Integration of dynamic LiDAR and image sensor data for route corridor mapping

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ABSTRACT:

Building and maintaining modern transportation infrastructure demands considerable expenditure for any nation. These terrestrial route corridor zones include road, rail and to a lesser extent waterways. Road networks range from the large highways and motorways covering hundreds of kilometres down to smaller street networks that may only be few hundred meters in length. These route networks attract their own unique set of spatial information requirements in terms of overall management. These include transportation planning, engineering and operation. High quality, timely spatial information is required of the entire route corridor which now extends past the narrow confines of the road surface and includes the area adjacent to the road edge as well as areas above and below the road surface. Comprehensive 3D spatial information is required, not only, of the network itself but also objects occurring along these route corridors. This information can be used to address the day to day engineering problems as well as more strategic issues such as road safety, congestions management and noise modelling. LiDAR systems are widely available and now used to record data from both aerial and terrestrial survey platforms. LiDAR outputs X,Y,Z points enabling reliable 3-D measurements as well as 2.5-D geometric surface to be produced. High quality imagery is also collected from similar airborne and terrestrial mobile mapping platforms. This paper examines the integration of road survey imagery and airborne LiDAR data-streams within a GIS in order to satisfy these spatial information requirements.

Background

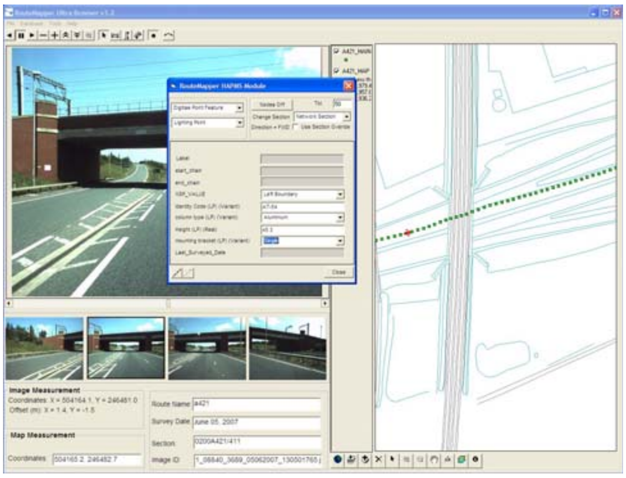
The importance of transportation networks is well documented and information across a broad spectrum is required to manage various activities that occur along these transportation corridors (McCarthy et al, 2007). This information is required for a variety of activities including; road maintenance, pavement condition, street furniture upgrade, safety analysis, road user charging and noise modelling. The importance of this information is borne out by a recent compilation of a specialised base mapping datasets by national mapping agencies, the creation of national standards for route corridor asset registers as well as the increase in specialist road network asset inventory software providers (McCarthy, 2007).

Geosptial 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 including 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 point-cloud structure of the route corridor to be constructed. These two sensors produce datasets with intrinsically different spatial properties with associated strengths and weaknesses in terms of the spatial data recorded. In this investigation, stereoscopic data collected from a road survey vehicle was integrated with airborne LiDAR data within a dynamic GIS environment. This study builds on initial work carried out at the National Centre for Geocomputation in 2007 (McCarthy, 2007).

Sensor Systems

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 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 include automatic feature extraction (Habib et al., 1999; Habib 2000; Tao 2000; Tau 2001 and Toth and Grejner-Brzezinska, 2004). Mobile stereoscopic image mapping technology is now reasonably well established. This is borne out by the wide ranging technologies and applications presented at the recent fifth international mobile mapping symposium, 28th to 30th May 2007, in Padua, Italy (MMT, 2007). There are a number of companies throughout the world offering this as a commercial service (McCarthy, 2007). RouteMapper is a typical example of one of these systems (McCarthy et al, 2007). This system is in operation in Europe and some of the datasets acquired by this system have been used to investigate the usefulness of integrating stereoscopic imagery with LiDAR data. In summary, the RouteMapper© system comprises four progressive scan cameras (1392*1024), a navigation unit, triggering modules and data logging capability. The system is calibrated any time the cameras are moved and resulting calibration transformation enables either monoscopic or stereoscopic measurements to be performed.

