COMPLEMENTARITY OF LIDAR AND STEREO IMAGERY FOR ENHANCED SURFACE EXTRACTION

Charles K. TOTH[*], **Dorota A. GREJNER-BRZEZINSKA**[**]
The Ohio State University, USA
[*]Center for Mapping
toth@cfm.ohio-state.edu
[**]Department of Civil and Environmental Engineering and Geodetic Science
dorota@cfm.ohio-state.edu

Working Group III/2

KEY WORDS: Sensor Integration, LIDAR, Digital Imaging Sensors, GPS/INS, DEM, Airborne Mapping.

ABSTRACT

Modern, integrated GPS/INS-based direct orientation systems, combined with multi-sensor imaging hardware such as digital cameras and laser ranging devices, allow the simultaneous collection of independent observations, offering a diversity of spatial/spectral information. This forms the basis for an optimal geo-spatial data fusion since different properties of objects are recorded, based on different physical principles of the sensors, bringing together complementary and often redundant information.

Light Detection and Ranging (LIDAR) sensors have shown remarkable developments over recent years, reaching at the same time cost-effectiveness and reliability, and currently represent a new and independent technology for a highly automated generation of digital elevation (DEM) and surface models (DSM). However, there are a few inherent shortcomings of the LIDAR technology such as the lack of correspondence to objects, no redundancy in the measurements, strong dependency on material features, missing visual coverage, etc. Recently, rapid digital camera developments have reached the performance level whereby such systems can be integrated into airborne LIDAR systems. The introduction of direct digital imagery into the LIDAR system has two primary benefits: 1) it can improve the surface extraction process, and 2) it provides the necessary visual coverage of the area. Both processes can be sufficiently automated, promising an almost near real-time mapping performance. This paper deals with some aspects of the sensor fusion problem of LIDAR with digital imagery for airborne surveying applications.

1 INTRODUCTION

1.1 Airborne Laser Systems

Airborne laser ranging (ALR) is not a new technology. What is new is that these systems have become affordable recently and ALR is about to enter mainstream mapping production. The earliest experimental applications of LIDAR date back to the 1970s and 1980s, but the technology was introduced to the mapping community only about a decade ago. Recently, the technology's maturity and also rapid developments of the GPS/INS direct orientation systems supporting ALR have increased the economical potential of laser-based systems. Three main periods can be identified with respect to applications. At the beginning, ALR was almost exclusively used for scientific explorations, mostly under NASA supervision. With improving technology and falling prices, LIDAR entered the commercial market roughly a decade ago. New companies were founded to offer data services for special applications such as transmission line surveying. Operating from helicopter or fixed-wing aircraft, these LIDAR systems typically had limited capabilities – the low flying height allowed only for corridor mapping, albeit the spot density was rather good. Finally, the third era of the LIDAR applications arrived by the late nineties. Further advancing technology as well as the affordability of LIDAR allowed traditional airborne surveying companies to acquire LIDAR systems and to integrate them into production under normal conditions. Most importantly, the flying altitude has been substantially extended; *DeLoach and Leonard* (2000) have reported about a LIDAR project with a 20,000-ft flying height.

Interest toward LIDAR systems in both academia and industry had increased dramatically by the mid- and late nineties. Most recently, the *ISPRS Journal of Photogrammetry and Remote Sensing* devoted a special issue to this topic (see **54**(2-3), 1999). An excellent primer for the basic principles of LIDAR systems is provided by *Baltsavias* (1999), while *Ackermann* (1999) offers a good review of the current status and future trends. Comparison between photogrammetry and LIDAR techniques is addressed by *Schenk* (1999) and by *Baltsavias* (1999). *Wehr and Lohr* (1999) discuss system structures and specifications. For typical applications, *Maas and Vosselman* (1999) and *Haala and Brenner* (1999) can be a good starting point for building extraction, while forestry mapping is discussed by *Kraus* (1998). A comprehensive review of the commercial developments is available from *Flood* (1999).

