

SENSOR FUSION: GENERATING 3D BY COMBINING AIRBORNE AND TRIPOD-MOUNTED LIDAR DATA

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KEY WORDS: LIDAR, Laser scanning, Remote sensing, Active sensors, 3D modeling, Terrain mapping

ABSTRACT:

Laser scanning provides structural and topographic detail previously unheard of. When conducting a LIDAR survey, however, it can be difficult or even impossible to collect measurements on all surfaces of a structure. Since LIDAR works under ‘line-of-sight’ principles, laser shadowing can be a significant issue. But since LIDAR sensors are available on several different platforms, sensor fusion can provide the means to generate complete, accurate solid models. Airborne laser scanners collect accurate georeferenced topographic data of large areas very quickly, while tripod-mounted laser scanners generate very dense, geometrically accurate data. Used in tandem, these scanners make it possible to generate complete solid models that are geometrically accurate on all surfaces. This paper documents the processing and fusing of airborne and tripod-mounted scanner data. The survey used an Optech Airborne Laser Terrain Mapper (ALTM) and an Optech ILRIS-3D laser scanner to survey Toronto City Hall in Toronto, Canada. The final product was a fused data set that represented the entire structure and its surrounding grounds.

1. INTRODUCTION

The acceptance of LIDAR as an accurate, effective method of data collection has revolutionized the remote sensing industry. While the ‘time-of-flight’ method of range detection has been employed on many different platforms since the 1960s, over the past decade LIDAR has used this fundamental concept to produce accurate, high-resolution data by collecting thousands of measurements per second. Systems are available in a number of variations and specialize in a number of applications. For example, Optech alone designs and produces industrial LIDAR, bathymetric LIDAR, airborne terrestrial LIDAR, space-based LIDAR and tripod-mounted LIDAR systems. While each specializes in a particular area, sensor fusion provides information that may not be available from any individual system.

The project described here demonstrates that fusing data from complementary LIDAR sensors can produce a complete, accurate solid model. Data was collected on the City Hall grounds of Toronto, Canada using an ILRIS-3D laser scanner and an Airborne Laser Terrain Mapper. The project consisted of collecting the LIDAR data, processing the data, aligning the data, fusing the data from each LIDAR system and, finally, creating the solid model.

Laser scanning systems are opening new possibilities for surveys and the documentation of difficult areas and objects. Such applications may be dense city areas, forest areas or electrical power lines. Laser scanning systems available on the market are presently in a fairly mature state of art, while the processing of laser scanner data (airborne and land-based) is still at an early stage. Airborne laser mapping is capable of rapidly generating high-density, georeferenced digital elevation data with accuracy that is comparable to traditional sensors. However, airborne laser mapping offers lower field operation and post-processing costs when compared to traditional survey methods. Point for point, the cost to produce is significantly less than for other forms of topographic data collection.

2. TECHNOLOGY OVERVIEW

As LIDAR technology becomes more prevalent, surveyors must become more educated about the strengths and weaknesses of this maturing technology. Discussions of LIDAR accuracy need to start from a common understanding of the technology’s capabilities and an agreed definition of what LIDAR accuracy is and how it is to be evaluated.

The manner in which LIDAR works can be simply explained. All laser-based instruments use the same principle: a laser generates an optical pulse; the pulse is reflected off an object and is returned to the instrument; a high-speed counter measures the time of flight from the start pulse to the return pulse; and finally, the time measurement is converted to a distance using the formula

$$R = (T * \Theta)/2 \quad (1)$$

where R = range in meters
T = time of flight of the laser pulse
 Θ = speed of light in meters per second.

Three mature technologies are combined in airborne laser mapping; a laser rangefinder (LIDAR), an inertial reference system (INS) and a global positioning system (GPS). These subsystems are integrated into a hardware system that can be mounted in a fixed-wing or rotary aircraft platform. The data that is acquired is used to rapidly produce digital topographic maps of the terrain beneath the flight path of the aircraft (Figure 1). The accuracy of the data is generally better than 15 cm, while the precision is better than 2 cm.