The mapping and analysis software, developed by the main author, comprises image, 2D map and database displays together with associated toolbars and drop down menus, Figure 1. This allows the user to navigate through the recorded data using interactive video controls or via the mapping interface. The user can click the play button 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. These measurements are usually confined to a 3D wedge shaped volume measuring 30m X 30m X 7m directly in front of the survey vehicle. 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.



Route Name: a421
Survey Date: June 05, 2007
Section: 0200A421/411

Figure 1. Road survey image mapping system depicting imagery and map displays.

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 server based component. This can be particularly useful if an organisation comprises many departments such as road planning, maintenance and operations.

Airborne LiDAR has been available since the late-1990s and has been accepted as an accurate, effective method for data collection (Iavarone, 2005). These 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 airborne LiDAR scanning technology at rates of up to 167kHz (Optech, 2008) enable reasonably large swaths of ground to be surveyed in a short time for a variety of end-user applications including flood-plain mapping, utilities, transportations and municipal surveying (Hill et al., 2000). Data processing still demands a reasonable amount of manual input but the resulting information content is also quite high. Data volume also needs to be taken into account with a typical 4km X 4km survey resulting in 64 million XYZ & intensity value points at 50cm sample spacing. 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.

The test section chosen for this study was along the A421 primary road in UK. This data was collected 6th May 2007. Corresponding airborne LiDAR was required for integration and evaluation. Environment Agency (UK) provided processed 1m resolution, LiDAR dataset for this study. The airborne point-cloud dataset was originally acquired over UK Midlands 23rd November 2006 (EA, 2008). The dataset is part of a vast archive of existing airborne LiDAR data acquired over various dates, at varying resolutions. This repository extends over a large part of England and Wales, These data are available to the researchers and public alike. For researchers, this is an invaluable source of high quality, base mapping data that can be put to a range of uses. Quite a number of countries across the globe are also building up large archives of airborne LiDAR. Extending the use of these data can help lower the up-front cost of collecting and processing LiDAR.

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. Kressler 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 utilised as a spatial repository, aiding LiDAR processing, or by providing an environment for checking data quality. This research project followed on from preliminary evaluation of imagery and LiDAR integration initiated at NCG in 2007 (McCarthy 2007), concentrating on value of integrating ground imagery and LiDAR geometric datasets. Various information regarding road side assets and infrastructure is required for efficient management. These include information relating to object location, dimension and condition state. Objects and features include bridges, walls, street-lamps, traffic-sign, road-markings, drainage, road-reflectors, pavement-condition, grade and camber (McCarthy, 2007).

A prototype browser enabling LiDAR, conventional 2D base-maps and stereoscopic data to be integrated together within a GIS was designed. This entailed modifying the software to allow a point cloud module to be integrated within existing browser, Figure 2.

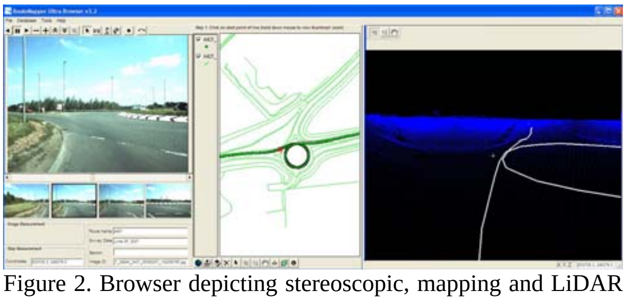


Figure 2. Browser depicting stereoscopic, mapping and LiDAR display, approach a roundabout on the A421 in UK.