1.2 Technology Developments

In recent years, LIDAR systems have established themselves as the strongest contenders for highly automated generation of digital elevation and surface models. Operational scanning systems easily provide a large number of elevation spots with excellent vertical accuracy (depending primarily on the quality of GPS/INS), and thus successfully compete with, to date, mostly stereo image-based surface extraction techniques. An additional feature that makes laser systems even more attractive is the fact that they can deliver multiple echoes from one laser pulse, for example first and last, which allows the separation of terrain or man-made objects from vegetation, as the laser beam can penetrate the vegetation foliage. Obviously, this technological transition is made possible by the high quality of contemporary GPS/INS systems, offering positioning accuracy in the range of 5-20 cm, which is compatible with the range quality offered by LIDAR systems. Modern GPS/INS systems meet this requirement rather easily, facilitating direct support to the demanding mapping applications (*Lithopoulos 1999*, *Abdullah* 1997, *Grejner-Brzezinska* 1998, *Skaloud and Schwartz* 1998, C*ramer* 1999).

High-resolution digital sensors, based on Charge-Coupled Devices (CCD), are rapidly approaching the resolution and performance level required in aerial mapping. Digital frame cameras in the 4K by 4K range already have been used in production and experimental systems are tested with 10K by 5K and 9K by 9K sensors (*Thom and Souchon* 1999, *Toth* 1999, *Bruce* 1998). Despite these impressive developments, the ground coverage offered by these sensors is still modest compared to the large-format analog cameras used in airborne mapping. To provide simultaneous visual information for LIDAR data, however, digital cameras already can provide sufficient ground resolution and coverage. Thus, combining LIDAR with high-resolution digital imaging sensors provides an excellent and novel solution to acquire surface data and to simultaneously produce the visual ortho-coverage of the area. Of equal importance, the digital images can provide much-needed redundancy to the LIDAR data and consequently can offer the potential to improve the LIDAR surface data. Expected rapid semiconductor developments make the use of direct digital imagery even more attractive. In fact, a sure sign of the changes is that both major analog manufacturers are already heavily involved in digital aerial camera developments (prototype systems are expected to be introduced during the ISPRS 2000 Amsterdam Congress).

The Center for Mapping at The Ohio State University has been a pioneer in developing modern mapping technologies. The most recent mobile mapping system developed by the Center is the Airborne Integrated Mapping System (AIMS™) – a tightly coupled GSP/INS integrated positioning system supporting primarily digital sensor-based image data collection (*Grejner-Brzezinska et. al.* 1998, and *Toth et. al.* 1998). The prototype system currently employs a 4K by 4K imaging sensor (*Toth* 1998), and recently, test flights in cooperation with EarthData Technologies were combined with a LIDAR sensor, providing all the illustrations used in this paper.

1.3 Surface Extraction

Digital elevation data play an important role in many mapping applications, such as spatial feature extraction and interpretation tasks. The demand for DEM has grown tremendously over the last decade. Orthophoto production, engineering design, modeling, visualization, etc., all need surface data at various scales and accuracy ranges. More importantly, the research community agrees that feature extraction in 3D spatial domain cannot be effectively completed without surface reconstruction, and vice-versa. Most currently used DEM extraction techniques are based on a combination of image domain feature- and area-based matching schemes, which are usually organized in a hierarchical structure. The performance of these systems is very good for smooth, rolling terrain at small to medium scale, but it decreases rapidly for complex scenes, such as dense urban areas at large scale. The primary reasons for the reduced performance are the lack of modeling of man-made objects, occlusions, and motion artifacts. In fact, these problems render the gray-scale stereo image-based surface reconstruction process into an ill-posed task. With the introduction of a variety of new spatial data acquisition sensors, the predominantly stereo image-based surface extraction techniques can be extended to incorporate additional sensory data such as range observations, multi/hyper-spectral surface signatures, etc. Obviously, an optimal fusion of sensors that are based on different physical principles and record different properties of objects brings together complementary and often redundant information. This leads ultimately to a more consistent scene description and results in a substantially improved surface estimation.