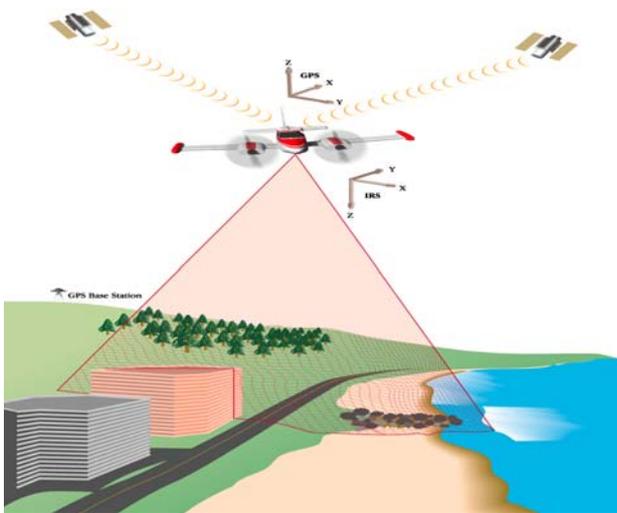


Figure 1. Airborne LIDAR scanning principle.

3. THE SITE

Toronto City Hall was built in 1965 at a cost of \$25,000,000 CAD. Its design was the result of an international design competition. The complex was envisioned as an ‘eye’, with the two large, semicircular buildings representing the eyelids and the saucer-shaped meeting hall representing the pupil (Figure 2). The buildings themselves are located on Nathan Phillips Square, a popular tourist destination that is often host to rock concerts and New Year celebrations, and contains skating rinks.



Figure 2. Toronto City Hall.

4. ALTM

The first set of data was obtained by Optech's Airborne Laser Terrain Mapper (ALTM).

4.1 Data Collection

Airborne LIDAR data was collected using an ALTM 2050 (Figure 3) mounted in a Piper Navajo aircraft. The ALTM 2050 collects 50,000 measurements per second and has a

maximum altitude of 2000 m. Data was collected from 850 m AGL, to maximize data accuracy and measurement density while still providing economical data collection. For this project, data was collected with a point density of 60 cm.

There were two main survey challenges. First, to maintain a relatively uniform distribution of points, a balance had to be maintained between scanner speed and aircraft speed. Second, the survey site itself presented a challenge that affected the method of data collection. The city core is dense and consists of very tall buildings. Laser shadowing on the roads between the buildings was therefore an issue. To minimize this effect, the sensor field of view was reduced from 40° to 20°. In addition, data was collected in a north-south pattern followed by an east-west pattern. While this significantly increased data collection time, it ensured that measurements were obtained over the entire area.

At a speed of 60 m/s, an altitude of 850 m, a field of view of 20° and an overlap of 20%, data collection took 37 minutes (including takeoff, transit and turns). In fact, to collect data for the specific area of interest took only about 10 seconds. This resulted in 500,000 measurements.



Figure 3. ALTM 2050.

4.2 Data Processing

Data processing took place at Optech Incorporated (Toronto, Canada). The entire process was done seamlessly using Optech's REALM Survey Suite software and a P3 500-MHz computer with 1 GB of RAM. Processing consisted of several major steps. Data preprocessing involved downloading the raw data and preparing to extract the information provided by individual sub-components (range, GPS and inertial data). GPS data from a reference station located no more than 20 km from the survey site was then combined with the airborne GPS to

generate a differentially corrected GPS trajectory. The GPS trajectory was used with the inertial data to produce a smoothed 200-Hz trajectory that included the roll, pitch and heading of the aircraft. Upon completion, range data was combined with GPS/inertial data to calculate the position of each measurement in a real-world coordinate system (UTM). The final result was a point cloud containing the coordinates and intensity of each measurement.

4.3 Data Alignment

Since airborne scanning combines several different subsystems, the error associated with each subsystem can propagate directly into the final data set. For a successful survey, the sensor must collect accurate ranges, use accurate GPS/INS data, and be properly calibrated. To ensure adequate GPS, this project mandated that:

- At least six satellites had to be tracked by the GPS receiver throughout the survey
- Elevation of the satellites had to be more than 15 degrees above the horizon
- PDOP had to be less than 4
- Base station had to be within 20 km of the survey site.

A properly calibrated system should produce very stable data in the overlap area of the data set. To verify this, sections were cut across the overlap areas to verify consistency. The average bias error detected in the data was less than 5 cm. Figure 4 depicts a cross-section of the data with each line coloured differently.

