Trends in Sensor and Data Fusion

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ABSTRACT

Airborne laser profiling is seeing increased use in a variety of survey and mapping applications. The ready access to georeferencing source data (i.e., GPS/IMU data) on such systems has driven a trend toward integration of ancillary sensors with LIDAR systems. These sensors allow a more detailed observation of the world around us and allow the collection of significantly more "bandwidth" from each data acquisition flight. Furthermore, the advent of ground-based LIDAR systems provides the opportunity for increased levels of detail where needed. Fusion of data from both airborne and ground-based sources allows additional possibilities not feasible with either sensor alone. Sensor and data fusion will be discussed as separate, though related concepts with examples given and conclusion drawn about the direction of these unique technologies and the challenges to be faced.

1. INTRODUCTION

Airborne laser profiling is seeing increased use in a variety of survey and mapping applications. For many years now, users of airborne LIDAR have added imaging capability, first with small format CCD frame cameras using only 1 MP focal planes, but more recently with focal planes as large as 22 MP. Ready access to the georeferencing source data (i.e., GPS/IMU data) available on airborne LIDAR systems has driven a trend toward integration of an increasing variety of ancillary sensors for production of georeferenced output. These additional sensors allow a more detailed observation of the world around us and allow the collection of significantly more "bandwidth" from each data acquisition flight, in effect increasing productivity in the data acquisition portion of the sensor workflow.

In parallel with this trend in the area of airborne sensors, the advent of ground-based LIDAR systems provides the opportunity for increased levels of detail where needed. Fusion of data from both airborne and ground-based sources allows additional possibilities that are absent with either sensor alone, including enhanced visualization where the high detail of ground-based systems can be presented in the context of the broader terrestrial environment.

We can see now that there are really two separate trends involved, sensor fusion and data fusion. We can discuss these two as separate, though related, concepts and discuss trends in each area as well as the challenges being faced in the course of giving multi-sensor integration and data fusion more broad appeal in the geospatial imaging marketplace.

2. SENSOR FUSION – A NATURAL TREND

There is a natural trend toward combining imaging sensors with LIDAR. One of the major components in a LIDAR system is a GPS/IMU subsystem, allowing the position and attitude of the LIDAR as well as that of any auxiliary sensor to be known at all points during the flight. Although the expense of GPS/IMU subsystems can be a significant deterrent to georeferencing a relatively low-cost image sensor, this deterrent does not exist when integrating the imaging sensor to an airborne LIDAR. The same source data from the GPS/IMU subsystem can be used to georeference both image sensor and LIDAR data.

Furthermore, the LIDAR system generates a dense surface model that can be used to accurately orthorectify image sensor data. This circumvents the need to use low-density DEMs or other *a priori* height models, and also eliminates the need to extract a digital terrain model by aerotriangulation of the image sensor data. This use of high-density DEMs from airborne LIDAR to orthorectify image sensor data not only improves the quality of the image sensor data product, but does so at a low marginal cost per pixel, since

- the GPS/IMU processing needed to support the image sensor is mostly complete during the course of processing the LIDAR data, and
- the airborne LIDAR DEM is essentially available at no extra cost.

3. AUXILIARY SENSORS – WHAT TYPES, AND HOW MANY?

Up until recently, the predominant auxiliary sensor was the CCD frame camera. These devices, which are currently available in array sizes to 22 megapixels, can provide RGB or CIR imagery. This imagery is generated using silicon focal planes with embedded Bayer array filtering, resulting in a native CFA (color filter array) format that can be stored or converted to RGB/CIR TIF format in-flight. Changing between RGB and CIR image collection requires exchanging external optical filters to change the bandwidth of interest. Lenses with a variety of focal lengths from 35 mm to 90 mm are commonly available to accommodate various data collection objectives.

More recently, integration of numerous other sensor types has been accomplished, including:

- thermal infrared line-scan sensors
- thermal infrared frame sensors
- multi-spectral frame sensors
- hyperspectral line-scan sensors

Typical performance characteristics are given in Table 1.

