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Planning Infrastructure Documentation with Aerial Laser Scanning

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Summary

Worldwide there are millions of bridges and overpasses that need documentation, inspection, and maintenance. Aerial laser scanning has the potential to assist in this process not only through the initial documentation stage but through the automated creation of three-dimensional, computational models and a further integration of that data with the surrounding environment. This paper outlines the difficulties related to effective vertical data capture for major infrastructure elements and recommends specific approaches towards a geometric optimization of this problem. Results of the current level of viability using a test area in Dublin, Ireland are included based on the application of this optimization.

Keywords: Aerial laser scanning; surveys; remote sensing; urban studies; three-dimensional models; geographic information systems; bridges; highway overpasses.

1. Introduction

Cost-effective stewardship of America's nearly 600000 bridges and highway structures poses several key challenges with respect to safe and effective inspection, permanent documentation, computational modelling, and subsequent financial allocation [1]. The stewardship problem is exacerbated by the absence of existing drawings for a large portion of these structures. For instance, in North Carolina, documentation exists for barely more than half of the State's more than 13000 bridges and overpasses [2]. With 90% of all passenger travel and movement of more than 50% of the nation's freight tonnage relying on these types of facilities [1], ensuring proper maintenance and upgrading is critical, but doing so without baseline information and in the absence of drawings is problematic, particularly within the context of budget limitations. In more densely populated portions of the world such as Asia and Europe, the situation is further complicated by surrounding facilities. In European cities, 20-25% of urban space is devoted to transport [3].

To date, decision-making relating to these types of structures has been done in a myriad of ways spanning from probabilistic-based inspection programs (e.g. [4-6] to prioritization-based intervention models (e.g. [7-8]). Physical inspections themselves have been augmented by the installation of sensors (e.g. [5, 9] and the application of remote sensing processes (e.g. [6, 9-11]). Presently, the application of laser scanning [also known as light detection and ranging (LiDAR)] has been restricted to the terrestrial format [12, 13], for two-dimensional (2D) feature identification as in the case of railway lines [14], or for the collection of terrain information [15]. Terrestrial usage involves the dispatching of a crew (typically in the form of a subcontract) and a one-time generation of a three-dimensional (3D) computer aided design (CAD) model. Recent developments, however, in aerial laser scanning (ALS), with respect to increasing quality and quantity of data capture, raises the question about the potential applicability of such an approach to aid in infrastructure documentation [16]. The generation of models (either CAD or finite element) from ALS holds great

potential for Urban Planners and Civil Engineers working in such seemingly disparate applications from vibration prediction to disaster mitigation. ALS offers the prospect of the auto-generation of key portions of such models combined with the advantages of both speed and worker safety. This paper presents a discussion of the geometric impediments to ALS flight planning to maximize the vertical data capture needed for such 3D model generation for both the generation of drawings where none exist and for rapid post-disaster analysis. Like traditional surveying, with the use of ALS many factors remain unknown (e.g. foundation depth and condition, reinforcement details, material characteristics), but what will be shown is that with intelligent flight planning, it will only be a matter of time until the advent of unmanned aviation vehicles combined with improved hardware resolution of such imaging will be sufficient not only for 3D model extraction for bridges and possible for defect identification, as well for a fraction of the cost and for enhanced worker safety.

2. Background

2.1 Technology

LiDAR is an active remote sensing technology that is used to collect 3D data [17]. The data are collected with aircraft-mounted lasers capable of recording range measurements at a rate of 5000 to 50000 pulses per second. The difference in time is measured from when a laser pulse is emitted from a sensor to when the closest object in the path of the laser reflects back the pulse. Using the speed of light, these time measurements can be converted into distance [18]. The LiDAR instruments collect 3D data. To make these data spatially relevant, the positions of the data points must be geo-referenced. Thus, high-precision global positioning system (GPS) antennae, mounted on the aircraft or equivalent systems, are used to determine the spatial positions of the data points. The end product is a collection of accurate 3D points that are geographically registered. Longitude, latitude, and elevation from the mean sea level (x, y, z) are stored for every data point [19]. Point coordinates are typically converted to a planar co-ordinate system through some form of elliptical transformation. The current generation of aerial LiDAR is capable of providing both horizontal and vertical information at high spatial resolutions. Accuracy of airborne LiDAR data is recognized to be of submetre accuracy for vertical measurements and centimetre level accuracy horizontal measurements [20]. The extent of LiDAR point density is dependent on fly-over height and intrinsic system factors, such as platform velocity, sampling frequency, and field of view [17]. The point density needs to be adjusted according to the application so that sufficient information is harvested, while not collecting excessively detailed data (e.g. [21]). Aerial LiDAR technology has been used in many areas of applications such as (a) content generation for a variety of GIS/mapping related products, (b) forestry management, (c) coastal engineering, (d) flood plain mapping, (e) disaster response and damage assessment, and (f) urban modelling. An advantage of aerial LiDAR is that it can collect 3D information about thousands of structures in only a few hours. The data can then be tied directly to a GIS base map. The city of Los Angeles has employed this approach to document its pre-earthquake, baseline condition. In case of a major earthquake, Los Angeles can be flown immediately again with the LiDAR, and an automated comparison of the images can be conducted. The disaster management community believes that through this approach, unprecedented levels of critical information will be available for decision-making regarding post-earthquake deployment of limited emergency personnel and resources.