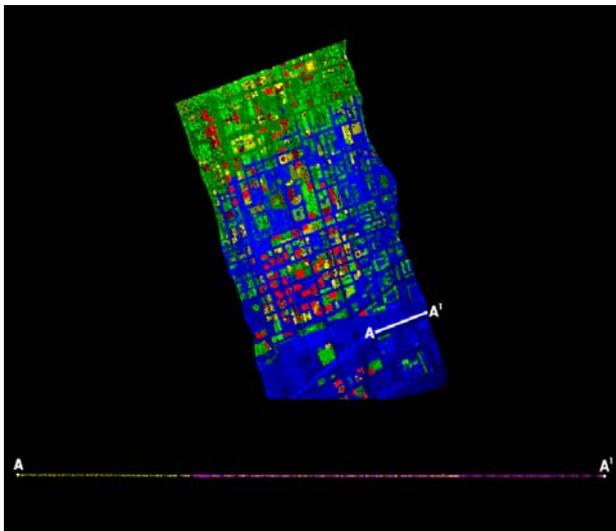


Figure 4. Cross-section of ALTM data.

5. ILRIS-3D

The second set of data was collected by Optech's ILRIS-3D tripod-mounted laser scanner.

5.1 Data Collection

The goal during ILRIS-3D (Figure 5) data collection was to collect a complete, accurate and dense data set of the Toronto City Hall and its surrounding grounds. Maintaining data accuracy while providing the information for data fusion was

critical. By choosing PolyWorks™ by InnovMetric to do the majority of the processing, we were able to simplify the survey preparation without sacrificing the accuracy of the final data. PolyWorks™ has unique capabilities arising from its focus on laser scanner processing utilities, and therefore offers many options not available from other software packages. One major consideration was the ability of PolyWorks™ to perform targetless scan alignment. This eliminated the need for targets, and thus significantly reduced the preparation necessary before data collection.

The characteristics of the survey site presented a challenge, primarily because of the dense city core and tall buildings surrounding the site, and also because construction and security limited access to the site. The City Hall is located in central Toronto and is surrounded on three sides by a series of tall buildings (Figure 6). As the two buildings of the City Hall are themselves relatively tall, obtaining a line of sight that allowed for economical data collection was challenging. Fortunately, the ILRIS-3D has long ranging capabilities (up to 1000 m). Where a long, direct line of sight was available, data could be collected at long range. This reduced the number of scans and thus the processing time. However, because construction and security concerns denied access to areas directly surrounding the buildings, data could not be collected on the lowest portion of the buildings.



Figure 5. ILRIS-3D laser scanner.

Data was collected over two days beginning January 3, 2003. A total of 12 scans were collected, ranging in resolution from 29 mm to 63 mm. The minimum and maximum range of the scans was 74 m and 164 m. The length of each scan was approximately 10 minutes, and the size of each data file was approximately 10 MB.

Data was collected from eight setups. In each case, the system operator was careful to ensure an adequate data overlap. Data overlap was vital for two reasons: to perform an accurate alignment, and to ensure that the data set was complete. While some shadowing was inevitable owing to access limitations, the system operator minimized this effect as much as possible. And while the characteristics of the survey made it impossible to collect data at a uniform range and with a uniform resolution, in

all cases data was collected at a higher resolution than that planned for the final solid model.

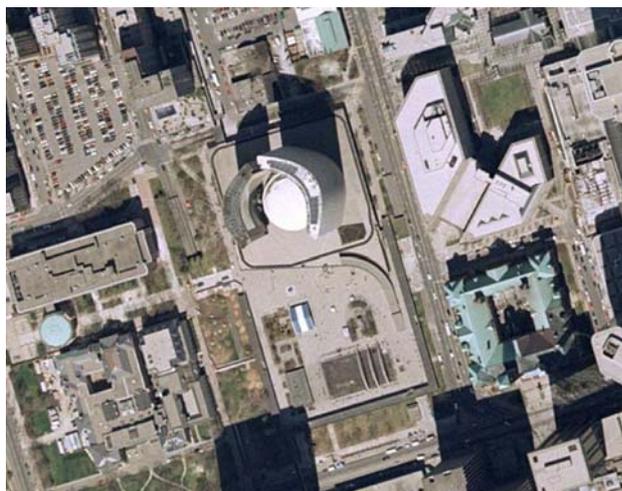


Figure 6. Aerial photograph of Toronto City Hall.

