Integration of LiDAR and stereoscopic imagery for route corridor surveying

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ABSTRACT:

Transportation networks are, typically, one of the most economically valuable resources for any nation and they often require a large percentage of GDP to build and maintain. These route corridors attract their own unique set of spatial information requirements in terms of overall management including planning, engineering and operation. Various disciplines within a road management agency require high quality, spatial data of objects and features occurring along these networks from road infrastructure, sub-surface pavement condition through to modelling noise. This paper examines the integration of relatively novel sensor data against some pressing spatial information requirements for a small European road management agency.

LiDAR systems are widely available and now used to record data from both aerial and terrestrial survey platforms. One of the chief LiDAR outputs are X,Y,Z points enabling a reliable 2.5-D geometric surface to be produced. Stereoscopic imagery is also collected from similar airborne and terrestrial mobile platforms. Both provide different datasets in terms of their respective optical and geometric properties. For example, stereoscopic cameras mounted on a survey vehicle record different data compared to LiDAR mounted near vertically on an airborne platform. Airborne LiDAR provides a more comprehensive geometric record whereas stereoscopic imagery can be used to provide a more comprehensive visual descriptor of the immediate route corridor. Acquisition systems for both sensors are relatively well understood and developed. Both systems collect large volumes of data that require a significant amount of data processing in order to produce useful information. A more efficient result can be achieved by integrating these two datasets within a GIS. Preliminary results of the integration of airborne LiDAR with ground based stereo imaging systems are presented.

Background

The importance of transportation networks including road, rail, air and water in most economies is underlined by the statistics for historic and forecast spending at national and international level (DOT, 2007; DFT, 2007 and DGEAT, 2007). The popularity of roadways, as one of the chief transportation conduits, has resulted in continued government investment in designing, building and maintaining these ever expanding networks (DGEAT, 2007). A broad spectrum of information is required to manage various activities that occur along these transportation corridors including infrastructure and asset data. This information is required for a variety of activities including; road maintenance, pavement condition, street furniture upgrade, safety analysis, road user charging and noise modelling. The importance of this information is borne out by recent compilation of a specialised base mapping datasets for the transportation industry by Ordnance Survey, the UK national mapping organisation (ITN, 2007). Also, within the UK, the creation of national standards for populating route corridor asset registers (HAPMS, 2007) as well as the upsurge of specialist road network asset inventory software (Exor 2007, Symology 2007). Data can be collected by a variety of remote sensing methods including; spaceborne, airborne and terrestrial sensor systems. Terrestrial-based systems include stereoscopic cameras mounted on road survey vehicles and airborne systems include LiDAR. Stereoscopic camera systems, usually mounted orthogonal to direction of travel, collect image data enabling 3-D, in-frame measurements to be extracted. These, together with any visual data such as, road sign damage can be stored in a database. Airborne LiDAR systems acquires XYZ point data using a vertically pointing sensor along the route network enabling a high resolution 2.5-D mesh of the route corridor to be constructed. These two approaches result in different spatial content with associated strengths and weaknesses in terms of the spatial information recorded. It has been demonstrated that a GIS is the most efficient and cost-effective system for handling route corridor infrastructure assets (Husone et al., 1997). Therefore, a more comprehensive record can be achieved by integrating the two sources of data within a GIS. This step paves the way for examining data fusion methods using multi-platform, multi-temporal LiDAR, imagery and indeed other sensor datasets.

Mapping Systems

Survey vehicle stereoscopic mapping system

Ohio State University’s Centre for Mapping was one of the first research groups to pioneer the development of dynamic stereoscopic image mapping systems for route corridor mapping back in the mid-1990s (Blaho and Toth, 1995; Bosler and Toth, 1995; Bosler and Toth, 1996; and Jeyapalan, 2004). Developments extended beyond stereoscopic image collection and measurement to automatic feature extraction (Habib et al., 1999; Habib 2000; Tao 2000; Tao 2000 and Toth and Grejner-Brzezinska, 2004). Mobile stereoscopic image mapping technology is now reasonably well established. In the UK and Ireland there are a number of companies offering this technology as an off-the-shelf system or commercial service (DCL, 2007; Lamda, 2007; Geo3-D, 2007; Omnicom, 2007; Yotta, 2007; PMS, 2007; PTL, 2007; and Romdas, 2007). The commercial potential of this technology is underlined by Yotta’s recent purchase of DCL in the UK for £5 million (Yotta, 2007). Similar developments in this area is repeated in other countries throughout the world. The author (now based at NCG) has been involved designing one particular variant; RouteMapper UltraX (RouteMapper, 2007). The underlying objective for RouteMapper UltraX was to design a fit for purpose mobile
mapping solution which could be easily replicated and transported for mobile mapping. Installation, calibration, operation and support had also to be relatively straight-forward, reducing this to a one-man operation.

