LIDAR ACTIVITIES AND RESEARCH PRIORITIES IN THE COMMERCIAL SECTOR

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ABSTRACT

Laser altimetry, more commonly referred to in the commercial sector as LiDAR mapping, is becoming a commonplace operational tool in photogrammetry, survey and mapping firms. Its use has grown rapidly over the past five years due to the increasing availability of commercial off-the-shelf sensors, advancements in the design and capabilities of the sensors themselves and an increased awareness of the advantages of using LiDAR technology for elevation data capture by end users. As a result LiDAR mapping has been experiencing strong growth, which in turn has spurred further developments in the technology and even greater demand for the data products. Due to the relatively small size of the lidar mapping sector, capital investment in internally funded research and development appears to be limited. As a result further growth and development of the technology in the commercial sector will depend heavily on the ability to work cooperatively with the academic and research sector to define common research priorities and objectives, especially as relates to specific applications. Education of end users to increase awareness and acceptance of the technology along with establishing approved methodologies and quality control guidelines are also areas of overlap between the commercial and government sectors. Potential research priorities given commercial sector needs will be discussed and ranked with an emphasis on software tools. Undeveloped aspects of research-oriented laser altimetry, especially as relates to waveform capture and analysis will be discussed in the context of potential commercial markets.

1 INTRODUCTION

Laser altimetry, more commonly referred to in the commercial sector as lidar mapping[1], is becoming a commonplace operational tool in the fields of remote sensing, photogrammetry, surveying and mapping. Laser altimetry is capable of rapidly generating dense, accurate, digital models of the topography and vertical structure of a target surface. It is an attractive tool for data end users in various application areas since the cost to produce the elevation data, point for point, can be significantly less than other forms of traditional data collection. For any application with a need for high density, high accuracy elevation models, laser altimetry offers unique technical capabilities, lower field-operation costs and reduced post-processing time and effort compared to traditional survey methods.

The use of lasers as remote sensing instruments has an established history going back more than 30 years. Townes and Schawlow first put the theory of the optical maser or laser forward in 1958. Maiman demonstrated the first successful laser – a ruby laser – in 1960. Through the 1960s and 70s various experiments demonstrated the power of using lasers in remote sensing including lunar laser ranging, satellite laser ranging, atmospheric monitoring and oceanographic studies. During the 1980s laser altimetry – essentially the measurement of height using a laser rangefinder - developed as airborne instruments such as NASA's Atmospheric Oceanographic Lidar (AOL)[1] and Airborne Topographic Mapper (ATM)[2] were deployed. Laser altimetry has been successfully demonstrated from a variety of airborne platforms and from near Earth orbit during the Shuttle Laser Altimeter (SLA) missions[3]. NASA currently has two satellite missions planned that will deploy laser altimetry; the Vegetation Canopy Lidar mission (VCL)[4] and the Geosciences Laser Altimeter (GLAS)[5]. Laser altimetry has also been used to provide us with spectacular images and detailed maps of Mars via the Mars Observer Laser Altimeter (MOLA)[6].

Today two distinct techniques in laser altimetry are being actively investigated by the research community; small footprint, time-of-flight laser altimetry and large footprint, waveform-digitizing techniques that analyze the full return waveform to capture a complete elevation profile within the target footprint. In addition to these research activities, a strong commercial sector is developing to address the demand for widespread access to lidar mapping capabilities and services in the private sector.

[1] The terms *laser altimetry* and *lidar* will be used interchangeable in this article with the additional understanding that in general we are referring to small footprint, time-of-flight topographic lidars not waveform-capture or bathymetric lidars. The term *small* is subjective but is generally taken to mean a footprint on the ground no larger than 1 m.

As of July 1st 2001 there were ~ 75 organizations worldwide operating ~60 sensors for commercial applications not including sensors being deployed by research groups. Growth rates in the commercial sector in terms of installed instrument base have been averaging ~25% per year since 1998 with projections for an installed instrument base of 150 – 200 sensors by 2005[7]. There are also a growing number of value-added resellers and product developers that include lidar mapping and lidar data analysis as an integral part of their activities. The majority of lidar mapping done in the commercial sector is based on time-of-flight systems that minimize footprint size and maximize repetition rate. Awareness of waveform capture techniques is far less common and it is not being actively deployed except in the much smaller laser bathymetry sector. Consequently research priorities in the commercial sector tend to focus on the analysis and manipulation of the massive data point clouds rather than waveform analysis or interpretation. However the background and skill sets of commercial practitioners of laser altimetry are predominantly from the survey and mapping fields, led by aerial photography and photogrammetry firms. As a result the depth of specific knowledge about laser altimetry in the commercial sector is less than in the research sector. Combined with other business drivers this is limiting investment in internal R&D, creating a greater need for co-operation between private sector firms and research institutes.