5.2 Data Processing

Data processing took place at Optech Incorporated, using PolyWorks™ and Optech software tools on a P4 1.8-GHz computer with 2 GB of RAM. At this stage, processing was limited to removing noise and aligning data sets. The fusion with airborne laser data and the creation of the solid model occurred later.

5.2.1 Data Preprocessing: The ILRIS-3D records data as an uncalibrated range, scan angle A, scan angle B and intensity. Before using third-party software, a proprietary software tool written by Optech must therefore be used to apply calibration parameters and calculate the XYZ coordinates of each point. At this stage a range or intensity filter may also be applied, and the data can be written to a number of different data formats. When the Cartesian coordinates were calculated for this project, each data set was viewed to remove erroneous or unnecessary data. For example, many people and vehicles were moving through the scene during the scanning. To produce a clean model, it was necessary to remove as much of this noise as possible. Although not time-consuming, this was a vital step.

5.2.2 Data Alignment: The alignment of each data set was done with Polyworks™, because it allows multiple scans to be aligned targetlessly. That is, the coordinate system of any image can be used as the base to which other images will be aligned. This is a semi-automated process that requires the user to coarsely identify at least one common point (tie point) between each adjoining scan. Common physical features are then automatically identified and used to perform the alignment. The average RMS error in the alignment of each scan was 0.015 m (Figure 7). In two cases, the alignment algorithm introduced a bias of approximately 1 m that was visible in the statistics and in the data. To eliminate this problem, more tie points were identified and greater care was taken when selecting them. The RMS was consequently reduced to 0.014 m. Upon completion, a ‘global’ alignment was executed to distribute the alignment error equally across each cutline (Figure 8).

Finally, redundant data was removed in the overlap area, thus decreasing the size of the data set. Removal was based on the scanner angle: if two measurements are collected on the same point, the measurement collected from nadir is inherently more accurate than the measurement collected from an oblique angle. Based on this assumption, data was flagged for removal according to the angle of incidence of the collected measurement. Figure 9 depicts the final aligned data set with intensity displayed.

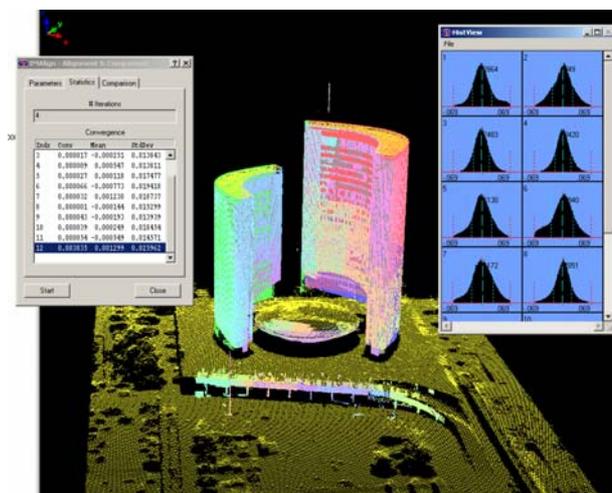


Figure 7. Alignment statistics for all data collected. Gaussian curves indicate a normal distribution of error.



Figure 8. Magnitude of alignment error for each ILRIS-3D scan.

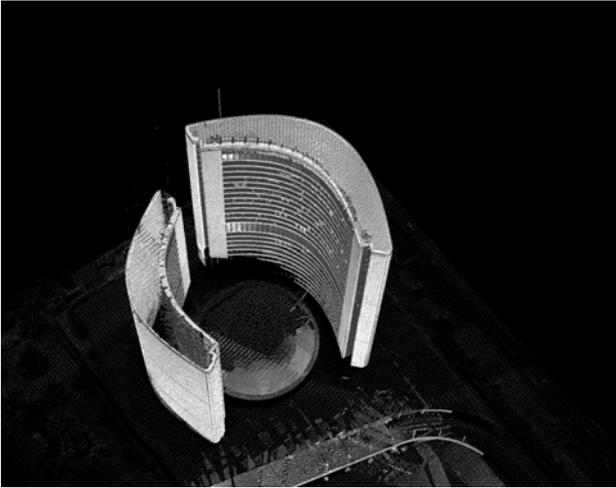


Figure 9. Aligned data sets with intensity displayed.