**RouteMapper UltraX stereoscopic mapping system:** Four progressive scan cameras (1392*1024), Figure 1, are connected to a dual Xeon 3.6 MHz datalogging PC via CameraLink. Synchronisation and triggering functions are provided using an industry standard module including a high speed GPS timing unit. Standard real-time, corrected DGPS is used as primary navigation module while various configurations of sensors can be used for secondary navigation depending on operating environment including optical distance measurement instrument through to full inertial measurement unit. Camera calibration is carried out each time cameras are moved, this is designed to be carried out in the field. A number of 3-D control points are set out directly in front of the cameras usually extending out to about 50m range and 7m in height. The resulting transformation handles camera model as well as exterior orientation with respect to a datum point on the survey van. This enables 3-D measurement to be carried out, using the DGPS antenna as the local datum point. All stereoscopic 3-D measurements are calculated with respect to this datum point. A secondary transformation is carried out to rotate this vector into local map grid coordinates. All measurements are usually carried out in the same plane as the survey van. Platform orientation, using an IMU is required for out of plane measurements. If there are two pairs of stereo, then two sets of calibration are performed.

The present system, Figure 3, handles four cameras, Figure 4, but has the ability to handle more using a simple client-server architecture. These are positioned and orientated ontop of the survey van depending on mapping requirements. The frame capture rate also depends largely on mapping requirements and associated vehicle speed. Typical capture rates vary between 3 frames per second and 8 frames per second. Over 1.2kW of power is provided using split chargers, deep cycle batteries and sine wave inverters. A stable power supply is one of the key ingredients to successful day to day operation of these systems.

The system, Figure 2, is powered-up at the start of survey. Self checks are carried out ensuring correct camera initialisation, adequate navigation operation and sufficient disk space. The progressive scan cameras are fitted with auto iris-lens enabling sections of route corridor to be surveyed under varying illumination.

**Figure 1. Road stereoscopic image mapping system**

The navigation, timing and image datasets are processed after survey. The prime function is to ensure that the correct navigation record is assigned to the correct image set. Secondary navigation is back interpolated where the primary source has failed. Additional sensor data such as ground probing radar (GPR) can also be integrated. The sampling rate can be set to match any sensor using standard interpolation techniques. The final step of data processing is to produce metadata for all survey datasets. This enables a large number of surveys to be rapidly accessed by the browser in a structured fashion.

**Figure 2. Front seat view of Routemapper_UltraX datalogging system on left and moving map display on right.**

**Figure 3. Rear survey vehicle view of Routemapper_UltraX datalogging system displaying main datalogging PC, primary & secondary navigation and associated power module.**

**Figure 4. Close-up of one of the cameras on top of the survey vehicle**
The browser software, Figure 5, comprises image, map and database displays together with associated toolbars and drop down menus. This allows the user to navigate through the recorded data using interactive image controls or via the mapping interface. The user can click play and view all four cameras whilst position of survey van updates dynamically in a moving map display. 3-D in-frame measurements can be carried out, recording both dimensional as well as positional information. This together with any additional attribute can be stored in the survey database. Standard GIS functionality is available including spatial and aspatial query. The browser is lightweight and designed so that users can learn basic functions in a very short time. Presently, 3-D line measurements require four separate mouse clicks. This is a task that could be more efficient with automated pattern matching.

Additional modules have been developed to enable specialist asset register construction. A wider audience can access this data over a recently developed, easy-to-use Internet browser plug-in. This can be particularly useful if an organisation comprises many departments such as road planning, maintenance and operations.