The Center for Mapping, together with the Department of Civil and Environmental Engineering and Geodetic Science at The Ohio State University, has been involved in digital photogrammetry research since the late eighties. After solving the problems of automatically establishing the relative orientation of a stereo image pair (*Schenk et. al.* 1991), substantial resources were committed toward surface reconstruction research in the early nineties. These efforts resulted in the successful development of two hierarchical surface reconstruction methods. The first procedure was built around a local least-squares strategy (*Yan and Novak* 1991), while the second technique was based on a global approach, integrating feature and area matching into one process (*Schenk et. al.* 1990, *Schenk and Toth* 1991, *Norwell* 1992). The second technique, called hierarchical warped image-based surface reconstruction, is based on sequential surface refinements achieved by using iteratively rectified images.

With the introduction of new spatial data acquisition sensors, especially the growing use of LIDAR systems, additional observations offering different spatial/spectral information can help to overcome the limitations of stereo image-based surface extraction techniques and the availability of stereo data can refine LIDAR spot positions. This two-way processing can result in more robust solutions and in improved accuracy. To pursue this idea, plans are underway at OSU to extend the hierarchical warped image-based surface reconstruction technique with laser observations. On a conceptual level, the dissimilarities between the LIDAR and stereo image reconstructed surfaces slightly resemble the contrast between feature- and area-based matching techniques. LIDAR, similarly to feature-based matching, delivers very robust data, but the horizontal localization and spatial density of the points is somewhat modest (as is the case with the conjugate primitives). On the other hand, area-based matchers can deliver excellent localization, provided that good starting approximations are available. This leads naturally to a hybrid surface reconstruction technique whereby feature-based global matching, usually the first phase of stereo image techniques, will be replaced with the LIDAR observations. In a very coarse interpretation, the whole stereo-image based surface reconstruction process is reduced to a local matching task whose main objectives are to refine and densify the elevation spots' coordinates.

2 DATA REPRESENTATION

2.1 LIDAR Data Processing

The processing of LIDAR data, the related algorithms and their use has been discussed actively in the mapping community. Of special interest are the removal of spurious spots, the separation of multiple return signals, the comparison of randomly spaced surfaces, the extraction of man-made objects, etc. An interesting and very essential problem is the error budget of the cleaned LIDAR data, especially that there is no redundancy in the system, not to mention the extrapolation character of the direct platform orientation. Although there are a large number of publications addressing either the entire error budget or one of its components, not much attention has been paid to approaching the problem from a data representation point of view. Despite the underlying objective of determining surface data, and thus addressing the overall surface data quality, the emphasis is typically on the accuracy of the individual LIDAR points. Our intention in this paper is to review the fusion of LIDAR data with direct digital imagery in a data representation framework.

2.2 Sampling of Surfaces

The surface description derived from LIDAR data is primarily given in a set of points, which is in fact a random or irregularly sampled representation of the actual surface. However, the real surface elevation data with respect to a mapping plane can be described as a two-dimensional continuous function:

$$S_c = f(x, y) \tag{1}$$

For practical reasons, the discrete representation is considered, which is obtained by an evenly spaced two-dimensional sampling of the continuos function:

$$S_d = H_{ij} \tag{2}$$

The question is how well the second format describes the first representation. Since the earth surface cannot be observed without limitations, such as the amount of details that should be discerned, the practical question is how to optimize the discrete representation for any given accuracy requirements in terms of surface deviations. In other words, what is the minimum sampling distance to keep the differences between the two representations under a predefined threshold? For example, for a topological map road surface roughness is irrelevant and shouldn't be considered. However, for road maintenance purposes, this information is more important than the global nature of the surface such as the road location in some mapping frame.