Such an approach, however, is currently restricted to two-dimensional (2D) representations. This is because, to date, the representations of structures that are generated are either 2D (i.e. outlines), or because of their extruded or instantiated natures do not reflect the true geometric and material characteristics of the vertical faces of such structures, which is known to be essential in the modelling of a variety of topics including blast-energy dissipation and urban wind corridor formation. The current alternatives are reliance on pixel-based photogrammetry or to model the geometry by hand

using modelling software, but this is both slow and inaccurate, and both approaches result in immutable systems that offer only limited opportunities for engineering-based analysis.

In contrast, although not traditionally employed in this way, ALS offers the potential to efficiently, rapidly, and simultaneously generate accurate 3D geometric models for multiple structures occupying large geographical areas. Traditionally, ALS has provided high quality data only for horizontal surfaces, as in the case of digital elevation models. Vertical surfaces, however, are harder to capture accurately, principally because the laser beam strikes them obliquely, but also because of shadowing effects. Both obliquity and shadows generate dead zones – regions in which data quality is either poor or non-existent. In particular, dead zones are generated by scan obliquity, façade shadows (structure self-shadows) and canyon shadows (inter-structure shadows). Thus, collecting good quality LiDAR data for vertical surfaces involves planning a flight path to minimize these effects; such vertical data are essential to the documentation, monitoring, and modelling of any bridge or overpass. The remainder of this paper, therefore, analyses these geometric constraints and provides recommendations on how to plan a suitable flight path to minimize these negative effects. As the most challenging situation would be a dense urban area, and infrastructure elements in urban areas are arguably some of the most heavily used (i.e. vehicles/day), this is the case that is presented in the form of a flight recently commissioned for the centre of Dublin Ireland.

2.2 Geometric Constraints on Flight Plans

There are six principal constraints on designing a suitable flight plan – locational geometry, flight geometry, vertical scan obliquity, self shadows, street shadows, and lateral scan obliquity.

Since the constraints on flight planning are principally geometric, characteristic geometry of urban environments must be acknowledged. There are three major factors that need to be considered – structure geometry, surrounding geometry, and street layout.

Structure geometry describes the shape of individual structures. For structural and economic reasons, most bridges and overpasses have vertical and horizontal planar elements. Because the variability of design and vehicular approaches is highly varied, this discussion is more easily understood and visualized by using the simplified rectilinear form that is common to most buildings and bridges, where vertical walls are arranged in rectangular or near-rectangular shapes. While not universally true, the rectilinear pattern is broadly true for most large urban aggregations and, as such, can be exploited when scanning. Where a bridge or overpass has a divergent orientation, flight paths can be easily altered to achieve the recommended orientation of the data capture to the object, as will be described subsequently.

Surrounding geometry depicts the shape of small groups of structures aligned along a common communication and transportation area. Typically, a street consists of two rows of parallel structures on opposite sides of an open space. Moreover, plots along a given street are fairly uniform in size and shape, with the result that barring topographic constraints, large parts of a city tend to have multiple streets parallel to each other. This, combined with the preferred rectilinear shape of most infrastructure, tends to impose a strong geometric configuration on cities as a whole, which can also be exploited when scanning both bridges and other structures (Figure 1). As will be discussed at the end of the paper is that because of the cost associated with ALS, it is important to be able to structure data capture for maximum usefulness (e.g. floodplain mapping and façade data capture). Surrounding geometry and the following street factor are of greatest relevance near abutments or where complicated structural installations occur (Figures 2 and 3).

Street layout describes the overall geometric structure of a city. While older portions of cities can be very complex, most cities fall into three basic patterns – regular rectangular grids, radial layouts, or topographic. However, within radial cities, the infill between the major radial streets tends to be rectangular in nature, as does the infill between topographic boundaries. As such, a reasonable

approximation of street layout is that it tends to be locally regular but may be irregular at a larger scale. This localized structure can also be exploited when scanning. For simplicity, the balance of this paper will assume that the city to be scanned is locally a rectangular grid, as shown in Figure 1 and that the bridges and their approaches connect as direct extensions of the street grid.