**Airborne LiDAR**

Airborne LiDAR has been available since the late-1990s (Hill et al., 2000) and has been accepted as an accurate, effective method for data collection (Iavarone, 2005). This high-resolution XYZ point data can be collected during the day or night onboard survey aircraft. LiDAR data acquisition has been well documented for a range of applications (Kidder et al. 2004 and Veneziano et al., 2002). Very fast scanning technology at rates of up to 150kHz enable reasonably large swaths of ground to be surveyed in a short time for a variety of end-user applications including floodplain mapping, utilities, transportation and municipal surveying (Hill et al., 2000). Some of the negative points include a requirement for rigorous ground control and data holes due to absorption by certain ground target material (Hill et al., 2000), false readings due to reflection from water bodies (Veneziano et al., 2002) and noisy data due to aerial water droplets such as clouds and mist (Hill et al., 2000). Data processing still demands a reasonable amount of manual input evidenced by one of the chief outputs automated production of bare-earth digital elevation model (DEM), being described as still “in its infancy” (Chen, 2007). The information content is also quite high for example, up to five levels of data processing resulting in five distinct data products have been identified (Flood, 2002). Data volume also needs to be taken into account with a typical 20km X 12km survey resulting in 25 million XYZ points (Kidder et al., 2004). Airborne LiDAR has also been used for route corridor design (Uddin 2002 and Veneziano et al., 2002) and route inventory (Shamayleh et al., 2003). In all cases, LiDAR has been found to increase mapping efficiency whether it is for planned routes or mapping out existing infrastructure.

An airborne LiDAR dataset, Figure 6, was provided for this initial study by Ordnance Survey Ireland, (OSi, 2007) using a Leica ALS50 150kHz airborne scanner (Leica, 2007) flown onboard a twin-engined aircraft at 4000’ AGL. The test section, acquired in September 2006, was over the N25, a small section of national roadway about 5km East of Cork city, Southern Ireland. Average dZ was reported to be better than 0.20m when checked against ground control. The data were processed to produce three separate products; a digital surface model (DSM), vegetation layer and buildings. Building outlines from orthophotos were used to automatically segment geometry from XYZ point cloud data.

**Integration of stereoscopic imagery and airborne LiDAR**

A number of researchers have examined the advantages of integrating LiDAR with other datasets within a GIS. Kidder et al (2004) carried out an evaluation of methodologies employed to make LiDAR compatible, consistent and useable within a GIS. These focused on data handling, error detection and geodetic transformation. One of the chief conclusions centred on understanding the errors in LiDAR data and advised further research before wholly relying on this dataset for certain applications. Kessler et al. (2006) integrated LiDAR, image data and spatial databases to produce a higher resolution building/land classification map. Rottensteiner et al. (2003) used aerial imagery to aid building outline extraction and recommended further examination of GIS datasets for assessing data quality. In all cases, GIS was perceived as useful whether as a spatial repository, aiding LiDAR processing or as an environment for checking data quality.

This research project focused on bringing together two data types that have been recently developed over the past decade and integrating these within a GIS with the specific interest in route corridor mapping. Spatial information is required by Ireland’s National Road Authority (NRA) for various uses including; Noise modelling, Asset mapping, and Safety. Some of the various features and objects are listed below in Table 1. There are, of course, a multitude of additional phenomena, features and objects occurring along the route corridor that are of interest to NRA. These are not dealt with here.
A prototype browser enabling LiDAR and stereoscopic data to be integrated together was required. A number of industry standard software applications, designed to handle point clouds, were assessed for their suitability for extracting 3-D vector data along route corridors and integrating this data directly within a GIS. These software applications included; Leica Cyclone (Leica, 2007), Point Cloud (Floating-Point, 2007), 3DReshaper (TechnoDigit, 2007) and Rhino 4.0 (Rhino, 2007). None of these applications were found suitable for this task.

The main stereoscopic browser engine was therefore modified to include stereoscopic image display, LiDAR display and conventional map display, Figure 7. The latter was populated by a simple plan view of elevation data. The LiDAR display was provided by a Microsoft .NET compatible SDK (ScienceGL, 2007) to enable preliminary integration of LiDAR with Stereoscopic imagery. DSM was exported as an ASCII point cloud and this file was read by the LiDAR SDK on start up and displayed as a textured mesh ranging in colour from blue to red, classified on height value. The test dataset covered a 5km section of route corridor.