From a strictly theoretical point of view, the problem of how well a discrete representation describes the continuous case is well understood from Shannon's information theory. Probably the most relevant and well-known expression is related to sampling frequency. Rephrasing it for our case in one-dimension, it is stated simply that if a surface has a given maximum detail level (the surface changes are less than a predefined value), then there is an optimal sampling distance, and thus, any discrete representation which has this optimal sampling distance (or shorter) can reconstruct (1) from (2) without any degradation.

$$d_{\min} \le \frac{1}{2f_{\max}} \tag{3}$$

In other words, if ***f***f_{max} is the highest spectral frequency for a given surface, then d_{min} sampling distance is sufficient for the complete representation of this surface. In fact, the continuous surface can be restored without any error from the discrete representation in this ideal case. Obviously, for two-dimensional representations the directional spatial frequencies can be considered.

$$d^{x}{}_{\min} \le \frac{1}{2f^{x}{}_{\max}} \qquad \text{and} \qquad d^{y}{}_{\min} \le \frac{1}{2f^{y}{}_{\max}} \tag{4}$$

One major problem with real surfaces is that vertical surfaces, in theory, would require an infinitely short sampling distance (the spatial frequency is unbounded). Another important aspect of the sampling process is the quantitaziation of the elevation data (basically the smallest elevation difference that can be distinguished). This is normally an overlooked aspect since on modern digital systems the number representation provides such a wide range that the error introduced by converting the continuous signal into a discrete one is really negligible.

3 MAIN CHARACTERISTICS OF STATE-OF-THE-ART SYSTEMS

3.1 LIDAR System

EarthData Technologies' AeroScan LIDAR, Fig. 1 is a custom-made high-performance system and represents the most recent technology available in airborne laser scanning. The data acquisition parameters can be adjusted in a wide range, providing considerable flexibility to accommodate the needs of various applications. Most remarkably, the flying height can be as high as 20,000 ft. The maximum scan FOV is 75 degrees. The maximum scan rate is about 7.5 Hz at 75 degree FOV or can go up to 20 Hz for smaller FOV's. The maximum pulse rate is 15 kHz. The laser sensor operates at the wavelength of 1064 nm, with pulse length of 11.7 ns and beam divergence of 0.33 mrad. The sensor system can record up to five returns. Operating with 40 degrees FOV at 65 m/s airspeed and at 2500 m AGL flying altitude, the along track spacing is about 3 m, while the cross track spacing is roughly 4 m. The illuminated footprint is 0.8 m and the typical accuracies on the ground are 0.25 m in cross track, 0.25 m in along track (somewhat smaller than the cross track value) and 0.15 m in height error.

Figure 1. EarthData Technologies AeroScan LIDAR system.

3.2 Digital Camera Systems

The first intensively tested airborne 4K by 4K digital camera system was based on a Hasselblad camera equipped with the BigShot™ digital camera-back. This system was developed as the image acquisition component of the prototype AIMS™ system developed by the Center for Mapping, OSU in the late nineties. A series of extensive tests have confirmed that first, the digital camera system can deliver mapping performance and second, direct orientation can provide high-accuracy position and attitude data (extremely important for this digital camera since the small footprint of the camera necessitates the elimination of aerial triangulation). Fig. 2a shows the AIMS™ experimental camera system. The CCD chip used in the AIMS™ system has a square pixel format with 15 micron spacing, resulting in an active sensor area of 60 by 60 mm. Equipped with a 50 mm lens, the camera system has a FOV of 62 degrees and the angular resolution is about 0.3 mrad.

Figure 2. a) AIMS™ prototype camera – b) EarthData Technologies Kodak MagaPlus 16.8i camera.

