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A spatio-temporal index for aerial full waveform laser scanning data

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ABSTRACT

Aerial laser scanning is increasingly available in the full waveform version of the raw signal, which can provide greater insight into and control over the data and, thus, richer information about the scanned scenes. However, when compared to conventional discrete point storage, preserving raw waveforms leads to vastly larger and more complex data volumes. To begin addressing these challenges, this paper introduces a novel bi-level approach for storing and indexing full waveform (FWF) laser scanning data in a relational database environment, while considering both the spatial and the temporal dimensions of that data. In the storage scheme's upper level, the full waveform datasets are partitioned into spatial and temporal coherent groups that are indexed by a two-dimensional R*-tree. To further accelerate intra-block data retrieval, at the lower level a three-dimensional local octree is created for each pulse block. The local octrees are implemented in-memory and can be efficiently written to a database for reuse. The indexing solution enables scalable and efficient three-dimensional (3D) spatial and spatio-temporal queries on the actual pulse data - functionalities not available in other systems. The proposed FWF laser scanning data solution is capable of managing multiple FWF datasets derived from large flight missions. The flight structure is embedded into the data storage model and can be used for querying predicates. Such functionality is important to FWF data exploration since aircraft locations and orientations are frequently required for FWF data analyses. Empirical tests on real datasets of up to 1 billion pulses from Dublin, Ireland prove the almost perfect scalability of the system. The use of the local 3D octree in the indexing structure accelerated pulse clipping by 1.2–3.5 times for non-axis-aligned (NAA) polyhedron shaped clipping windows, while axis-aligned (AA) polyhedron clipping was better served using only the top indexing layer. The distinct behaviours of the hybrid indexing for AA and NAA clipping windows are attributable to the different proportion of the local-index-related overheads with respect to the total querying costs. When temporal constraints were added, generally the number of costly spatial checks were reduced, thereby shortening the querying times.

1. Introduction

Aerial Laser Scanning (ALS) is increasingly being adopted as an effective means for documenting the built and natural environments. In its most basic form, a laser scanning dataset is an amalgamation of three-dimensional (3D) data points, collectively referred to as a *point cloud*. Handling point clouds is challenging since the data are often voluminous and unstructured. Even with limited densities (e.g. less than 10 points/m^2), a country-wide point cloud typically consists of hundreds of billions of points, occupying tetra-bytes of disc space (e.g. AHN, 2014). The newest ALS data acquisition technology can acquire as much as 65–70 points/m^2 in a single flight line (e.g. Moser et al., 2015; Rahman and Gorte, 2008). In addition, point clouds are distinct from conventional raster and vector data, as there is not an inherent spatial data structure between the individual points within a point cloud. Consequently, management of such large, dense, and unstructured datasets has been a challenge that has attracted intensive research efforts (e.g. Krishnan et al., 2011; Martinez-Rubi et al., 2015; Mosa et al., 2012; Otepka et al., 2012; Ramsey, 2013; Ravada et al., 2010; van Oosterom et al., 2015).

However, these previously groundbreaking solutions are not immediately applicable to efficient management of the data

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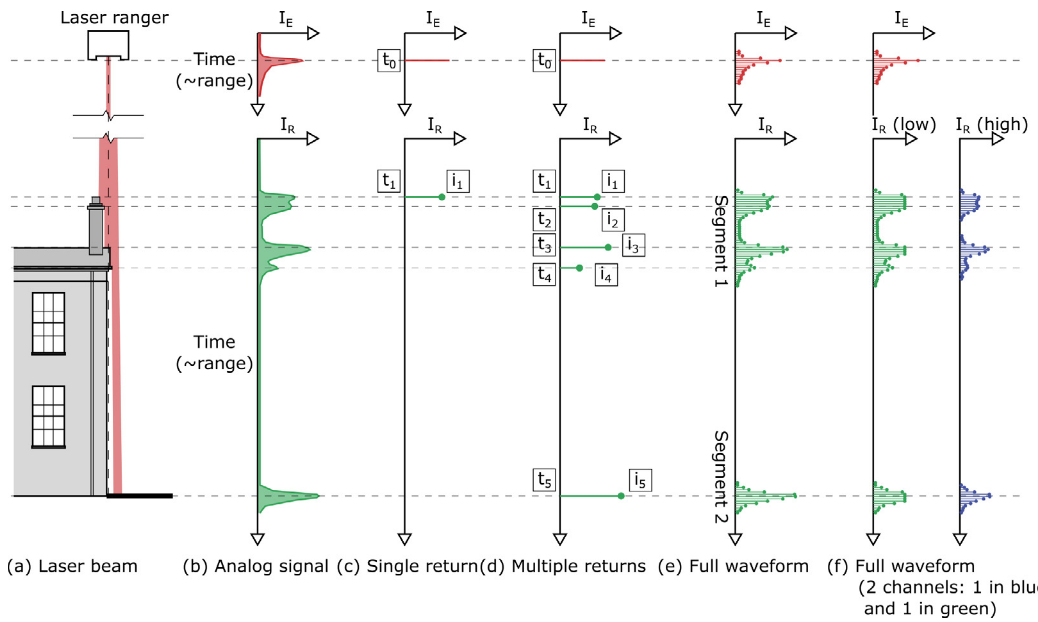