A range of functions such as loading external XYZ points, setting viewing geometry, measurement extraction and graphical drawing were used to integrate the LiDAR point cloud environment with image space. The test data covered a 10km section of road that was surveyed by both road image mapping data as well as airborne LiDAR. The road survey vehicle acquired imagery using four forward facing cameras; one camera pointing to the left, the next two, in stereoscopic configuration, pointing forward with the final camera pointing to the right. All three data displays were linked with the default master position set to the image module since the camera position field of view were fixed at the time of survey. The user can control navigation through the integrated image and LiDAR datasets in any of the three display environments using mouse controls or toolbar buttons along the tool bar. This allows the user zoom, pan, query and measure. Measurements in one window were mirrored in the other two display environments. For example, measurements can be carried out in the image window with the resulting point or line plotted in all three displays. Measurement of objects in 2D map display was confined to the XY plane.

Useful measurement range within the road image survey system was confined to a 3D wedge shaped volume extending outwards, in front of the vehicle, 30m along a centre line, +/- 15m to the left and right of this centre line and 10m upwards in height. The user was alerted anytime measurements fell outside this calibration volume since results could be erroneous. Objects in any display could be identified, measured and associated attributes stored in the main browser database. Later, these same stored objects could be picked from a table and their associated location, dimensions and attributes could be instantly displayed. This action caused all three mapping environments to display retrieved object's position and/or dimensions.

Results and Discussion

Imagery was collected at rates of 4Hz whilst travelling at speeds of between 75km/hr and 100km/hr. LiDAR, on the other hand, was collected by a downward pointing scanning sensor. The LiDAR data was processed into geometric blocks covering large tracts of topography, infrastructure and buildings. Loading route data using this conventional data structure can be inefficient since the user is typically only interested in a 3D corridor represented by the route centre line and extending typically +/- 100m on either side. Some pre-processing is required to subset out this route corridor from a much larger dataset. Bringing road survey imagery and LiDAR datasets together within a GIS results in a more dynamic mapping environment. The static LiDAR display needs to update user position and mimic the smooth movement along the route corridor, updating the view-shed each time the survey position and camera images refresh.

LiDAR and image data acquire different scene properties in terms of thematic attribute, resolution and field of view so, choosing various viewing geometries to handle both displays is important. The default user interaction mode naturally follows the path taken by the road survey imaging system since this is fixed at the time of survey. The default viewing geometry needs to take into account the various data acquisition parameters including; camera models, sensing geometry, resolution of both survey cameras and LiDAR instruments In this test, user position in the point-cloud display had to be elevated and field of view (fov) extended in order to orientate the user and carry out measurements. The 1m resolution of the point-cloud made it difficult to instantly spot correspondence in terms of visual cues between LiDAR and more visually rich image data.

The obvious differences between road survey imagery and airborne LiDAR deal with each sensor's ability to record various scene content properties, Figure 3. Road survey cameras collect data orthogonally as the vehicle moves along the road. Imaging range is controlled by horizontal and vertical fov as well as vehicle position on the road network.

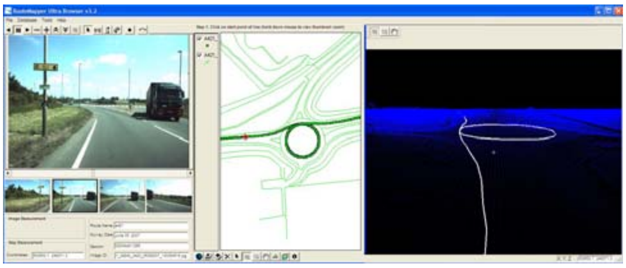


Figure 3. Browser depicting scene content differences between image and LiDAR sensors datasets

This tends to limit the view of the came to the immediate road corridor, in front of the vehicle, if pointing forward. There is very little chance of recording data behind walls, over bridges or on top of embankments. High quality imagery with resolution at the centimetre level can be acquired even at speeds of 100km/hr. This enables the 1cm cracks on the road pavement surface to be viewed and measured. Information on road signs can be read, as can their condition, Figure 4.

Figure 4. Road-sign at full resolution, taken from main image display, Figure3, illustrating detail recorded by survey vehicle.