Sensor Type	Spectral Region (nm)	FOV (degrees, cross track)	Array Size (along-track x cross-track)
RGB CCD Frame Sensor	400 - 680	23 – 55	4079 x 4092 to 4080 x 5440
CIR CCD Frame Sensor	510 - 900	23 – 40	4079 x 4092 to 4080 x 5440
Thermal Line Scanner	8000 – 12000	48	1 x 320
Thermal Frame Sensor	8000 – 12500	63	240 x 320
Multi-Spectral Fame Sensor	615 – 685 and 815 – 885	33	1024 x 1528
Hyperspectral Line Scanner	400 – 1000	40	288 spectral bands x 525 pixels
Airborne LIDAR (for reference)	Typically 1064	0-75	Typically 500 – 1000 postings across FOV

Table 1. Typical auxiliary sensors used with airborne LIDAR.

How many sensors is "enough" will depend on the application. Most often, visual documentation of the area being flown with LIDAR is needed, so it follows that the most common multi-sensor integration involves the addition of an RGB frame sensor to the LIDAR system. These sensors provide 4 to 8 times the spatial resolution of the LIDAR system and thus add a significant amount if information to the captured scene. Roughly 50% of all ALS40 and ALS50 LIDAR systems incorporate at least a single CCD frame sensor. While most frequently used in RGB mode, the CIR mode is used where automatic classification algorithms will be employed to determine land use, vegetation stress, impermeable surfaces or other attributes. It is important to note that a small number (perhaps 5%) of users actually employ twin CCD frame sensors, one for RGB image collection and one for CIR image collection. This strategy eliminates the need for the filter changes required when switching a single sensor from RGB to CIR mode.

In the commercial markets, thermal sensors are typically used for a variety of remote sensing applications, including studies of power transmission line loading, thermal pollution in waterways and real-time monitoring of wild fires. Thermal sensors are the only auxiliary sensor type that matches the LIDAR system's ability to operate at night. There is substantial variation between the different types of thermal sensors available and so the user may be forced to make trade-offs between spatial resolution and thermal sensitivity or dynamic range in order to select the most appropriate sensor for the application at hand. It is important to note that thermal imaging sensors have long played a key role in defense applications. Given the increasing interest in airborne LIDAR from the defense community, it seems logical that the combination of airborne LIDAR and thermal imaging will be at the top of the list for defense sensor fusion.

Multi-spectral frame sensors typically employ two or more CCD frame sensors, each employing specialized spectral filtering to isolate specific wavelengths of light reflected from the terrain below. Differences in the intensity of reflected radiation making it through the various spectral filters can be used to aid in species identification or vegetation stress.

Hyperspectral line sensors can be used for a host of remote sensing activities from detection of surface minerals to automatic classification of vegetation below, and the utility of these sensors is limited only by their spectral coverage and the software needed to process the data.

Since the majority of the auxiliary sensors depend on solar illumination, it follows that the advantages of these sensors are lost when conducting LIDAR operations after dark. Although the 24/7 nature of LIDAR capability might not apply to all auxiliary sensors, it is still clear that the advantages of common production workflow elements will still allow more accurate, more efficient production of data products from the auxiliary sensor than would be possible using the sensor in a stand-alone configuration.

This raises the question, "How many sensors is enough?" Although the integration of one or two CCD frame sensors is most common, there are examples of the integration of significantly more sensors with a single LIDAR sensor. In one case, what started as an integration of a single 16 megapixel camera, thermal line scanner and an ALS50 LIDAR (shown in Figure 1) has now blossomed into a highly compressed sensor pallet with the following sensors:

- ALS50 LIDAR
- 16 megapixel frame sensor (RGB or CIR, depending on user-installable filter selected)
- Hyperspectral line scanner (can be swapped for thermal line scanner)
- Multispectral frame sensor
- Thermal frame sensor.