2.2.1. Flight Geometry

While the flight path is notionally controllable, in practice it is easiest to fly in a straight line. Thus, most survey flight paths tend to be a set of straight lines (as opposed to a zigzag or radial pattern). Moreover, for a given altitude of flight, the ALS unit scans points on the ground, within a relatively fixed lateral offset (although this is dependent on the altitude of the ground). Since each straight line flown corresponds to a rectangular strip of ground scan, flight planning is principally a question of choosing the rectangular strips to be scanned in such a way that the overlap covers the desired area. Given straight-line flight paths, this means that the most cost-efficient method to fly is a series of parallel flight paths, whose strips cover the entire area with minimal overlap, as shown in Figure 1. For vertical surfaces of bridges and their abutments further adjustments are necessary.

Fig. 1: Ideal urban grid pattern with standard flight path superimposed.

Fig. 2: Ha'penny bridge in Dublin, Ireland with buildings abutting the bridge approaches.

Fig. 3: Grattan bridge in Dublin, Ireland with approach built into the River Liffey's quay

2.2.1.a. Vertical Scan Obliquity

The principal geometric difficulty with LiDAR scans of vertical surfaces is that as the ALS scanner flies above a city, the laser beam scans a fairly narrow range of angles beneath the scanner – up to 30° away from the vertical. Moreover, the points from which the laser beam is reflected are at uniformly spaced angles, not uniformly spaced distances. For conventional use of ALS for horizontal surfaces, the resolution therefore degrades from a spacing of RN directly underneath the scanner to a spacing of roughly $RN \sec^2 \theta$ at an angle θ away from the vertical (Figure 4). For angles $\theta < 30^\circ$, this degrades by at most 35%, thereby providing nearly uniform horizontal resolutions. For vertical surfaces, however, as visible by the vertical bars on the right side of Figure 4, the spacing of scan points on vertical surfaces becomes larger and larger, as the vertical surfaces approach nadir – the point directly beneath the scanner. Intuitively, this is reasonable, since a vertical surface directly under the scanner will be parallel to the laser beam, which will, therefore, strike the entire surface. In other words, the closer a vertical surface is to nadir, the worse the vertical scan resolution will be on that surface. As a result of this, guaranteeing scan quality of a particular level requires treating the data directly beneath the flight path, and for some distance off

to the side, as useless for the purpose of recording vertical surfaces: paradoxically, this dead zone of low quality vertical data is the zone of the highest quality horizontal scanning. The flanks of the scan, in contrast, have the highest quality vertical scan and lowest quality horizontal data, as shown in Figure 4. From this observation, it follows that the dead zone from one flight path will have to be scanned in the flank of another flight path. Ignoring overlap here for clarity, this is most conveniently achieved, if each flank has the same width as the dead zone (or possibly a rational fraction of it). The impact on scan quality of the width of the dead zone is addressed later in the paper, but for now, consider that the dead zone and flanks are of equal width, and that each is 1/3rd of the total scan width (Figure 4).

2.2.1.b. Self Shadows

In addition to dead zones caused by vertical scan obliquity, not all vertical surfaces in the scan area will appear on the scan, as a result of shadows – since the laser is a form of light, it is blocked by solid objects. Since any solid object has a side facing the scanner and a side facing away, the side facing away will be self-shadowed by the side facing toward the scanner, as shown in Figure 5a. The consequence of this, shown in Figure 5b, is that to acquire both sides of a given object, there must be (as a minimum criterion) a scan once from the left and once from the right. Even though each flank provides good quality vertical, data, it only does so for half of the vertical surfaces in the zone. Specifically, the flank to the east of the flight path will only provide data on west-facing surfaces, and the flank to the west of the flight path will only provide data on east-facing surfaces. Complete scan coverage thus requires that every structure be covered from both flanks, one from each of two different flight segments (Figure 6).

2.2.1.c. Street Shadows

While self shadows are the result of a structure shadowing itself, scans may also be blocked by the effect of street shadows, in which a bridge or overpass is shadowed by a flanking. Geometrically, the effect of these shadows depends on the height of the shadowing structures and the distance between the two structures, as can be seen in Figure 7a. If the distance w between the structures is less than $h \cdot \tan \theta$, then the bottom of one structure will be shadowed by the adjacent one. Although h , the height of the structure is immutable, the distance between structures is measured perpendicular to the flight path. If the flight path is parallel to the street, these distances are minimized, as shown by width w_1 in Figure 7b. However, flight paths at an angle to the line of the street will effectively increase the distance between structures, as shown by diagonal w_2 in Figure 7b. Since in this case a perpendicular street grid was assumed, the optimal angle for avoiding street shadows is to fly at a 45° angle to the street grid, and thus to the structures themselves.

