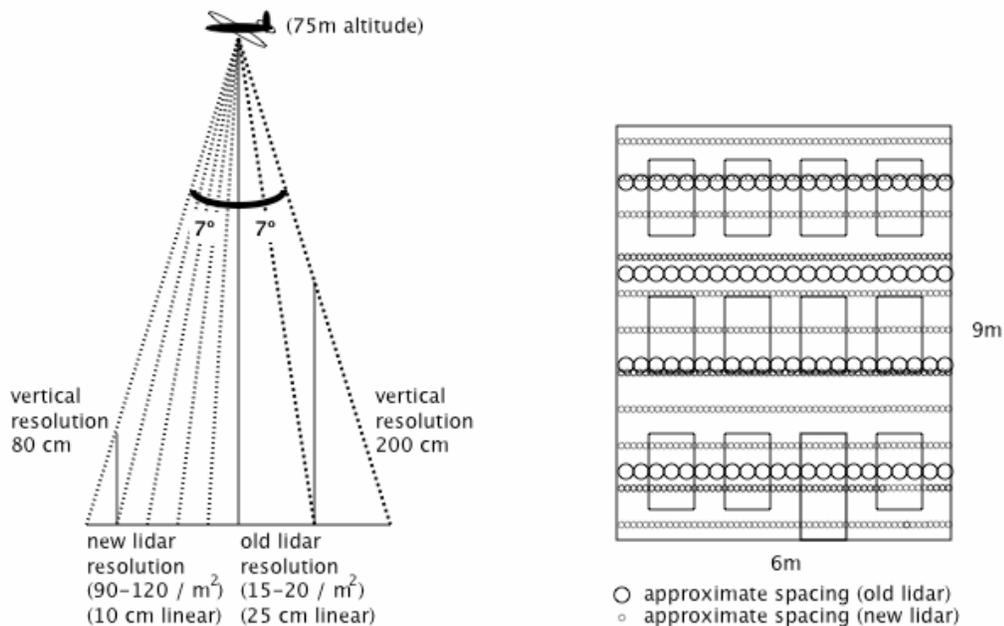


Figure 1. Airborne LiDAR sampling density with 2005 and pre-2005 technology

As a specific example, details of the MENSİ GS200 purchased by University College Dublin in December 2004 under the auspices of the Urban Institute Ireland are presented. The scanner has a 200 m range, with a ground-plane resolution of 3 mm at 100 m, and 1.5 mm accuracy in range measurements (Mensi, 2005). In addition to range data, the MENSİ GS200 provides co-referenced image data in the form of red-green-blue (RGB) color data and return intensity (Figure 2). At a range of 100 m, therefore, the smallest detectable feature is 6 mm, with those of 12 mm be-

ing detectable reliably. If the scanner can be placed perpendicular to the plane of interest, the resolution can be improved, but if the scanner must work obliquely (e.g. scanning the cornice or roofline), the resolution degrades in a manner similar to what occurs during airborne LiDAR façade capture.

Although considerably superior in resolution to airborne LiDAR, 3DLS does not provide complete building shape, requiring registration of multiple scans from the faces of the building plus the roof. The roof poses particular problems, since it is not always possible to find suitable positions for the 3DLS scan; instead, the roof may be taken from airborne LiDAR data, or potentially from a higher, nearby building using the terrestrial unit.