EarthData Technologies has recently augmented the AeroScan LIDAR system with a digital camera component, which is based on a Kodak MagaPlus 16.8i 4K by 4K camera, Fig. 2b. In contrast to the AIMS™ imaging component, the EarthData solution represents a technologically more advanced system in terms of using a faster CCD chip and by adhering to a rigid camera body design. The Kodak CCD chip features a 9 micron pixel spacing and consequently a 36 by 36 mm sensing area. With the 50 mm lens, the system has a FOV of 40 degrees and the angular resolution is about 0.2 mrad. Another important improvement of the EarthData system is a faster image acquisition rate; the maximum data cycling was about 5 sec for the AIMS™ system, while the Kodak sensor can go down to 2 sec.

4 FUSION OF LIDAR AND IMAGE DATA

4.1 Data Characteristics

The raw LIDAR data represent ranges with respect to the data acquisition platform (aircraft). After the reconstruction of the aircraft motion and applying some mapping frame, the elevation spots are available as a function of the horizontal location, forming 3D point clusters or lines with the point density depending on flying height and speed, surface slope, sampling frequency, the laser's field of view, etc. The fact that laser systems provide 3D coordinates can be considered, on one hand, as their limitation, as virtually no object information is provided. In essence, laser scanning is not capable of any direct pointing to a particular object, and the resulting coordinates refer to the footprints of the laser beam. From a radiometric point of you, the LIDAR system is a narrow-band active sensor, providing a spectral signature of the imaged objects (this potential is hardly used and LIDAR systems typically don't deal with reflectance signal intensity).

The parameters of the images acquired by airborne frame digital cameras are rather well known. Obviously, the sensor model is based on the very same central prospective projection used for large-format aerial cameras. The only notable difference to analog film comes from the radiometric behavior. CCD sensors respond to incoming light in the 0.4-1.1 micron range. Depending on the optical filter used, CCD images may cover only the visual part of the spectrum or some subpart of it. In addition, CCD sensors exhibit a linear characteristic and provide a much a finer intensity resolution compared to analog film.

4.2 Sampling Pattern

The footprint of the laser beam and the ground pixel size of the EarthData LIDAR and digital camera system as discussed above are very comparable and also both systems work with similar FOV's. For our discussion, the typical LIDAR data acquisition configuration described above will be considered. Fig. 3 depicts a surface patch showing the LIDAR spots and the back-projected image (stereo pair) pixel tessellation. As illustrated, there are three independent irregular sampling patterns. Of course, the irregularity depends primarily on surface undulations and to a lesser extent on the sensor orientation. The ratio between the LIDAR and image samples is about 1:60. Since the LIDAR system may receive multiple returns, the effective sampling size for this rare situation can be smaller as indicated on the lower-right LIDAR footprint in Fig. 3 where the laser beam hits a break line. A completely missing LIDAR spot is another likely anomaly; for example, due to surface slant or due to specific materials such as tar (which has no response in the narrow LIDAR spectral band) it is possible that no laser return will be detected at all.