6. DATA FUSION

Two methods were available to fuse the ground and airborne sensor data: georeferencing the ground and airborne data, or aligning both data sets by identifying common points.

The airborne scanner automatically provides georeferenced data with the onboard position and orientation system. The fusion of the point clouds is therefore fairly seamless, as long as the data from the ground scanner is georeferenced. Georeferencing the ground data requires surveying several identifiable points. The software can then use these coordinates to triangulate the true position and orientation of the data set. Once georeferenced, the two point clouds can be displayed in the same reference system. However, the data fusion is only as accurate as the ground control. Owing to the error inherent in the position and orientation system, the accuracy of airborne LIDAR data is typically no better than 10 cm. When georeferenced, the accuracy of ground LIDAR data is generally better than 2 cm. Therefore, it is possible that this method can produce a gap between the two data sets as wide as 12 cm.

The second option for data fusion applies the same technique as the alignment of multiple ground-based scans (described in section 5.22): common points between the airborne data and the ground data are identified and then used to coarsely align the data sets. When coarse alignment is complete, overlapping data defines the surface characteristics necessary to perform fine alignment adjustments. This method does not require a control survey of the ground scanner data. Since the airborne data is inherently georeferenced, preserving its coordinate system while adjusting that of the ground data effectively georeferences the data collected by the ground scanner as well. However, this transformation includes the error inherent in the airborne data (defined primarily by the quality of the navigational sensor and the GPS) and the error associated with the alignment process.

For this project the data was fused by using redundant data to align the data sets. Since the final product was a solid model, seamless fusion was deemed more critical than absolute accuracy. When georeferencing the ground data, its accuracy was maintained (to the level of a static control survey). However, a gap appeared at the cutline as a result of the difference in accuracy between the two scanners. Alignment based on the airborne data forces the ground data into the same

coordinate system. While the accuracy of the ground data degrades slightly (it is limited to the accuracy of the airborne data, 10 cm), the resulting data set makes a seamless transition between the sensors.

The major obstacle in fusing the data was identifying enough redundant data to complete the alignment. This was a challenge because airborne data provides information on the top of the structure, while ground data provides data primarily on the side of the structure (Figure 10).

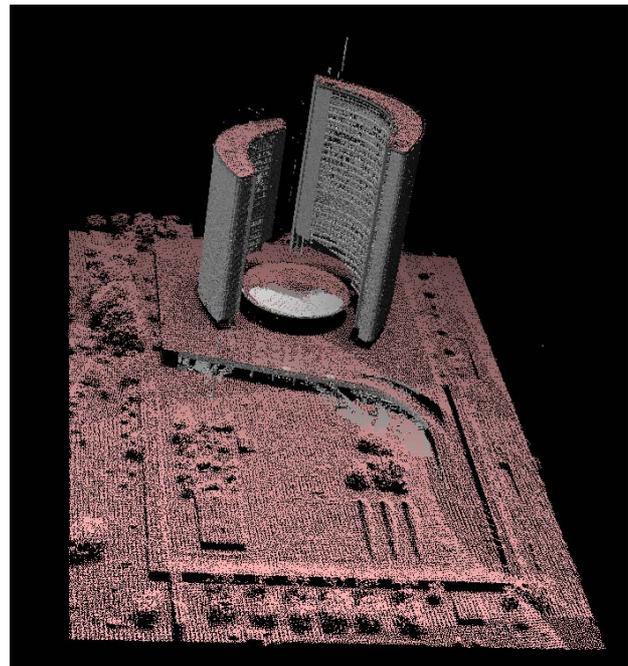


Figure 10. Fused sensor data: ILRIS-3D data is grey, ALTM data is pink.

To accommodate this, the corners of roofs were used as tie points. Using this method, even with very little redundant data, one can be confident that an accurate tie point is selected based on the geometry of the two data sets. In addition, one structure had a sloping roof that allowed data to be collected by both sensors. This was extremely helpful because it provided many redundant measurements with which to complete the automatic 'fine alignment'. The RMS of the fusion was 17 mm. Based on the available data and the goal of the project, the magnitude of the error was very acceptable.