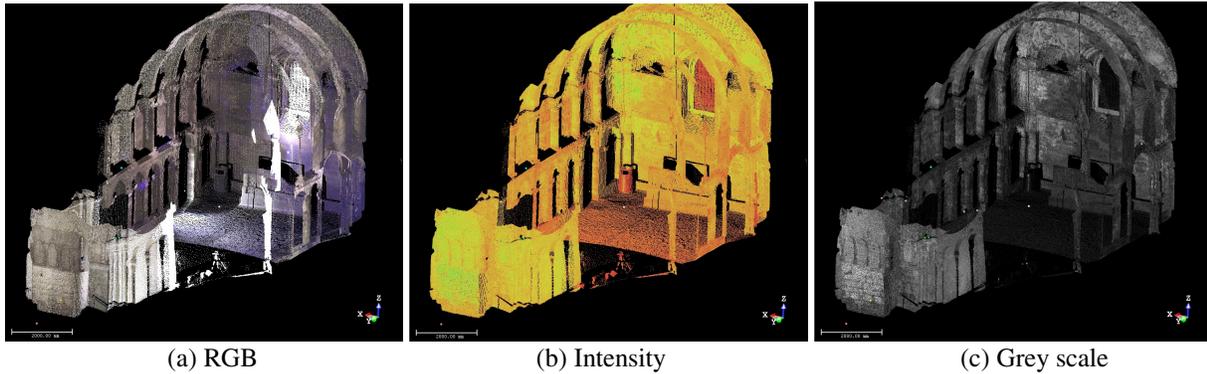


Figure 2. Sample of output

Expense is currently a major impediment to use of 3DLS. The base unit, software, and initial training costs vary from \$100,000 to \$150,000 depending upon the manufacturer and model. In addition to this initial investment, there is the need for regular personnel related to the scanner. To effectively support such a system, at least one full-time technician must be available to keep the equipment working and to maintain related computer systems. This involves several steps. The first is setting up of the scanner on site using survey registration points for highest accuracy and seamless merging of the resultant point clouds. Once the data has been gathered, the management and processing of the point clouds is handled by the technician, with the raw data being stored in a structured database. Despite these substantial expenses, if sufficient numbers of projects can be performed annually, it is feasible to deliver results at a lower cost per building. Additionally, in recent years the cost of the equipment has decreased in parallel with substantial technical improvements in resolution, rotational angles, and software.

Automated FEM Mesh Construction

Currently 3DLS is regularly used to document existing structures to create as built drawings, where none exist (Schuller 2001, Meade 2002). The scanned images are converted into computer aided design (CAD) compatible files. Theoretically, these could be used as the basis for generating first-order approximations for FEM meshes. Even though (as will be described in detail below) significant limitations exist in attempting to generate FEM meshes from knowledge largely restricted to a building's exterior, the load-bearing nature of the most vulnerable buildings (i.e. unreinforced masonry structures) provides a reasonable viability of such an approach, since the unreinforced masonry buildings have most of their load-bearing structure visible as part of the building envelope.

To date, efforts at automated FEM mesh generation have focused on importing the data into CAD packages as an intermediary processor. This approach has several significant limitations: (1) the 3DLS point cloud data processing is based on pre-established geometries, which are regular and planar and may not reflect the existing building geometry; (2) CAD programs rely upon straight lines and uninterrupted planes resulting in unintentional "correcting" of the condition of the existing displaced/distorted structure; (3) CAD's autocorrecting prevents mesh convergence without which the FEM is unusable – presently FEM meshes cannot be generated from CAD without significant hand correcting; (4) only a surface mesh is created, which is insufficient. Even by supplementing exterior data with expensive, interior scans to obtain wall thicknesses and floor positions, insufficient information exists to robustly construct the mesh. To overcome these obstacles advances are needed in the following areas: data point cloud decomposition, supplemental data set linkage, and feature extraction of new, hybrid datasets.

When creating a mesh of an existing building, each structural element must be identified [type, size, position (with respect to a fixed axis) and each connection condition must be specified (i.e. unrestrained, pinned, or fixed)]. The traditional approach is to generate a mesh manually or with a combination of CAD files and manual input. For

most existing urban structures, CAD files are not available. In fact, for the majority of urban structures, structural drawings of any type are not available.

Automating the FEM process for above ground structures using 3DLS requires capturing the relevant images (Figure 3.a), decomposing the point cloud into planes (Figure 3.b), removing the non-structural elements (Figure 3.c), identifying the specific structural elements and internal structural system (not shown), and generating the mesh (Figure 3.d) based on the identified geometry, element identification, and selected material properties. Various forces and/or loads are then applied to the FEM.