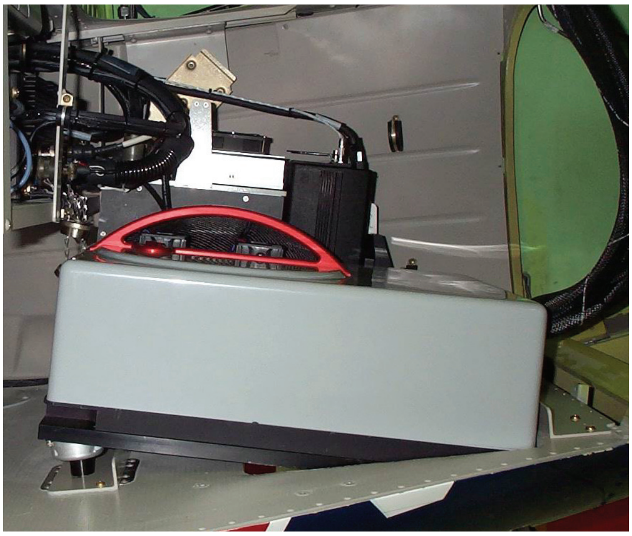

Figure 1. Example of multi-sensor integration (ALS50 + 16 megapixel + thermal linescanner).

This combination of sensors allows orthorectified data to be delivered for a wide range of spectral regions simultaneously, thus providing complete topographic and spectral data for a particular site without the variability or error that might be introduced by flying the same terrain in multiple missions.

4. CHALLENGES IN SENSOR FUSION

There are a number of challenges to be faced when integrating multiple auxiliary sensors with the LIDAR system. These challenges exist in all facets of the workflow, from system integration to planning and operation to sensor data processing. For example:

- *Rigid IMU-to-sensor connection*. It is imperative that all sensors are rigidly mounted to the LIDAR scanner. Since one premise of multiple sensor integration is to take advantage of the GPS and IMU data being recorded for the LIDAR, one must insure that the mechanical relationship between the auxiliary sensor and the IMU must be as rigid as it is between the LIDAR scanning optics and the IMU. Any lack of rigidity will manifest itself as inaccuracy in the georeferencing of the auxiliary sensor data.
- *Sensor-to-GPS/IMU subsystem electrical integration*. It can be challenging to make various sensors play together in a consistent manner. To date, most sensors have evolved as stand-alone systems. Therefore, a whole range of interfaces is seen when integrating these sensors to the GPS/IMU subsystems. The natural index between sensors and the GPS/IMU subsystem is GPS time, but there is inconsistency between sensors regarding where the frame (or line) acquisition time is being stored. Furthermore, there are a limited number of auxiliary sensor interfaces available in the current generation of GPS/IMU hardware. Also, there is inconsistency with respect to the display of any real-time data associated with a particular auxiliary sensor. It is clear that more work needs to be done to standardize the interfaces between sensors GPS/IMU subsystems in order to create a more “plug and play” level of integration. To that end, the new Leica IPAS GPS/IMU subsystem has been designed with 3 external sensor interface ports. Each port contains event mark input, 1 Hz GPS time mark output and GPS time message output.
- *Lens calibration*. This is accomplished using a combination of terrestrial calibration targets and often some type of in-flight verification based on flight data over a calibrated test field.

For CCD frame sensors, this calibration is typically performed by the manufacturer, since these sensors are normally used as metric devices. The lens distortion coefficients are supplied in an outgoing test report, and the coefficients can be entered into photogrammetric software. For other types of sensors, lens calibrations are not always available. Some of these sensors are of relatively low resolution and the manufacturers might assume that the users of these lower-resolution sensors might not be very interested in the use of their sensors as metric devices. As we progress toward an ever more information-centric world it seems that all sensors, almost regardless of resolution, might ultimately be used as metric devices. Therefore, it seems a reasonable expectation that sensor manufacturers and/or integrators should be capable of performing this activity.