The advantages and disadvantages of the two sensors in terms of collecting useful road network information are summarised in Table 1.

Sensor	Advantages	Disadvantages
Road Survey Imagery	Very high resolution detail	View-shed limited to number of cameras available
	Multiple view sheds	Unable to view behind walls, tops of bridges, embankments
	Record data under tree canopy, tunnels and bridges	Affected by environmental conditions such as sunlight, rain, low illumination conditions
	Comprehensive measurement and attribute information available	Poor measurement accuracy sometimes results from poor navigation eg long tunnels, heavy traffic in city centre.
	Offers a very realistic view of immediate route corridor	
Airborne LiDAR	Uniform, synoptic dataset	Relatively coarse 1m resolution
	Ability to record sight-lines, camber, grade, curvature over long lengths along road lines	A lot of standard roadside features missing such as street lamps, barriers, road markings

Table 1. Advantages and disadvantages of sensor datasets

The position, dimensions and state of road-side safety barriers, communication cabinets, street lamps, traffic signs and drainage infrastructure can usually be recorded using one of the multiple camera views. Safety barriers, communication, drainage and ventilation systems under bridges and in tunnels can be imaged and mapped. In contrast, point-cloud data acquired by airborne LiDAR, is a poor second at first glance. Compared to the visually rich spatially encoded imagery, the 1m resolution point-cloud seems quite sparse, with very little detail, devoid of obvious road-side objects like road markings, road signs, street-lamps, barriers and kerb-stone. This LiDAR dataset was collected from an aerial platform a few thousand feet above the ground. Current sensor technology onboard airborne platforms at these sorts of altitudes will be limited when compared to road survey systems. A lot of routes in the Northern Hemisphere are surrounded by trees and hedges. Downtown city areas can have very tall buildings and relatively narrow thoroughfares. These natural and man-made features often hinder comprehensive surveying from the air.

However, LiDAR enables large feature classification and measurement including those outside road survey cameras' field of view. Road lengths, widths, camber, curvature, grade can be easily measured. Blind-spots along linear route sections can be computed. Embankments, bridges, roundabouts can be measured. Offsets from road centre-line to buildings behind walls can readily be recorded. All of these mapping tasks would be impossible to carry out using the road image mapping system on its own. It is certainly more efficient to measure, classify and record details of road side features using this integrated approach. Measurement accuracy was in close agreement where objects were clearly identifiable and within range in both image and LiDAR datasets. In one example a bridge was identified and measured as 6.8m above the ground, Figure 5.

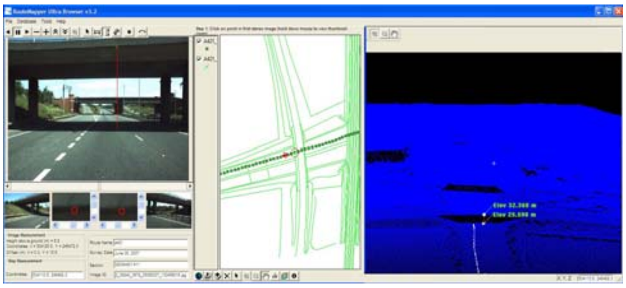


Figure 5. Browser depicting integrated measurement.

The main overall shortcoming of road survey image data relate to the relatively short effective measurement range and the lack of an overall, synoptic view. The chief shortcoming of this LiDAR dataset is the associated relatively coarse 1m resolution. However in most cases, the shortcomings of one dataset are handled by the other. A summary of advantages of integration are listed in Table 2. Having the capability to analyse both stereo imagery and LiDAR datasets within a GIS meant that objects and features could be classified with additional descriptor information and with greater certainty. Work-flow, in terms of understanding, classifying and measuring the network becomes faster. The two datasets intrinsically integrated extends the usefulness of the browser enabling other engineering disciplines make use of the same data.