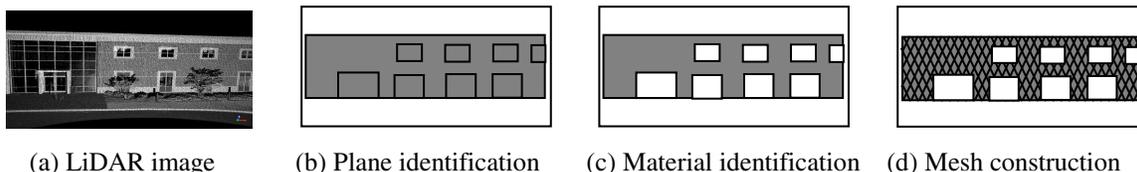


Figure 3. Schematic transformation of the real structure into a FEM mesh

Ultimately, the success of FEM models depends on accurate representation of geometry, material composition, and structural elements. Geometry can currently be determined from 3DLS-sourced point clouds with attached color and intensity information, while material composition and structural elements need to be deduced from the visual and geometric information (Zerger and Smith 2003). Since 3DLS data consists of hundreds of thousands of discrete points in space for an object, as opposed to a surface or volumetric model, the point-based data must be converted into geometrically defined surfaces for further processing. These surfaces must be defined not only by the location of individual points, but by which points connect to each other, that is *surface topology*. Current algorithms for deducing surface topology work well for individual objects (e.g. artistic models or machine parts) and commonly assume smooth, curved surfaces (Hu et al. 2004). Moreover, small-scale geometry and topology is assumed to be as important in the object's shape as large-scale features are (Zwicker and Gotsman 2004). For buildings, however, these assumptions are less important. Large-scale, structural information must be distinguished from small-scale, detail information. Existing methods can be applied to detect individual buildings or abutting groups of buildings, and then geometry can be used to decompose individual buildings into architectural primitives to distinguish details that may be ornamental or incidental (Davis et al. 2002, Hu et al. 2003). This approach can be based on the known vertical orientation of most buildings. From an initial building footprint and position, a set of hypothesized wall planes can be generated from which to assign the 3DLS points to wall planes. Once assigned, each point can be plotted in the wall plane and a surface topology will be generated with respect to that wall plane (Hu et al. 2004). From there, the deviation of each 3DLS point from the wall plane can be established to construct a *bump map*: a planar function representing the deviation from the wall plane of the entire surface (Rottensteiner 2003). With such information, roof elements can be extracted by existing methods followed by geometric collection of individual triangles into larger near-planar regions (Hu et al. 2003). These surface extraction routines will result in a set of planes representing the walls and roof surfaces of the building, along with a map of local deviations from these planes representing smaller scale features and details. The work can be verified against aerial photographs.

Once the principal geometric surfaces of a building are established, the next task is to recognize architectural features such as windows, decorative bands, and cornices. Since these architectural features have substantially uniform geometric deviations from that of the wall plane, they can be detected in the corresponding deviation maps. The identification and isolation of these elements will assist in deducing the building's structural features. By classifying elements according to their horizontal and vertical orientation, a geometric decomposition of the building's walls into architectural façade elements can be produced. Since these features generally form planes parallel to, as well as close to the wall plane, they can be detected by finding regions of consistent geometric deviation from the wall plane in the deviation map corresponding to the individual wall. Non-structural features, such as parapets, can also be detected by correlating roof and wall planes to detect elements extraneous to the base building box; note that the 3DLS information must be supplemented by roof data to distinguish individual buildings, to obtain roof details for buildings, and to supplement 3DLS data for the upper reaches of the building façade. This is especially critical when the structures are attached or semi-attached, such as where two buildings share a party wall.

Recovering macro and microstructure features, such as recessed windows and archways, is possible by using multiple images of the same structure from different angles. These image-based modeling techniques, along with image analysis of the textures to determine material, can be augmented to predict the locations of load-bearing walls and other macro features. The architectural elements can then be represented as separate geometric objects with

their own base planes and deviation maps, to provide the base information from which to classify buildings. The deviation maps can then be used in conjunction with the color and intensity images to determine the type of material for each building element (Figure 4). Combined with the architectural model resulting from the surface decomposition, this data can be used to classify each building.