- *Boresight calibration*. Another challenge in sensor integration is ensuring that all sensors are properly boresighted so that the angular relationship between all sensors and the common IMU is known. There are well-known methods for resolving this challenge when it comes to CCD frame sensors by using actual flight data from a calibrated test site. Boresight calibration is most critical for this type sensor since their spatial resolution tends to be the highest of all the auxiliary sensors used with airborne LIDAR. These same methods could be applied to other sensors so long as the photo-recognizable targets on the test site are visible in the wavelengths of interest. Otherwise, a sensor-specific target field would be needed.
- *Simplifying sensor control*. The manufacturers of various auxiliary sensors have, in general, structured operator interfaces that are unique to the stand-alone usage of their systems. In the case where several of these sensors are integrated on a single aircraft, though, it is hard to justify a dedicated user interface for each sensor. The extra space, weight and power consumption of multiple monitors, keyboards, pointing devices (or laptops computers integrating all of these functions) may simply not be available in the confines of light aircraft. Therefore, it is clear that all user interfaces need to be software modules that can be run simultaneously with user interfaces for other sensors on the same piece of computing hardware. This is typically accomplished on the ALS50 by either running the auxiliary sensor's GUI on the ALS50 Laptop Control Computer, or by running the ALS50 GUI on the control computer of another sensor. Though this method is quite successful with two sensors, it can be much more cumbersome with more than two sensors. Some standardization of GUI structures (i.e., information displayed and the visual placement of control adjustments) would go a long way toward reducing the amount of display "real estate" required and would also simplify operation.
- *Mission planning*. Each sensor has its own unique parameters that affect the way a data acquisition mission would be constructed. Flying heights, aircraft speed, and line-to-line spacing must be resolved relative to some criteria, such as ground sample distance, for one or more auxiliary sensors. The AeroPlan mission planning software used for the ALS50 LIDAR allows calculation of operating scenarios for various auxiliary sensors all while determining appropriate settings for the ALS50. Future versions may also include the ability to designate one or more "lead" sensor(s), where the GSD requirements imposed on any lead sensor would automatically become the driver for flying height and thus line-to-line spacing. Other sensors would simply be "going along for the ride", but would be configured for best possible performance given the flight parameters dictated by the "lead" sensor(s).
- *Post-flight processing*. The current generation of GPS/IMU software tends to be tailored to single-sensor operation. The extraction of sensor trajectory information for the LIDAR system tends to be accomplished separately from the calculation of exterior orientation files used to properly orient the data from auxiliary sensors. Some productivity enhancement would result from the ability to extract all the needed trajectory information for all sensors

in a single "batch" operation. In the area of orthorectification it is also highly desirable for the photogrammetric software to take in DEM or DSM data directly on output from the processing of LIDAR data. This capability is now resident in Leica Photogrammetry Suite (LPS), allowing direct input of LAS-format LIDAR data to orthorectification processes without any format conversions.

- *Data visualization*. Upon orthorectification of all sensor data, it should be easy to "change one's point of view" from a spectral standpoint, using simple commands to look at the output of the various auxiliary sensors in a single geographic area, while allowing rapid zoom and roam through the multi-sensor data set. Though some visualization software can accommodate LIDAR + camera data in an intuitive manner, the ability to accommodate more than one auxiliary sensor is lacking.
- *Data exploitation*. While looking at data from multiple sensors, it is important to be able to see one spectral region without losing the unique data from other bands. On the surface, this is a human interface problem. Although it is quite intuitive to place a single attribute (e.g., color, reflectivity, or classification, see Figure 2) onto a LIDAR surface, the availability of software for visually representing data from different spectral ranges simultaneously is limited at best. The IMAGINE software suite contains a Spectral Analysis Workstation module that enable tailored display of multi- or hyperspectral data. Furthermore, the development of true multi-sensor exploitation software promises to get more from the combination of multiple sensors than from the sum of the information inherent in each sensor alone.

