Aerial Flightpath Considerations for Documenting Urban Heritage Using Laser Scanning

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Abstract—This paper provides guidance for the planning of urban heritage documentation using aerial laser scanning. The paper presents standard industrial considerations typically undertaken by commercial data providers and the additional factors that such be raised in the planning stage when urban heritage documentation is the goal.

Keywords—aerial laser scanning, light detection and ranging (LiDAR), urban, city centre, heritage, historic architecture

I. INTRODUCTION

Laser scanning [also known as Light Detection and Ranging (LiDAR)] has been used in various forms of heritage documentation for about two decades for general documentation [1-3] and to capture damage [4,5]. This is especially true for terrestrial units as their speed, accuracy, and ease of use have vastly improved, along with a nearly order of magnitude decrease in cost. Although satellite and aerial imagery still dominate non-terrestrial documentation, aerial laser scanning has become vastly more popular and more accessible. However, optimizing aerial laser scanning (ALS) usage for urban heritage poses extra challenges that may be unknown to potential consumers of such data. These considerations are described below.

II. BACKGROUND

A. Usage History

The history of ALS has been integrally tied to documenting large tracks of land for applications such as flood-plane mapping and forestry [6,7]. While the technology has also been applied to land use planning and disaster management (e.g. [8]), these applications relate predominantly to terrain features and/or rural considerations and typically involve the creation of a digital terrain map (DTM) or digital surface map (DSM) [collectively considered as digital elevation maps (DEMs)]. As the aerial laser technology was developed to capture ground elevations, the laser unit is oriented largely perpendicular to the ground. Although the ALS unit rotates from side to side, the main orientation of the unit is downward. This complicates the capture of vertical surface data as the ALS equipment mounting is fixed in a largely downward direction. Since the ALS unit is oriented perpendicular to the ground, only when the unit swings to a side are the data that are of greatest interest for urban heritage documentation visible. These oblique data points are of little assistance for capturing rooftops, but are essential for façade and other wall documentation, as will be discussed in detail in subsequent sections of this paper.

Fig. 1. Aerial laser scanner unit orientation and sweep

The equipment orientation cannot be readily reconfigured as it is coupled with a sophisticated set of other data capture equipment, which may include video, still imagery, and global positioning devices. Thus data capture considerations must be conducted within some fixed geometric constraints.

B. Quoted Data Density

Aerial laser scanning data providers calculate the anticipated final data density based on expected wind speed, aircraft height, and the specifications of the actual laser scanning unit. The result is a fairly accurate estimate of the expected number of points per square metre that will be generated on the ground per flight strip (fig. 2). While this is helpful for roof representation the data density on vertical and near vertical surfaces will only be a small percentage of this (fig. 3). The reason for this is shown in figure 4. While the pulses are emitted at regular angles from the ALS unit, it is the intersection with the built environment that is a major limiting factor.

III. SHADOWING CONSIDERATIONS

The other challenge related to vertical data capture in urban areas is shadowing. Hinks et al. [9] identified two forms of shadowing: self-shadows and street shadows (which in the contribution herein are referred to as projected shadows). Any time the ALS’s line of sight is blocked, data of the occluded...
area cannot be obtained from that vantage point. Thus, a full understanding is needed as to types of shadowing that occur in urban areas.

![Diagram showing calculation of horizontal surface resolution](image1)

Fig. 2. Calculation of the horizontal surface resolution ($R_s$), as a function of the density per square metre of data points as projected onto the ground.

![Graph showing linear resolution](image2)

Fig. 3. Linear resolution for the vertical and horizontal data capture as a function of the horizontal offset angle (after Hinks et al. 2009).

While the scanner is on one side of a building, the other side is of course not visible (i.e. self-shadowing), but in urban areas the situation is much more complicated, as one building may obscure the line of site to another (i.e. projected shadowing). Both self-shadowing and projected shadowing are shown in figure 5. The extent to which projected shadowing occurs depends upon many factors. With respect to the built environment this involves the nearby building heights, their relative spacing to each other, and the street widths.

With respect to the ALS flight, the amount of occlusion is controlled by several factors: (1) the height of the aircraft with respect to the target building(s); (2) the distance of the aircraft from the target building(s); (3) the orientation of the aircraft; and (4) the positional limitations of the ALS unit.

Figure 6 shows the authors’ study area – an area of about 1km$^2$ in Dublin, Ireland’s city centre with the flight path superimposed on top. The flight strips were oriented 45 degrees from the general grid pattern of the major streets to help maximize data capture. Additionally, the flight strips were acquired with an intentional one-third overlap to address the nadir shown in figure 1. This is described in further detail in Hinks et al. [9].

![Schematic flight path](image3)

Fig. 4. Visual schematic of the change in horizontal versus vertical data distribution.

![Depiction of self-shadowing and projected shadowing](image4)

Fig. 5. Depiction of self-shadowing and projected shadowing.