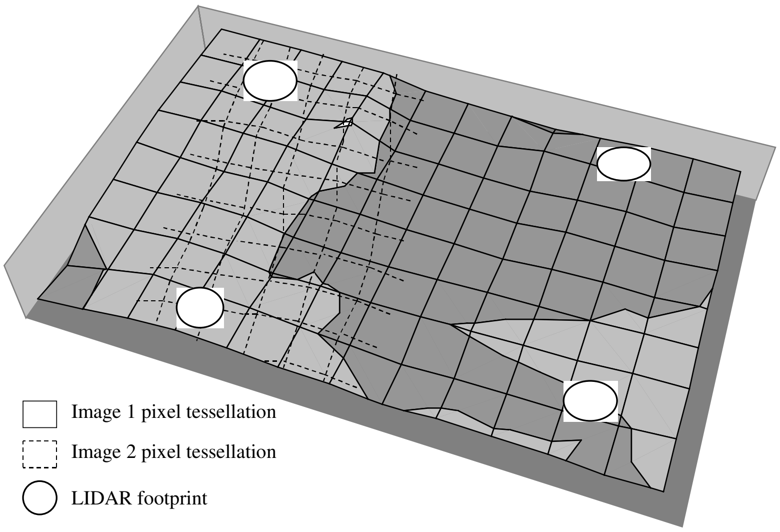

Figure 3. Footprint distribution of the image ground pixels and LIDAR spots

To assess the impact of the different sampling rates of the LIDAR and imaging sensors with regard to the surface extraction problem, two approaches can be considered. First, if the sampling rate of the LIDAR system (typically defined by the cross track direction) is adequate to properly describe the surface, i.e. Eq. 4 is satisfied. This is usually the case for rural areas with modest surface undulations. In these situations, the use of image data to support the surface extraction process is rather limited and is mainly restricted to fill in areas with missing LIDAR spots. Except for these rare cases, the primary purpose of the simultaneously acquired image data is visual coverage, the ortho-rectified backdrop of the surface. The second and more important case is when the sampling rate of the LIDAR system is not adequate for the required surface representation with respect to the requirements of the mapping objective. This is the typical case for urban areas and will be discussed in the following.

4.3 Under-sampling over Urban Areas

Surveying of densely built-up urban areas is in high demand and yet this is one of the most difficult mapping tasks to perform. This is primarily due to the large number of man-made objects with lots of vertical surfaces, occlusions, shadows, moving objects, etc. Probably the surface discontinuities, generally called break lines, represent the most difficult problem, and from a strictly theoretical point of view, they would require a diminishingly small sampling distance. Consequently, this is the case where anything that can increase the sampling frequency for the LIDAR system is appreciated. Multiple laser returns, which are used primarily for vegetation separation, can virtually increase sampling rate locally by providing two (or more) observations for one laser pulse; for example, from the ground and from rooftops. However, this is a very rare scenario since the probability that the laser beam hits the edge of a building is very small. Therefore, the only way to introduce additional information into the surface extraction process is the use of simultaneously acquired imagery. It is important to note that the images come fully oriented. On the one hand, digital cameras capture them and thus the interior orientation is automatically given (basically preserved from the camera calibration). On the other hand, the LIDAR system assumes the use of a high-quality direct sensor orientation system, which by design easily provides the exterior orientation data.

Surface extraction from stereo imagery has been intensely researched and several implementations of various concepts have been commercially available for production for many years. Although none of these techniques is flawless, the expertise in image matching is a significant asset that can and should be exploited to complement the sparse LIDAR spot-based surface extraction process. One of the principal problems in image matching is finding good approximate locations. Once they are found the refinement of the matched locations is less problematic in most of the cases. In a combined approach, the LIDAR spots can serve as initial matched locations (seed points of extremely high quality) and then additional matching points can be searched around the LIDAR locations to densify the surface points. Various interactions can be built into this system such as inferring from certain image patterns to an object hypothesis then applying it to clean LIDAR data or vice versa. Fig. 4 shows an image patch with overlaid LIDAR observation and the representative surface profiles, including LIDAR spots, stereo image-derived surface points and the photogrammetrically determined ground truth.