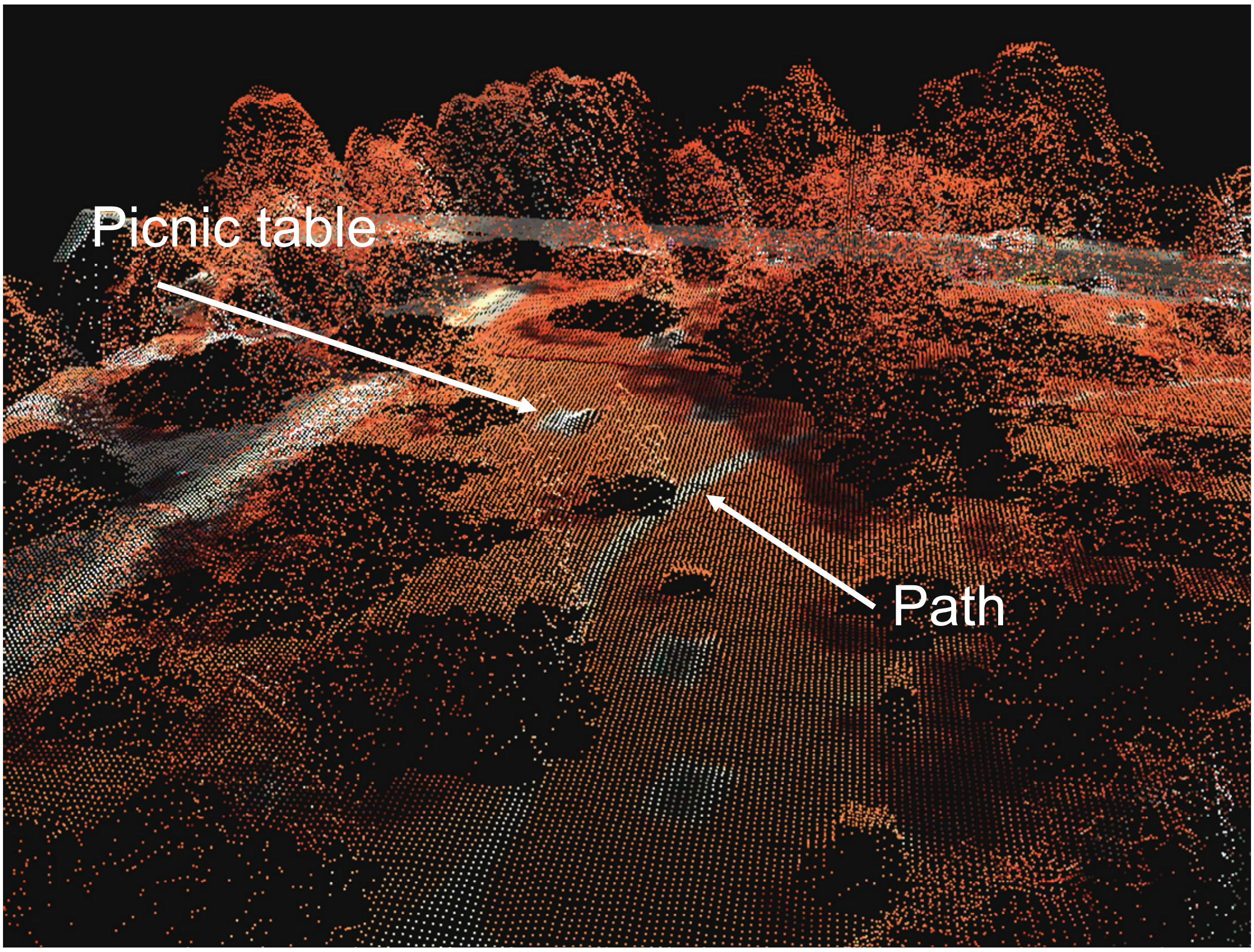

Figure 2. Fusion of LIDAR and CIR CCD frame sensor data (image courtesy Spectrum Mapping, LLC).

5. BEYOND SENSOR FUSION – THE FUSION OF GROUND AND AIRBORNE DATA SOURCES

The development of ground-based LIDAR systems has paralleled that of airborne LIDAR systems. In many ways, the development of airborne systems may be considered to be more rapid, with pulse rates doubling roughly every 2.1 years. At first glance, one might think that airborne systems would be able to generate similar post spacings to ground-based LIDAR in the not-too-distant future. As high-performance airborne LIDAR systems acquire data at faster and faster rates, the potential does exist to decrease post spacing. This is especially true if the aircraft is allowed to fly at low altitude (or otherwise cover a narrower swath). This is further enhanced if the system is mounted in a platform with a very slow forward speed, such as a helicopter. In an effort to provide a legitimate comparison, the average post spacing of various airborne LIDAR systems over time has been calculated assuming a 40-degree swath (similar to initial ground-based systems) and system mounting in a helicopter with 30 knot forward speed. The results are compared to the typical post spacing of ground-based LIDAR systems (i.e., 2-3 cm posting). The results are summarized in Figure 3 below:

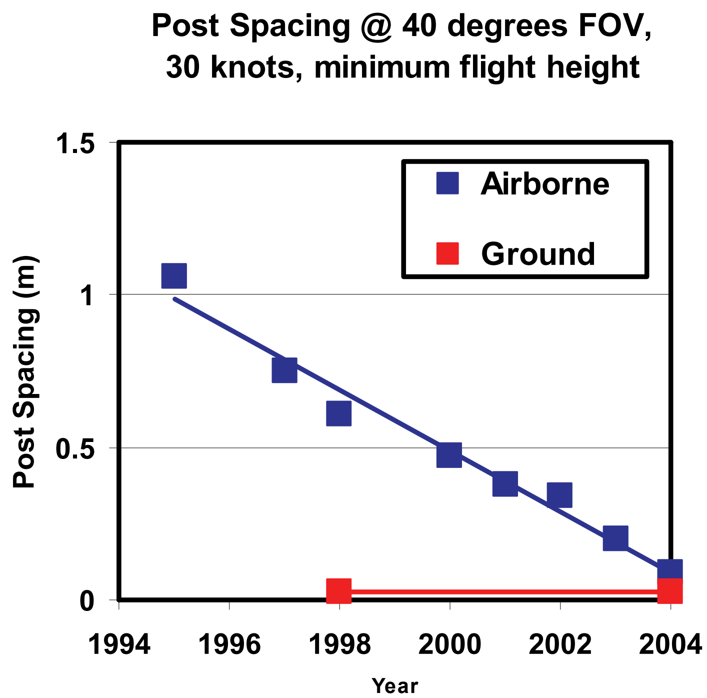

Figure 3. Post spacing of airborne and ground-based LIDAR systems.

The results provide an interesting picture. Does this mean that the two technologies are converging? Perhaps they are in some way.

Today's airborne LIDAR systems could perhaps achieve 0.090 m average posting versus 0.025 for ground-based systems in a full-scene scan. This is a factor of 3.6 in post spacing, so the two technologies are not as close together as they look in the graph. Furthermore, reducing post spacing in both the X and Y directions captured by the airborne system would require a factor of $3.6^2 = 13$ higher pulse rate. Even if the rapid pace of advancement in airborne LIDAR is kept up, we would not expect to see this level of performance until at least the year 2011. Furthermore, obtaining spatial data under overhangs will forever remain impossible for airborne LIDAR.

Therefore, it makes sense to consider the fusion of both airborne and ground-based LIDAR data sets. The high spatial resolution of ground-based LIDAR provides the needed level of detail in a concentrated area, while airborne LIDAR provides the geographic context surrounding the detailed area, as shown in Figure 4.