![Schematic flight path of the authors’ low-level 2007 ALS of a portion of the city centre of Dublin Ireland](image5)

Fig. 6. Schematic flight path of the authors’ low-level 2007 ALS of a portion of the city centre of Dublin Ireland.
The average flight height was 400m, which was the lowest permissible by the Irish Aviation Authority in 2007 for a helicopter over this portion of Georgian Dublin. The resulting output was typically 225 points per square metre when all 44 of the flight strips were merged. Most of the buildings were each captured by 6 flight strips. A small portion of the resulting data set is visualised in figure 7. The upper and lower insets are detailed images of typical occlusions caused by overhanging roofs.

![Image](image1.jpg)

**Fig. 7.** A small visualised section of the 2007 point cloud with two instances of occluded areas enhanced for clear portrayal.

IV. **Reducing Occluded Areas**

Since the factors related to the built environment will not change, optimization must focus on the flight path planning, where aircraft position can be altered to some extent. On one hand that extent is limited with respect to aviation authority approval (particularly with regard to minimum flight height). On the other, if the aircraft is positioned too high, even though occlusions would be minimized, the data density may not be sufficient. Within these minimum and maximum bounds, choices can be made as to aircraft height as shown in figure 8. The orientation of the flight path (figure 9) and the offset distance of the ALS unit from the scanned area are two other main parameters. Each of these has a major impact on occlusion levels and more specifically, which structures will be occluded.

![Image](image2.jpg)

**Fig. 8.** Flight height choice can be made according to the aviation authorities limits.

![Image](image3.jpg)

**Fig. 9.** The flight path planner motion is defined as the direction and distance from the scanned area.

To better understand how the three parameters of height, offset distance, and orientation angle each influence the data capture, a series of images are provided in figures 10-12 for a synthetic set of buildings. The buildings are placed in a regular grid so that groups of them are equidistant from each other similar (although in a highly simplified version) of what might be found in an urban area. The buildings are represented by simple rectangular forms, and while there are variations in heights, these do not deviate significantly from the average building height in the area.

![Image](image4.jpg)

**Figure 10** shows a flight path oriented 120 degrees to the positive x-axis, at an offset distance of 200 m, and with the data being captured from a height of 250 m. Figure 11 shows the same scenario but with the flight height decreased to 150 m. As can be seen in a comparison of figures 10 and 11, three things happen. First, the number of buildings on which some
form of occlusion occurs increases from 7 buildings in Figure 10 to 12 buildings in Figure 11. Secondly, in Figure 10 when the greater flight height of 250 m is used, occlusions appear at a maximum of only one side per building. At the lower flight height, 5 buildings suddenly have two occluded sides. The third change relates to the size of the occluded areas. The occluded areas in Figure 10 all grow substantially in Figure 11.

If the lower flight height of Figure 11 is retained, along with the 200 m offset distance, but the orientation is modified from 120 degrees to 85 degrees, significant changes again occur with respect to the occlusions, as shown in Figure 12. Similar to the 120 degrees orientation flightpath, 12 buildings showed occlusions. In this case, however, the 5 additional occluded sides shown in Figure 11 do not appear. Instead, three roof areas are now showing occlusions. Given what is known about the relatively good coverage of roof areas, the parameters shown in Figure 12 are definitively superior to those in Figure 11, but still not as good as to those in Figure 10, as quantified by not only the 4 additionally occluded buildings but the large occlusion patches. Without calculating the patch sizes for a particular study area the exact extent to which this occurs is not easily quantified but the qualitative difference is readily apparent.

While these simplified exercises are valuable to gain a feeling for how the parameters interact, they cannot be definitively understood without a more in depth appreciation for the complexity of actual urban areas. These factors are discussed in the following section.

V. STUDY AREA

For the purpose of verification, a portion of the actual study area was selected. Within this is a cluster of buildings. These are shown in Figure 13 as part of a digital surface model; the entirety of the dataset is publicly available for free downloading [10,11]. From that data, plus building footprints, the schematics of the buildings were extruded (Figure 14).

As can be seen in Figure 14, even these highly simplified versions of the buildings are extremely complex with respect to various roof shapes and features, as well as to the positioning of the buildings with respect to each other, along with their much more varied heights.
When the flightpath occlusion algorithms were tested on this group of buildings, the anticipated occlusions aligned well with the occlusions that were experienced during the actual ALS flight. For one randomly selected cluster, the shadowed area calculated was 12.66 m², while the shadow in reality was 11.85 m², this means that a 93% match of the occluded area was achieved. The relatively small difference can be easily understood. Firstly, the algorithm’s input requires the flight height as a constant, but in reality the aircraft is always moving so that the selected height represents only a typical height over the area and not the exact height at which every point is obtained. Secondly, the aircraft experiences pitch, roll, and yaw as it flies. None of these factors are included in the current working model.

VI. CONCLUSIONS AND FUTURE WORK

By being able to predict aerial laser scanning occlusion levels as well as locations during flightpath planning can be of invaluable assistance when working in urban areas. This is especially true when façade information or data on other vertical features is desired. This paper shows the very first outputs of a set of algorithms that are under development to generate a robust occlusion prediction tool. Future efforts will focus on the various output qualities based upon differing levels of available input data (e.g. street layout, street width, typical building height). The approach will also be tested with multiple data sets.