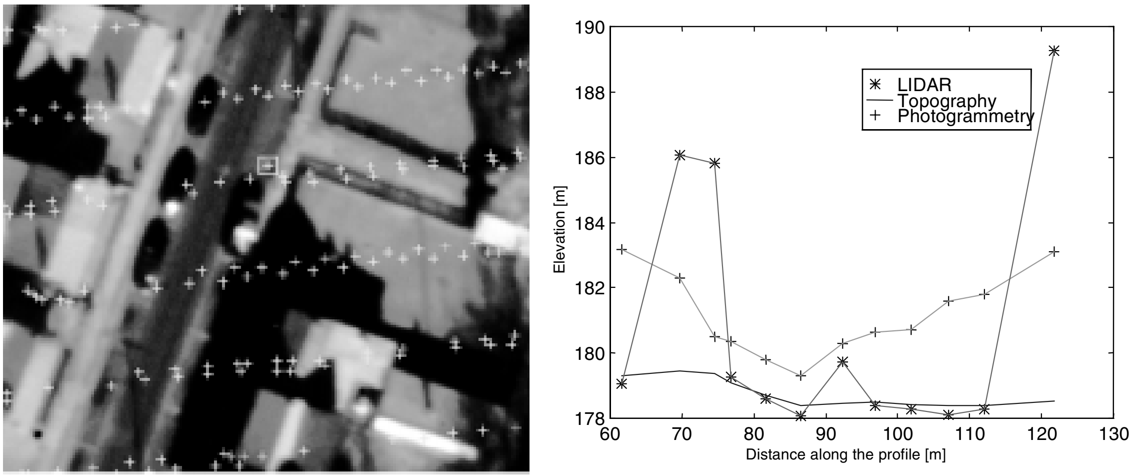

Figure 4. LIDAR surface elevation point locations.

The surface profiles nicely demonstrate that the LIDAR data show an excellent match to the ground truth for flat areas, showing at the same time buildings and other man-made objects not present in the topographic surface. For example, the first peak of the LIDAR profile from the left represents a building, while the smaller peak in the center is a car. The stereo image-created elevation points exhibit the typical smoothed out pattern with smeared surface discontinuities (the vertical offset noticeable over flat areas is probably due to some boresighting discrepancy). As a result of the under-sampling of the surface by the LIDAR system, the shape of the car in the LIDAR profile is like a pyramid. Based on the higher resolving power of the imagery, a better surface modeling of the car and its neighborhood seems feasible from the imagery (the hypothesis for the car can be inferred from the LIDAR data and then it can be applied in the image matching process).

5 CONCLUSIONS

In this paper we examined the feasibility of combining high-performance LIDAR data with simultaneously captured digital images to improve the surface extraction process. The parameters used in our examples represent current state-of-the-art LIDAR technology and commercially available digital camera systems. Our investigation was limited to the conceptual level and addressed only a specific aspect of a rather complex topic – the question of surface sampling. Although our discussion was incomplete, the examples, we hope, clearly demonstrated the potential of fusing LIDAR data with simultaneously acquired imagery to improve the surface extraction process.

The already existing difference in the sampling rate between the LIDAR data and the image resolution on the ground simultaneously offered by the digital camera provides the potential to improve the surface extraction process. Currently, the rate is about 60 image pixels for every LIDAR spot. Since image matching on a pixel-to-pixel level is not feasible, by assuming small clusters of pixels, a densification factor of 5 can be achieved easily even at moderate calculations (the optimal surface point spacing vs. pixel size question itself is a topic of high interest). Since the pulse rate of LIDAR cannot be increased without limits due to the travel time of the pulse, and the digital camera resolution is likely to grow, thus the densification factor will continue to improve even further. This may change with the introduction of the focal plane array LIDAR sensors.

In summary, the actuality of integrating a digital camera into LIDAR systems comes from several facts. First, the medium-resolution, direct-digital images simultaneously acquired with the LIDAR data can provide the necessary visual backdrop for the surveyed project area. Second, the use of imagery introduces the so far missing redundancy to the LIDAR data acquisition and thus, even at medium ground resolution, the stereo coverage can contribute meaningfully to the surface extraction process, especially for areas with sparse LIDAR spot distributions. Third, these systems are already available at an attractive price per performance ratio (the price of a 4K by 4K digital camera system is comparable to the price of the onboard GPS/INS system and is certainly much lower than the price of the LIDAR system itself). In fact, we strongly believe that the use of such complementary imaging systems will be mandatory for any quality LIDAR systems in the future. A further benefit of the simultaneously captured digital imagery is that it provides a fallback potential for unexpected situations such as when the direct orientation data is missing or troubled; for example, instrument failures, or GPS outages, etc.