Browser Feature	**Comment**
Realistic representation of route corridor	Combined image and point-cloud display result in more comprehensive representation of route
Object measurement and classification	More comprehensive record of road-side asset since user can see detail at road side as well as behind walls, embankments. Accuracy of measurements of large items can be checked
Work-flow	Much faster work flow since large objects (bridges, embankments) can be measured using LiDAR and smaller objects located and measured using road survey imagery. Less time spent checking accuracy of measurement.
Extended usefulness	Ability to classify and measure relevant features within a 100m distance of road centre line extends the usefulness of this route mapping tool eg Noise Mapping

Table 2. Listing of advantages of integrating road survey imagery and airborne LiDAR within a GIS

Integrating road survey imagery and aerial point-clouds poses some questions in how these data should be handled. Is XYZ point-cloud data the most efficient data structure to store and display this data? Should some attempt be made to use information from both image and point-cloud data to help automate or semi-automate infrastructure mapping along route corridors? How are differences in sensor acquisition geometries dealt with? These questions are more easily handled within a more advanced data fusion investigation. A number of researchers have examined data fusion of image and LiDAR datasets. These research projects dealt with data collected from similar platforms and highlight some of the problems such as modelling scene objects, handling occlusions and dealing with multi-sensor registration (Habib et al., 2005; Habib et al., 2004; Iavarone, 2005; Lee et al, 2008; Zhang et al. 2006 and Youn et al., 2008). Therefore, additional hurdles need to be overcome in order to develop future data fusion techniques for multi-sensor datasets collected from multi-platforms.

In parallel, dynamic road based terrestrial LiDAR survey systems are being developed commercially to collect route corridor data from moving survey vehicles (Geospatial, 2007; 3DLaserMapping, 2008). One recent system is based on the 200kHz pulse rate, RIEGL LMS-Q560 sensor. This system has an effective measurement rate of 100kHz with a range of between 30m 1800m and associated accuracy of 20mm. These can be combined with 39MP, calibrated digital cameras for route corridor surveying. User requirements are increasingly seeking high resolution, 3D models of transportation networks together with timely information pertaining to road-side asset condition for a variety of engineering, management and strategic planning tasks. These involve developing new algorithms to increase automation in road asset inventory to help reconstruct the network and associated infrastructure in 3D as well as the ability to detect and record change. All of these developments indicate the growing interest in data fusion and development of automated asset-focused change detection algorithms using multiple, cross platform imagery and LiDAR datasets.

Conclusions

Road networks are expensive to build and maintain but occupy a strategic position in any modern nation's infrastructure inventory. Road survey imaging systems, although a relatively recent technology, now play a significant role in mapping route networks throughout the world. Airborne LiDAR data are becoming increasingly available and provide an additional mapping layer. Bringing these two datasets together in a GIS enables a more comprehensive 3D representation of the route corridor as well as increased efficiencies in terms of mapping the underlying infrastructure. A prototype browser was designed and assessed in terms of user interaction, object measurement and classification, work flow and overall usefulness. Shortcomings, in terms of road inventory information, arising from one sensor are handled by the other sensor's dataset. The resulting integrated approach extends the usefulness of the datasets enabling additional engineering tasks to be accomplished such as road-safety assessment and noise modelling to be carried out.

Data fusion techniques are topics under investigation by a number of researchers. These are focused around multi-sensor datasets acquired from similar platforms. These techniques will need to be extended to handle multi-sensor, multi-platform datasets. Integrating these two multi-sensor, multi-platform datasets provides an environment to understand the various issues. New, rapid scanning, terrestrial LiDAR data acquisition systems integrated with 39 MP digital cameras already exist. These will continue to produce vast quantities of data. Data fusion and automated change detection algorithms will play a pivotal role in ensuring that data processing and geo-information generation keeps pace with developments in the data acquisition field. All of these factors have to match the rising expectations of users in terms of more comprehensive 3D representations and automation in not only mapping route infrastructure but also identifying and recording change in a timely, cost-effective fashion. Integrating these two datasets within a GIS, albeit a small step, is nevertheless a step closer towards attaining these goals.

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