<table>
<thead>
<tr>
<th>Feature/Object</th>
<th>Dimensions</th>
<th>Location (Road Centre Line)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Infrastructure</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Roadside Kerb</td>
<td>10cm (continuous)</td>
<td>&lt;50m</td>
</tr>
<tr>
<td>Road centreline/Central reservation</td>
<td>10cm – 10m (continuous)</td>
<td>&lt;5m</td>
</tr>
<tr>
<td>Safety barrier</td>
<td>10cm (upto 250m)</td>
<td>&lt;75m</td>
</tr>
<tr>
<td>Bridges</td>
<td>30m X 100m X 8m</td>
<td>&lt;75m</td>
</tr>
<tr>
<td>Embankments</td>
<td>30m X 500m X 50m</td>
<td>&lt;150m</td>
</tr>
<tr>
<td>Walls</td>
<td>50cm X 15m (continuous)</td>
<td>&lt;150m</td>
</tr>
<tr>
<td><strong>Street Furniture</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Street lamps</td>
<td>20cm X 15m</td>
<td>&lt;75m</td>
</tr>
<tr>
<td>Traffic signs</td>
<td>50cm X 5m</td>
<td>&lt;75m</td>
</tr>
<tr>
<td>Road surface signs</td>
<td>6m X 10m</td>
<td>&lt;75m</td>
</tr>
<tr>
<td>Traffic lights</td>
<td>50cm X 3m</td>
<td>&lt;75m</td>
</tr>
<tr>
<td>Milepost markers</td>
<td>10cm X 75cm</td>
<td>&lt;75m</td>
</tr>
<tr>
<td>Telecom points</td>
<td>50cm X 2m</td>
<td>&lt;75m</td>
</tr>
<tr>
<td>Drainage</td>
<td>50cm (continuous)</td>
<td>&lt;75m</td>
</tr>
<tr>
<td>Road stud reflectors</td>
<td>15cm X 15cm</td>
<td>&lt;75m</td>
</tr>
<tr>
<td><strong>Engineering</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sight line</td>
<td>Upto 5km</td>
<td>&lt;75m</td>
</tr>
<tr>
<td>Slope/Grade</td>
<td>+/- 45-degrees</td>
<td>&lt;75m</td>
</tr>
<tr>
<td>Camber</td>
<td>+/- 10-degrees</td>
<td>&lt;75m</td>
</tr>
</tbody>
</table>

Table 1. Features and objects occurring along a route corridor

The current position can be set in the browser so that the user was occupying the same position in all three displays; stereoscopic, LiDAR and map at any instant. The user can control navigation through the data in any of the three display environments using mouse controls or toolbar buttons along the tool bar. Pre-stored objects in the underlying database could be chosen from a table. This enables the browser to update all three display environments and display the stored data. Measurements can be carried out in the stereoscopic or LiDAR windows with the resulting point or line plotted in all three displays. Volume measurements, including embankment and cutting estimates, can be computed in LiDAR display.

LiDAR records XYZ geometry over the entire route corridor, collected from plan view. This allows the user to measure large features such as embankments as well as small features such as drainage gullies. Measurements can be carried out relatively quickly since all mouse clicks take place in the one display.

Figure 7. Browser depicting stereoscopic, mapping and LiDAR display, off ramp to the left

However, objects like road signs and traffic lights cannot be easily classified as to state of repair or indeed, in some cases, object type. Obstructions such as tree canopy, tunnels and bridges result in holes in the data or missing sections. Integrating both datasets resulted in a more comprehensive digital record of the route corridor and allows all features listed in Table 1 to be classified, measured and stored. The ability to measure 3-D features at a location as well as more synoptic road measurements using LiDAR, all within a single display, increased productivity. Having stereo imagery integrated with LiDAR meant that objects and features could be classified with additional descriptor information and with greater certainty.
This preliminary study raises a number of issues regarding suitable data structures, display geometry, temporal differences, system architecture and interface that need addressing when integrating these two datasets, as shown in Table 2. A suitable data structure is required to integrate LiDAR with a GIS. This data structure should be able to handle LiDAR collected from both airborne and terrestrial platforms, the geometric features to be extracted as well as linear nature of route data. It is likely that lengthy route corridors will result in very large data files. These should be stored in smaller files and smart preloading techniques used to manage their retrieval and display. The viewshed of LiDAR and stereoscopic displays should match in terms of position, orientation, vertical and horizontal fields of view (FOVv, FOVh) & range. Dataset resolution should be similar so, that differences between scale, dimension and detail are minimised.