2 COMMERCIAL SECTOR ACTIVITIES

Prior to 1995 laser altimetry was generally conducted using custom-designed sensors operated by research groups or built by commercial survey firms to exploit niche markets. Such custom-developed sensors required organizations to dedicate significant resources to the effort and develop expertise in various normally unrelated disciplines. The majority of these efforts were based on single prototype designs, limiting their ability to create and service a broad, sustainable, sector-wide demand for the technology. However, since 1995 a commercial off-the-shelf (COTS) instrument market has developed which has removed many of these constraints for organizations wanting to incorporate laser altimetry in their operations. The availability of COTS sensors has increased access and driven a much more rapid adoption of the technology.

Today the commercial deployment of laser altimetry continues to expand rapidly due to the increasing availability of commercial off-the-shelf sensors, advancements in the design and capabilities of the sensors themselves and an increased awareness by end users and contracting agencies of the advantages of using lidar technology for elevation data capture. Commercial laser altimetry is in the process of establishing itself as a robust, cost-effective operational tool, although application-specific methodologies are still being developed in many areas.

Unlike research organizations, which are primarily driven by scientific goals and objectives, the commercial sector is driven by the need to define and address profitable markets for the various data products. Due to the relatively recent introduction of the technology many of these end products are still being defined and there is on-going research and analysis by both private and public groups in to the best methodologies for addressing each application.

In practice commercial work is currently dominated by small footprint, time-of-flight techniques. In time-of-flight lidar instruments the distance or range from the sensor to any reflective surface beneath the platform is determined by measuring the elapsed time between the generation and return of each laser pulse. By scanning the laser across the path of the platform, a wide swath of laser range data is captured along the flight path. These laser ranges are combined with platform position and orientation information during post-processing to create a geo-referenced point cloud that is essentially a digital 3D model of the surface beneath the platform. In the commercial sector small footprint, time-of-flight lidar mapping has established itself as a robust, cost-effective operational tool, but the technology is still developing and the commercial sector is still developing appropriate business models for effectively delivering this type of data to the end-users. While full waveform capture is being used in commercial laser bathymetry, its use in topographic applications is still limited to scientific and research programs.

Depending on the particular application, laser altimetry can be viewed as either a complementary or a competitive technology when compared to existing survey methods. For many applications, airborne laser altimetry is currently deployed in conjunction with other more traditional sensors including standard aerial film cameras, digital cameras, hyperspectral scanners or thermal imagery. Integration of multiple sensors in to a single platform – sensor fusion – is a relatively high priority in the commercial sector. In general, laser altimetry is best viewed as an addition to the remote sensing toolbox that can add significant value to the data products produced, either independently or in conjunction with other sensor systems. Deploying airborne laser altimetry within a field survey can provide additional value depending on project specific goals and deliverables. Since each individual end user has particular needs and specifications that they expect to be met, laser altimetry may not meet these expectations without support from traditional survey methods. However, in certain applications, such as forestry or coastal engineering, laser altimetry offers unique capabilities not achievable with any other technology. Several reviews of the main commercial application areas have been published.[8,9,10] Approximately 60% of the commercial activity conducted today is focused on generating bare earth DTMs for orthorectification of imagery and the generation of contour maps in the 5′ to 2′ c.i. range. Significant additional work is being done using lidar-derived DTMs in hydrological modeling and flood risk assessment and urban modeling for a variety of applications such as telecommunications. Two major projects that serve as examples of how commercial lidar mapping capabilities are being applied to large government-funded mapping efforts are the Puget Sound Lidar Consortium; Kitsap County Survey[11] and the North Carolina - Floodplain Mapping Program[12] - both of which can act as guidelines and benchmarks for organizing large area lidar surveys.

3 PROCESS FLOW AND CHALLENGES

In the commercial sector a high priority must be placed on meeting client and end user expectations for data quality, accuracy and delivery schedules. As a result, many of the challenges and research priorities identified by commercial firms focus on optimizing the workflow from mission planning through field data collection to post-processing and final QA/QC. There can be significant differences between the planning and execution of a commercial mapping project and a research field campaign, most notably in scope, size, volume of data acquired and the need to operate to the professional standards and practices as established by the survey and mapping community. Automation, increased reliability, rigorous quantification and appropriate reporting procedures are all key areas of importance to commercial entities. A secondary priority is the manipulation of the data in to an application-specific mapping product for the end user. To understand the research priorities from the commercial perspective, it is useful to review a typical workflow on a commercial project:

1. Flight planning.
2. Sensor calibration.
3. Field data collection.
4. Preliminary QA/QC in field.
5. Repeat 3 and 4 as required; often for 20+ days on larger projects while workflow continues.
6. Post-processing:
    a. GPS quality check.
    b. Trajectory generation.
    c. Geo-referencing.
    d. Full point cloud generation.
    e. Project segmentation in to manageable area/file sizes and terrain/feature classifications.
    f. Automated Classification.
    g. Initial QA/QC.
    h. Manual Classification.
    i. Final QA/QC.
    j. Deliverables (girding).
7. Reflight, rework.