2.2.2.c. Lateral Scan Obliquity

A related problem to vertical obliquity is lateral obliquity – the orientation of the vertical surface relative to the laser beam. Since the laser beam is perpendicular to the flight path, this implies that horizontal resolution is best for surfaces parallel to the flight path. Although, at first sight this implies that flight segments should be parallel to the street grid, this would cause each structure or group of structures to have to be scanned from four different directions (see Figure 8a). If, however, by flying diagonally to the street grid (see Figure 8b), only two distinct scans are required to capture all four vertical surfaces, provided that a degradation of scan resolution (i.e. increased horizontal spacing of the scan points) is acceptable. Since the vertical resolution is typically much worse than the horizontal resolution, this is generally acceptable. Provided that the horizontal spacing does not increase beyond the vertical spacing, therefore, the number of scans required to capture reasonable vertical details can be halved. However, if any structure lies at an angle to the street grid, oblique scans of individual facades may result, so it is wiser to retain scans from all sides. Moreover, diagonal flight paths also help minimize the negative impact of street shadows.

<p>Fig. 4: Horizontal and vertical scans and dead zone beneath scanner.</p>	<p>Fig. 5: Self shadows</p>
<p>Fig. 6: Overlapping flanks for full coverage.</p>	<p>Fig. 7: Street Shadows</p>
<p>Fig. 8: Orthogonal and diagonal scans</p>	<p>Fig. 9: Final flight plan on idealize grid</p>

2.2.2.d. Flight Planning

The simplest approach is to set the dead zone equal in width to the flanks – e.g. for a total scan width of 300m, the dead zone and flanks should each be 100m wide. From Figure 6, setting the distance between the flight paths equal to this width is shown, although a slight reduction may be desirable to achieve some overlap and avoid lacunae in the data. Thus, diagonal flights can be seen to be preferred. As such, the ideal flight path will consist of a series of parallel lines diagonal to the

local street grid and diagonal to any bridges and overpasses, spaced at a distance of $1/3$ the total scan width from each other, in order to guarantee that each structure is correctly scanned on all principal faces with a maximum of scan resolution and a minimum of shadowing (Figure 9).

Fig. 10: Pedestrian bridge at Dublin Castle

Fig. 11: Pearse St. DART Bridge

3. Results and Viability Assessment

At current Irish aviation restrictions of 500 m minimum fly height, combined with the most recent generation of aerial LIDAR equipment available in 2006, a scan of a portion of Dublin Ireland's city centre was made. Using the new flight plan, when considering buildings, major architectural details and the general structural form were visible and available for extraction. The bridges fared less well, with specific architectural or structural elements more difficult to identify because of their relatively modest surface area and thinner features (fig. 10). As shown by the lower panels of these two figures, the data quality is insufficient for surface rendering and other further processing, but by comparing these results to what was obtained from a single pass (fig. 11), the advantages of the rethought flight plan are evident. Although these results may seem presently untenable, recent work by the authors in using this same ALS data set to generate FEM models completely automatically has shown a process, although far from perfection, that does converge without error and without any manual intervention [26]. Finally, the cost of achieving the Dublin aerial LiDAR flyover was approximately \$9000/km² and was based on a total day-long capture of 6 km². Although perhaps financially out of reach for many communities, aerial LiDAR of bridges and overpasses holds the distinct advantage of being simultaneously useful to a wide range of end users for applications as

broad as flood plain mapping to landslide identification to disaster management and coastal erosion. As such, cost-sharing incentives should be strong amongst various governmental agencies and organizations, thus substantially decreasing the cost of such data acquisition. Flight plans would have to be optimized for all potential end users.

Fig. 12: O'Connell Street Bridge in Dublin, Ireland

4. Discussion

When considering both financial and technical issues, the current resolution limitations are readily apparent. However the potential of using LiDAR to document previously undocumented bridges and overpasses for the purpose of generating permanent documentation and possibly computational models seems almost within reach technically. This may even be possible for the rapid assessment of such structures in a post-disaster situation such as Hurricane Katrina. Although the underside of a bridge would not be captured, unless the ALS unit was mounted on a small, unmanned unit (something not accomplished to date), the future potential of the technique is clear in terms of advantages of speed and worker safety.

5. Summary

Future ALS equipment has the potential to return significant amounts of data related to the vertical details of bridges and related infrastructure in urban environments. The successful acquisition of such data is, however, highly dependent on an alternative consideration of flight plans, where high quality data exists within the traditional flight plan's data capture (namely in the flanks, instead of at nadir) and the application of a flight plan that is set diagonally to the main orientation of the structures of interest. Although both of these aspects are readily achievable within the current state of practice, both are counterintuitive, with respect to traditional practice that has to date focused on the capture of elements in the horizontal plane, as opposed to those in the vertical.