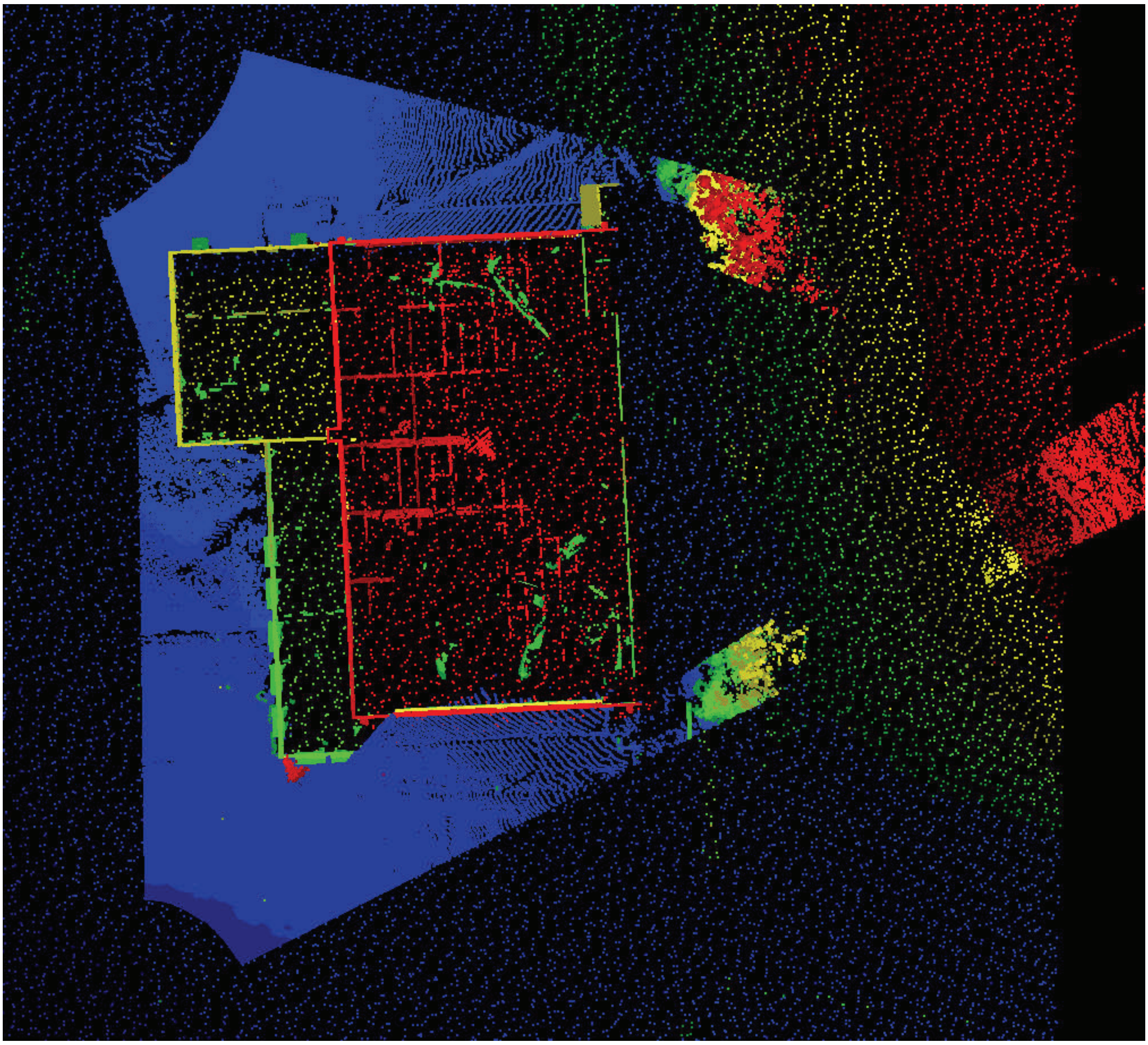

Figure 4. Overhead view of fused data set, highlighting the higher density of ground-acquired data.

The main challenges in this area of data fusion involve accommodating the inherent differences in the format of ground-based and airborne LIDAR data. Ground-based LIDAR software and data formats have been optimized for ultra-fast zoom and roam capability, while readily handling all the ancillary data associated with ground-based LIDAR. On the other hand, the airborne LIDAR industry has focused on a more flexible data standard (called the LAS file format) that allows tracking of user-defined ancillary data while preserving interoperability of the core data across a wide variety of editing, visualization and exploitation software. The ready fusion of airborne (i.e., LAS format) data with ground-based LIDAR data will depend on the development of fast importers for each LIDAR sensor's unique data types.

6. SUMMARY AND CONCLUSIONS

Simultaneous multi-sensor data acquisition is now a reality, providing broad spectrum data at low data acquisition cost. Sensor manufacturers and integrators are making steady progress in simplifying integration of these sensors through the development of more flexible GPS/IMU interfaces, improved user interfaces and rigorous sensor calibration, while sensor source data processing remains an area that will benefit from continued development, providing future significant gains in overall productivity. Steady progress has also been made in improving productivity in the orthorectification of image sensor data with the introduction of direct LAS file import functions.

Fusion of ground-based LIDAR data with that of airborne systems is now feasible and users can look forward to increased speed of this data fusion as time goes on. The benefits of this type of fusion are readily apparent, and the use of such fused data should expand significantly over the coming years.

Finally, the true frontier in the use of multi-sensor platforms is visualization and exploitation. The data available in each contributing sensor must ultimately be considered in the context of data available from the other sensors in the platform. This will ultimately provide information that is greater than the sum of the components derived from each individual sensor.

7. ACKNOWLEDGEMENTS

The writer wishes to acknowledge the contributions of Geoff Jacobs at Leica Geosystems HDS for ground-based LIDAR market background, Chris Gibbons at Leica Geosystems HDS for providing ground-based LIDAR data and Don Marsh at Leica Geosystems GIS & Mapping for his assistance in creating the fused data sets used in this paper.