Figure 4. Sample material textures

Because 3DLS only detects a building's surface geometry, more information is generally needed to ascertain the building's structural system, which is essential to FEM construction. To achieve this, a library of paradigm structures is needed. Each paradigm building should represent a construction style and method identifiable over a specific geographic domain and time period. These classifications can be used to form the basis for a selection of a structural system with which to inhabit the external geometric features. Of particular importance for these paradigm structures is identification of type, size, and spacing of the structural elements and their connection details and material properties. Of lesser importance but still required knowledge is the same information for non-structural elements. If one knows the general dimensions of a building and its external materials, the specifics of its structural system can be narrowed to a limited set of alternatives, which will be largely restricted based on the predominant building styles, methods, and materials used within a limited geographic area over a certain temporal period (e.g. 1880-1900 Philadelphia).

By devising paradigms through architectural and engineering surveys of buildings within a construction area, buildings such as row houses can either be decomposed into individual structures or represented as a single, large combined structure, depending on the best structural representation for engineering purposes. Building paradigms in the library should be distinguishable by major architectural features, materials, and geometry. Such identifiers can be based on a combination of standard architectural classifications and architectural elements and material distinctions. Additionally, paradigm foundations must be integrated into the mesh. As many of these decisions were dictated by empirical knowledge (e.g. Kidder 1916), the approach is not as complicated as may at first seem.

The creation of such libraries has been successfully used internationally for risk management in the earthquake community. Highly localized examples include efforts by Baronio and associates to classify rubble wall types in northern Italy for the purpose of screening the probability of aseismic treatment success of grouting (Baronio et al. 1992). Similar efforts are currently being conducted in Greece to provide rapid community-level risk assessment as a means of rating a town's seismic vulnerability based on its building stock. Such attempts are not fundamentally different from the very large-scale efforts that have been underway for over 10 years to create a World Housing Encyclopedia (WHT, 2005). Unlike the efforts outlined above, which directly take library information to inform engineering decision-making, the proposed course of action enables an entirely distinct and further layer of analysis, which would not be possible merely through the direct application of the categorical information. To achieve this higher functionality, a FEM mesh needs to be created for every paradigm building in the library. These prototypes are not used directly to instantiate the study area. Modification is needed to transform the paradigm mesh into a meaningful structure for a specific building.

For each building identified and decomposed from 3DLS point data, an automatic or semi-automatic classification system needs to be developed to assign the building to a particular class in the library. This classification depends on material properties and geometric positioning and regularity of features such as windows and doors. Additionally, because the library is populated with FEM meshes generated only from paradigms, the meshes cannot necessarily be applied directly as the structural system of an actual building. A method is needed to adjust the size, placement, and number of structural elements to correspond to the architectural and geometric features of the specific building. As an example, depending upon a building's width, individual structural elements or entire floors may need to be replicated with or removed from the mesh (Figure 5). To achieve this, two strategies can be applied. The first uses a coordinate system to reference a series of planes from which other planes (e.g. the windows) are removed. Alternatively, use of an actual object creation routine can be tried. The first possesses the advantage of geometric

simplicity, but the object creation approach allows greater precision in the assignment of material attributes (e.g. thermal coefficients, density, strength). Both approaches are supported by leading commercial meshers.

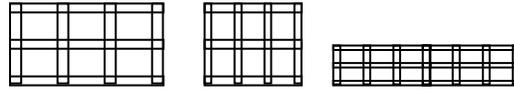


Figure 5. Modification of paradigm to match specific building characteristics

The above recommended process has many limitations, the extent of which cannot be quantitatively assessed without a large-scale implementation of such a program verified against full, traditional, manually constructed FEM meshes. Such an effort is just being launched by the lead authors at the University College Dublin, as a joint effort between Civil Engineering and Computer Science,

Conclusions

Although 3DLS is not currently a viable option for all stages of the adjacent excavation cycle, in terms of condition assessment, damage prediction, and real-time monitoring, the technology possesses many of the key elements that will make it a creditable option, at least for large-scale projects and for companies that conduct a large amount of this type of work. Major technological impediments that remain focus on transforming the 3DLS point cloud into elements that are recognizable by a commercial FEM mesh generator and ensuring that those elements represent a sufficient portion of the structural system to generate a meaningful FEM mesh.

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