<table>
<thead>
<tr>
<th>Type</th>
<th>Item</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data Structure</td>
<td>LiDAR data structure</td>
<td>Most suitable structure and format of LiDAR data. Logically store a route as a number of smaller models and use pre-loading techniques to load/flush sections as user moves through the data</td>
</tr>
<tr>
<td>Geometry</td>
<td>View shed</td>
<td>Coincident in terms of position, orientation, FOVv, FOVh, &amp; range</td>
</tr>
<tr>
<td>Resolution</td>
<td></td>
<td>Similar resolution so that scale/dimension/detail appears approximately the same</td>
</tr>
<tr>
<td>Temporal</td>
<td>Data Acquisition</td>
<td>Minimise time difference between acquiring two datasets</td>
</tr>
<tr>
<td>System Architecture</td>
<td>Software Environment</td>
<td>Suitable software environment to enable integration of LiDAR data structure with GIS</td>
</tr>
<tr>
<td>&amp; Interface</td>
<td>Displays</td>
<td>User-switchable between locked and independent. Independently re-sizable.</td>
</tr>
<tr>
<td></td>
<td>Navigation</td>
<td>Intuitive mouse and buttons</td>
</tr>
<tr>
<td></td>
<td>Orientation</td>
<td>Overview map showing user position</td>
</tr>
<tr>
<td></td>
<td>Measurement</td>
<td>Concurrent display of measurements in all displays (where possible)</td>
</tr>
<tr>
<td></td>
<td>Digitising</td>
<td>Enable basic 3-D on-screen digitising of point, lines and polygons</td>
</tr>
<tr>
<td></td>
<td>Work flow</td>
<td>Logical order enabling user to view data and carry out measurements.</td>
</tr>
</tbody>
</table>

Table 2. Issues to be considered when integrating stereoscopic imagery with LiDAR within a GIS

Time interval between data acquisition of either imagery or LiDAR should be kept to a minimum so that scene information is similar. Fundamental system architecture is central to providing an easy-to-use toolset for integrating LiDAR data with a GIS. This should be easy to use and intuitive with a logical structure in terms of work flow so that the user can easily retrieve, measure and record data along the route. Converting LiDAR XYZ data into structured 3D vector data is not a trivial task. This is more difficult for natural landscapes compared to man made structures. Route corridors are typically a mixture of man-made and natural features. A simple 3D, on-screen, digitising tool is a fundamental requirement. This would allow user to digitise bridges, embankments, walls, safety barriers and on and off-ramps. Automated and semi-automated algorithms will be required, in the future, to help reduce LiDAR point cloud data to component 3D route corridor infrastructure vector datasets.

A number of researchers have investigated various integration and more advanced data fusion techniques. Elementary integration of LiDAR and stereoscopic imagery was developed by Yamuchi (2006) for automated guidance. Fusion of LiDAR and aerial imagery especially, when acquired from different platforms, is not a trivial exercise. Elstrom et al., (1998) developed stereo-based methods for integrating colour imagery with LADAR. Habib et al. (2005) investigated registration of aerial LiDAR and imagery to a common reference frame using straight line features. Zhang et al. (2006) investigated the potential of integrating aerial imagery with LiDAR using simulation, Habib et al. (2004) examined the integration of LiDAR and photogrammetry for close range applications. Iavarone (2005) describes the results of fusing aerial and terrestrial LiDAR data sets.

Dynamic terrestrial LiDAR survey systems have been developed commercially to collect route corridor data from moving survey vehicles (Geospatial, 2007; 3DLaserMapping, 2007). The 3DLaserMapping system can collect up to 40,000 points per second with a positional accuracy of better than 1m whilst the point-to-point accuracy is better than 3cm within the point cloud. These developments indicate the growing interest in data fusion using multiple, cross platform imagery and LiDAR datasets.

Conclusions

Stereoscopic imagery collected from road survey vehicles and LiDAR have developed considerably over the past decade. Both have a significant role to play in mapping and recording route corridor infrastructure. Integration of these two datasets results in much more efficient approach to providing the diverse spatial information required by national road agencies.

A number of key issues need to be addressed in designing a GI system based on integrated stereoscopic imagery and LiDAR datasets. These revolve around data structures display geometries, temporal characteristics of data together with system architecture and interface.

Advances in data fusion methodologies using cross platform LiDAR as well as LiDAR & imagery is evident in the literature. Terrestrial LiDAR systems mounted on survey vehicles are now available commercially. These developments point to greater cross-platform sensor integration and richer data fusion outputs in the very near future. Integrating LiDAR with a GIS is a reasonable first step.
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