Fig. 1. Range recording methods.

handling challenges presented by the FWF digitisation version of the laser scanning (Hug et al., 2004) now becoming more readily available (e.g. Laefer et al. 2017). With FWF digitisation capabilities, laser scanners can deliver raw sensor data including the raw transmitting and receiving signals (i.e. the waveforms), as well as the 3D geometries of the signal transmitting paths (i.e. the laser pulses). These additional data components have been shown to be useful for a variety of applications, from tree classification (e.g. Fieber et al., 2013; Koma et al., 2016; Mallet and Bretar, 2009) and building edge recognition to vertical object detection (e.g. Jutzi and Stilla, 2005; Jutzi et al., 2005; Parrish, 2007). As for the data management implications, the emergence of the new FWF data components (i.e. waveform and pulse) significantly complicates devising an optimal data indexing solution since FWF data are far more complex and voluminous than conventional point clouds.

Towards addressing the issues of storage and more specifically indexing FWF laser scanning data, this paper proposes a novel system for FWF laser scanning data management suitable for large-scale datasets. Representation of data and metadata in a systematic and storage efficient way is part of the considerations. To facilitate data visualisation, analysis, and exploration, scalable and efficient access to the data are also critical to the database design. Core to this is the use of an appropriate data indexing solution to avoid having to trawl through the entire storage system to find a specific piece or group of data. To this end, a scalable index storage strategy is proposed to provide an advanced spatio-temporal, bi-level mechanism capable of supporting a number of spatial and spatio-temporal queries commonly required for data exploration, visualisation, and processing.

2. Full waveform LiDAR data acquisition and delivery

In its most common form, ALS is a surveying technique that uses a laser to actively sample the surrounding visible surfaces. The majority of airborne laser scanners measure range based on the time-of-flight principle. By precisely measuring the time (t) that a spontaneous light pulse needs to complete a round-trip between a ranger and a target object, the range to the target can be computed as $R = (v \times t)/2$, where v is the speed of light (i.e. 299,792,485 m/s).

There are several range recording mechanisms (Fig. 1) of which the simplest triggers the time counter of the ranging device twice per emitted pulse. The first trigger starts the timing, and the second stops the time. In this *single-return* recording mode, one pair of time values results in one range measurement and the associated returning optical strength (Fig. 1c). However, there are cases when an emitted laser pulse returns multiple *echoes* (i.e. the reflected signal exceeds the ambient noise). Typically, multi-echoes are observed when a laser beam traverses through partially opaque objects such as tree canopies or objects partially occluding the laser pulse footprint (e.g. Fig. 1a). These objects reflect and diffuse a fraction of the laser energy, with the remaining signal reaching further objects. The *multiple return* recording mode incorporates this scenario, by enabling the optical sensor to trigger the time counter multiple times. The resulting recorded data are multiple, time-intensity pairs (Fig. 1d). These values allow computation of ranges and laser intensity values for multiple targets encountered along a laser beam's path.

The more advanced and demanding method of recording ranging data is *full waveform* recording. In that case, optical power, as a function of time on the receiving sensor, is sampled at a very high frequency (i.e. nano-seconds). The recorded data have the form of time histories of the receiving optical amplitude, which may cover multiple possible reflective targets (Fig. 1e). Additionally, a time history of the emitting signal power is often recorded in the FWF mode. Notably, some FWF ALS systems (e.g. Riegl Q680i) record returning signals on two different channels to broaden their dynamic ranges (Fig. 1f). Compared to the discrete return recording, this more complete recording approach has two main distinctions: (1) detection of reflective targets can be performed post-flight, which might allow more rigorous analysis to be used; and (2) the available raw waveform of the data may provide better insight into illuminated objects, particularly when the objects are semi-opaque (e.g. tree canopies).

Whether the recording method is single return, multiple return, or full waveform, the data recorded during a scanning mission are typically defined within the non-stationary scanner's coordinate system. Thus, post-flight processing is needed to integrate the