Private sector firms are generally not open about their internal process efficiency, but evidence strongly suggests that anywhere from 60% - 80% of the labor on a given project is allocated to steps 6(h) and 6(i); manual classification and final QA/QC. This is especially true on very large area mapping projects. As a result, most research by commercial data providers, funded either internally or by partnering with research groups, is focused on reducing the amount of time to complete the QA/QC process by minimizing the amount of manual classification that is required. More efficient algorithms for extracting the bare earth surface – automated feature extraction - combined with better tools for effective manual review of the data after automated filtering are a high priority.

In addition sensor development by the instrument vendors is an area of on-going activity with the primary focus on higher repetition rate time-of-flight instruments, higher operating altitudes and effective integration of digital cameras and other sensors with the laser sensor. Repetition rate promises to be a continuing benchmark. 50 kHz sensors are already being field-tested and it is likely that 100 kHz sensors will be online by 2005 at the latest. Reliability of the instruments in the field is also becoming a priority as a larger installed base of instruments and competition between data providers serves to shift the focus from the novelty of the technology to providing a quality data product on budget and on schedule.

4 RESEARCH PRIORITIES

From a commercial perspective the research priorities can be broken in to five key areas:

1. Automated or semi-automated sensor calibration in the field to an accepted and approved methodology.
2. Efficient automated feature extraction for various end user applications.
3. Development and integration of new techniques in sensor design and capabilities.
4. Software tools.
5. Training.

Calibration

Unlike aerial photography which has a well-defined set of procedures and metrics for quantifying the accuracy and calibration of a given camera, commercial lidar sensors are not yet required to be calibrated by a third-party. As a result each operator has established their own in-house calibration process and procedures, usually against different standards and test ranges. While there are similarities between many of these ad-hoc procedures, a more formal methodology needs to be developed and made standard across the commercial sector. Issues need to be resolved such as what organizations should be responsible for managing this independent calibration process, what test ranges need to be established and where, and how the results should be presented and reported to assure end users of proper sensor calibration. However the research sector can play a key role by investigating and analyzing independent verification methods and design-independent sensor calibration techniques that can be easily transferred to the private sector. Professional organizations such as ISPRS and ASPRS clearly have a role to play here as well.

Automated Feature Extraction

Automated feature extraction is an area of key interest to the commercial sector. Various firms have internal programs to develop proprietary algorithms to accomplish these tasks, or work in conjunction with research institutes on development programs, however such efforts restrict the access to the techniques developed and are rarely peer-reviewed. The underlying theoretical basis for these proprietary algorithms is often not known by the end user. A more open source approach to defining, manipulating and classifying lidar data would help spread the use of the technology. However it is unlikely that private sector firms will spearhead such an effort. Research or academic institution that are developing such techniques can play a role in ensuring such valuable tools are widely reviewed and critiqued and then made available to the end user community. A major area of interest is how to effectively integrate the object information contained in intensity data in to automated classification routines. While intensity information, the strength of the return signal, has been available for several years and research groups are looking at its applications, it use in the commercial workflow has not been addressed. In addition to

actual algorithm development, the establishment of benchmark tests to quantify the accuracy and efficiency of existing and future algorithms against common data sets would be extremely useful.
With the arrival over the next few years of even higher density data sets, development of software tools and algorithms capable of handling the data are a necessity. In addition investigation in to information extraction from dense data could be useful.

Software Tools
The emergence of robust, reliable software tools that are available to the entire community will be one of the most significant areas of change in the commercial sector in the next five years. Currently, the vast majority of the processing, manipulation and classification of lidar data is conducted using proprietary software developed independently by researchers, the data providers or provided by the sensor manufacturer to its clients but not available as a separate package (e.g. Optech's REALM software). The current situation presents a significant barrier to end users as lidar processing is presented as "black box" with limited insight in to the actual manipulation of the data and a very limited ability of the end user to recreate, reclassify, manipulate or modify the data sets they are provided. The fact that few of these proprietary classification algorithms have been published or opened up to peer review is also a concern among academics and researchers. However, by its very nature as open-format data representing a well-defined geospatial point cloud, lidar data is relatively easy to manipulate by third-party software. To date there are only a few software products on the market that can efficiently handle the large point densities generated by state-of-the-art lidar sensors – easily in excess of 100s of millions of points for even moderately sized projects - but this situation is changing rapidly. Third-party products specifically designed for manipulating lidar data are starting to appear and existing mainstream software developers such as ESRI are moving to integrate lidar data manipulation in their existing product suites. The availability of appropriate software tools for the entire end user community will eventually replace the proprietary, black box solutions common today. This will open up the post-processing workflow and fundamentally change the existing value chain, presenting a serious challenge to the "status quo" of the first generation of commercial data providers. By 2005 the availability of a suite of commercial off-the-shelf software tools will shift the primary product requested of lidar data providers from bare earth DTMs to the more basic geo-referenced, all-points laser point cloud.