7. SOLID MODELING

Several decisions had to be made before modeling the data. Because information was collected on three sides of each building, a 'shrink wrap' modeling algorithm had to be employed to model the fourth side. Optech chose PolyWorks™ as the modeling software, owing to our familiarity with it and confidence in it. Also, since airborne and ground data were collected at different resolutions, maintaining the full resolution of both would require processing separate models. Instead, it was decided to process the entire model as a single file, for two reasons:

1. To ensure a smooth, seamless transition between data sets. If each model were processed individually, cutlines would

be sharp and much more visible. This would necessitate additional manual editing.

2. File size limitations overrode the need for a full-resolution model. Since the area being surveyed was quite large (175 x 275 m) a full-resolution model would not be manageable with an average, commercially available computer. For this reason, the project mandate was to produce a solid model under 150 MB.

Polyworks™ allows the user to customize several options to optimize data processing. Most important, the user can input a spatial neighbourhood threshold, surface sampling step, smoothing options and data reduction tolerances.

Surface Sampling Step: This parameter defines the sampling step of the TIN model that is to be created. For example, to create a full-resolution model, the sampling step is set to the measurement spacing of the data. For this project it was impossible to generate a full-resolution model because of file size and processing time limitations (at full resolution the solid model would have had 50,000,000 triangles). The sampling step was set to 8 cm to maintain a relatively high resolution with a manageable file size.

Smoothing Options: The user can set a smoothing radius and a smoothing tolerance. The smoothing radius defines the size of the smoothing radius, while the smoothing tolerance defines the maximum distance a point can be moved from its original position. No smoothing was used when processing this model.

Data Reduction Tolerance: The data reduction option eliminates unnecessary triangles by using fewer triangles to define flat surfaces while preserving edges and curves. Depending on the tolerance, this can greatly reduce the size of the solid model. Care must be taken, however, because a very large tolerance eliminates valid features that are smaller than the tolerance. For example, if the tolerance is set to 10 cm, no feature with a depth change of less than 10 cm is visible. The project used a tolerance of 2 cm. This effectively reduced the model from 24 million triangles to 4.3 million triangles.

The final solid model (Figures 11 and 12) had 4.3 million triangles, with a resolution of 8 cm and a file size of 125 MB.



Figure 11. Solid model of data.



Figure 12. Two-meter cross-sections of the solid model.

8. CONCLUSIONS

Airborne and tripod-mounted laser scanners are complementary sensors that utilize the same core technology. One sensor excels where data collection with the other sensor is difficult. Sensor fusion enables data collection on all surfaces, and creates true 3D solid models. The benefits, however, do not end there.

Airborne scanners are ideal for broad, large-scale surveys while tripod-mounted scanners provide high-quality data on a smaller scale. The combination of these characteristics offers endless possibilities. For example, imagine doing an airborne survey of a large metropolitan city like Toronto. Important structures can be scanned with the tripod-mounted scanner and added to the database. In essence, a high-resolution, dimensionally accurate 3D model of an entire city can be created in a relatively short time. This information would be invaluable for topographic surveys, disaster simulations and similar needs.

This paper demonstrates that data collected from two LIDAR platforms can be fused in a straightforward, easy manner. Since the product produced by each is very similar, fusion involves little planning and few extra steps. It does, however, require certain considerations. First, the difference in the magnitude of error inherent with each scanner means that the alignment of the two data sources can never be perfectly seamless. Second, the survey plan must accommodate the data overlap that is necessary for data fusion. If this is not possible, then the ground data must be georeferenced. Finally, as with all LIDAR sensors, the data sets are very large. High-end computing equipment is therefore a necessity. These considerations require careful planning, adequate equipment and an understanding of the fundamentals of the technology. Building on this base, it is now clear that data fusion produces clean, accurate and eminently useful data.

ACKNOWLEDGEMENTS

The support from Optech's Terrestrial Survey and Laser Imaging data processing groups is gratefully acknowledged. The authors would specifically like to thank Colin Young-Pow and Warwick Hadley for their hard work in collecting and processing the data.

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