Finally, we would like to emphasize that although the laser scanning data acquisition technology is already considered fairly mature yet the data processing and modeling techniques still require significant research and further developments.

ACKNOWLEDGMENTS

The authors would like to acknowledge the support of EarthData Technologies for providing test flights and valuable technical discussions.

REFERENCES

Abdullah, Q., 1997. Evaluation of GPS-Inertial Navigation System for Airborne Photogrammetry, ACSM/ASPRS.

Ackermann F., 1999. Airborne laser scanning – present status and future expectations, ISPRS Journal of Photogrammetry and Remote Sensing, 54(2-3), pp. 64-67.

Baltsavias E. P., 1999. A Comparison between Photogrammetry and Laser Scanning, ISPRS Journal of Photogrammetry and Remote Sensing No. 54(2-3), pp. 83-94.

Bruce, M., 1998. An ultra high resolution, electro-optical framing camera for reconnaissance and other applications using a 9126 by 9126 pixel, wafer scale, focal plane array. Proc. SPIE XXII, Vol. 3431, pp. 144-154.

Cramer, M., 1999. Direct Geocoding – is Aerial Triangulation Obsolete, Photogrammetric Week '99, pp. 53-58.

DeLoach S., Leonard J., 2000. Making Photogrammetric History, Professional Surveying, Vol.20, Number 4. pp. 6-10.

Grejner-Brzezinska, D. A., 1998. Direct Platform Orientation with Tightly Integrated GPS/INS in Airborne Applications, Proceedings of ION GPS, pp. 885-894.

Grejner-Brzezinska, D. A., Da, R., Toth C., 1998. GPS Error Modeling and OTF Ambiguity Resolution for High-Accuracy GPS/INS Integrated System, Journal of Geodesy, 72(11), pp. 628-638.

Lithopoulos, E., 1999. The Applanix Aproach to GPS/INS Integration, Photogrammetric Week '99, pp. 53-58.

Norvelle, F.R., 1992. Using Iterative Orthophoto Refinements to Correct Digital Elevation Models (DEM's), ACSM-ASPRS Annual Convention, Vol. 1, pp. 347-355.

Schenk, T., Li, J.C., Toth, C., 1990. Hierarchical Approach to Reconstruct Surfaces by Using Iteratively Rectified Images, Proc. Int. Soc. of Photogr. and Remote Sensing ISPRS, Symp. Comm. V, vol. 28, part 5/1, pp. 464-470.

Schenk, T., Li, J.C., Toth, C., 1991. Towards an Autonomous System for Orienting Digital Stereopairs, Photogrammetric Engineering and Remote Sensing, Vol. 57, No. 8, pp. 1057-1064.

Schenk, T., Toth, C., 1991. Reconstructing Visible Surfaces, Proc. SPIE, Vol. 1526, pp. 78-89.

Schenk, T., 1999. Photogrammetry and Laser Altimetry. ISPRS Comm. III, Vol. XXXII, part 3-W14, pp. 3-12.

Skaloud, J., Schwatrz, K.P., 1998. Integrated airborne navigation systems for photogrammetry, Int'l Archives, ISPRS Comm. II, Vol. XXXII, part 2, pp. 139-154.

Thom, C., Souchon, J.P., 1999. The IGN digital camera system in progress, Photogrammetric Week '99, pp. 89-94.

Toth, C., 1999. Experiences with frame CCD arrays and direct georeferencing, Photogrammetric Week '99, pp. 95-109.

Toth, C., 1998. Airborne Experiences with a 4K by 4K CCD Sensor, Proc. ASPRS-ACSM, CD-ROM, pp. 163-168.

Toth, C., Brzezinska, D., 1998. Performance Analysis of the Airborne Integrated Mapping System (AIMS™), Int'l Archives, ISPRS Comm. II, Vol. XXXII, part 2, pp. 320-326.