New Techniques in Sensor Design: Waveform Capture
While there are several areas of development being investigated in sensor design, waveform capture promises to be the most interesting. An alternative technique to the basic time-of-flight method that dominates the commercial sector, waveform capture involves recording the entire return waveform from the laser pulse rather than just the time-of-flight. By capturing the full return waveform, detailed information on the entire vertical structure within the laser footprint is obtained and ground topography can be detected even with canopy openings of only a few percent. This type of waveform characterization of the complete canopy profile can have significant value in scientific research and may have commercial importance in the forestry industry. Perhaps more important for the commercial sector, waveform capture from large footprint sensors has been demonstrated as an effective method of determining the ground surface underneath even the densest canopy. Experimental flights of NASA's Laser Vegetation Imaging Sensor (LVIS)[13] were able to successfully and accurately record the topography beneath dense rainforest in Costa Rica[14]. Small footprint time-of-flight sensors become suspect in dense, complex canopy as not only must they successfully penetrate through the gaps in the canopy to the ground surface, but post-processing of the point cloud must employ filtering algorithms to correctly classify those returns that are from the ground from those that are from canopy or other features. Even the most advanced algorithms have difficulty accurately extracting the ground surface with 100% fidelity, especially in areas of low, dense ground cover, significant relief or where sudden changes in topography such as gullies or sharp grade breaks mimic man-made features. The complex interaction of the laser pulse with the distributed vertical target is also a concern when trying to determine the point of reference for a time-of-flight sensor. As a result, waveform-capture sensors offer a powerful alternative approach to map the bare earth beneath dense canopy.
Based on the state-of-the-art in commercial sensor design today, it is likely that by 2005 waveform-capture sensors will be in operation in the commercial sector. Such sensors will likely address niche commercial markets such as scientific research in forestry, topographic mapping beneath very dense canopy and calibration/validation of global lidar data sets available from satellites such as VCL. They may also find a market in large area topographic mapping, such as statewide mapping efforts, when grid-spacing requirements do not require the high-density capabilities of a high repetition rate time-of-flight sensor.

Training
While not a specific area of research, the training of highly qualified persons and the introduction of laser altimetry in to remote sensing and mapping curriculums at both the graduate and undergraduate level is a priority for the private sector. Due to the fact laser altimetry is relatively new technology there is a gap between the commercial sectors staffing needs and the available talent pool of experienced, trained personnel. This gap covers both highly qualified persons with experience in laser altimetry at the graduate level and qualified data analysis staff at an undergraduate level, as well as knowledgeable field personnel. The resulting shortfall is causing some staffing shortages as well as promoting a relatively high turnover of staff as people move from firm-to-firm within the sector. As with any high-tech sector, such a cycling of people from firm-to-firm can have short term benefits as it helps to spread best practices and improve the overall depth of knowledge in the sector but if the underlying shortages are not address, further adoption of the technology can suffer.
However this shortage is being addressed as more universities and colleges incorporate laser altimetry and lidar mapping as part of their remote sensing and GIS curriculums. Over the past few years lidar technology has been introduced at the post-graduate and graduate levels, the undergraduate level and even in some cases the high school level. This development is extremely encouraging however the introduction of the material is being addressed at different paces in different areas, a key factor

apparently being the co-location of a principal investigator actively pursuing research in laser altimetry. It can be assumed that given the anticipated growth in laser altimetry as a common operational tool, the need for trained personnel will increase and students with at least some exposure to lidar technology will be better equipped to secure these opportunities. A national or regional scholarship program to support and promote research and education in laser altimetry would be beneficial to both the private and public sectors.

5 CONCLUSIONS

Laser altimetry is becoming a commonplace operational tool in remote sensing, photogrammetry, survey and mapping. As the underlying technology is still dynamic and capital investment in private sector R&D is limited, a strong, co-operative relationship between the commercial sector and research organizations will be important to furthering the adoption of the technology. Recognition of research priorities from the private sector point-of-view balanced against the scientific objectives and research goals of government and academic institutions will lead to a mutually beneficial development of the technology and a widerspread adoption of laser altimetry as an every day tool.

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