APPENDIX N — *SideSwipe™* — VEHICLE MOUNTED SIDE SCAN LIDAR

Introduction

Mosaic Mapping Corporation is a publicly traded company with over 18 years of experience delivering high–quality airborne and ground–based mapping products to a diverse international customer base. Headquartered in Ottawa, Canada, and with offices in Calgary, Canada and Houston, USA, Mosaic owns and operates a total of 7 LIDAR systems — three low–altitude helicopter mount ALMIS-350 systems, and four high–altitude fixed–wing ALTMS systems — thus making the company one of the world's largest providers of high–quality LIDAR mapping services. With the advent of its newest LIDAR innovation, SideSwipe, the firm is preparing to field a number of these revolutionary ground–based LIDAR systems.

SideSwipe Background

In 2002 Mosaic's Research and Development team initiated feasibility studies that centered around the re–engineering of its ALMIS–350 LIDAR system for use on ground–based vehicles. Consultations with Ontario's Ministry of Transportation (MTO) suggested that such a system would be useful in numerous MTO projects, and Mosaic's own feasibility studies indicated that the technological challenges could be addressed. A prototype system was developed and successfully operated on a rolling test bed.

Figure N1 — Map of Afghanistan

In June 2003 Mosaic learned about a project to provide engineering grade mapping of approximately 566 kilometers of desert road in Afghanistan. Afghanistan's main highway, known as Highway 1, starts in Kabul, passes through Kandahar, ends in Herat, and traverses some 1062km en route. Much of the road surface, and several bridges, have been destroyed as a result of more than 20 years of neglect, not to mention years of civil war. Consequently, the journey from Kabul to Herat is an arduous one that can take as long as one week to complete.

Surveying crews had already employed conventional ground–based techniques to map the highway from Kabul to Kandahar, but progress was slow, and alternative methodologies were being considered. The immediate reaction was to employ one of the low–altitude helicopter–based ALMIS–350 LIDAR systems on the project. However, consultation with military experts proved that such an approach could be dangerous given Afghanistan's state of unrest. Thus, with conventional ground–based techniques deemed to be inadequate, and now, with conventional airborne LIDAR techniques also out of the question, the decision was made to develop the ground–based LIDAR test bed into a production tool.

Some Details

ALMIS–350 is a high–precision low–altitude LIDAR system that utilizes a Laser Mirror Scanner, a digital SLR camera, and a tightly coupled GPS/IMU. The GPS/IMU determines the position and attitude of the moving platform and of the sensors. The software that ties each of the component parts together represents several years of intense research, development, and refinement — it is essentially the "glue" that differentiates this system from others — and lends the system an inherent flexibility that allows alternative configurations to be considered.

Initial tests involved turning the laser through approximately 90 degrees so that the scanner was able to record data to the side of the vehicle, with the GPS antenna located approximately above the IMU in order to minimize errors due to the GPS to IMU lever–arm uncertainty. Clearly, the principal difference between this installation and that of a helicopter centers around the orientation of the laser. Depending on the mission and the objects that are to be scanned (e.g., tall buildings, highways etc.) a tilt angle of between 70° and 110° is applied to the laser so that it points at the required objects. As the vehicle moves along the street or any other corridor of interest, the laser constantly scans the entire right–hand–side of its trajectory with a swath width of 60°.

Figure N2 — Test Bed Installation on Truck

Theoretical Accuracy

SideSwipe's theoretical accuracy is a function of several component parts, as outlined below:

Scanning Distance (m)	10	50	100
GPS Accuracy (m) [1]	± (0.02 + 5ppm)	± (0.02 + 5ppm)	± (0.02 + 5ppm)
Beam Divergence (m)	0.030	0.150	0.300
IMU Accuracy (0.05 deg)	0.009	0.044	0.089
Laser Distance Accuracy (m) [2]	0.020	0.020	0.020

Notes:

[1] Dual–frequency double differenced data, equipment operated in kinematic mode.
[2] Assumes reflection off hard surfaces

Table N1 – SideSwipe Error Sources

In conventional airborne LIDAR work using the ALMIS–350 typical accuracies are of the order of a few cm vertically and 20 to 25cm horizontally.

Table N1 indicates that the system should achieve horizontal accuracies of the order of 4 or 5cm regardless of scanning distance, and vertical accuracies of the order of 5 or 6cm at a scanning range of 10m (note that vertical accuracy degrades with increased scanning distance). Therefore, because SideSwipe essentially turns LIDAR on its side, the situation with respect to accuracy changes. It can be seen that similar accuracies are achieved in both the horizontal and vertical components.

Test Results

Ground truth data are available for a 10km section of Rural Route 6 (RR#6) in North Gower, Ontario. Consequently, the area represents a controlled test range where Mosaic has conducted numerous high accuracy tests using the ALMIS–350 system. Figure N3 depicts digitally enhanced SideSwipe data collected where RR#6 and Hwy 416 intersect.

Both the SideSwipe test bed and, more recently, the SideSwipe production system have been subjected to numerous rolling trials at the controlled test range where, in most cases, the vehicle maintained a more or less constant velocity of 80km/h. Table N2 summarizes SideSwipe's accuracy when compared against the ground truth data:

Surface Type	Sample Size	r.m.s. error (cm)
Center Line Road	47	4.3
Edge of Pavement	68	3.7
Edge of Shoulder	45	2.8
Guard Rail	20	4.0
Property Line	30	4.9
Toe Slope	44	4.8
Ditch	40	4.6

Table N2 – SideSwipe Test Results

Overall, the results are extremely positive, with the entire survey corridor showing an r.m.s. error of about 4cm (or 7cm at the 2σ confidence level). Hard surfaces such as the road's center line do even better, showing 2σ accuracies of about 4cm (a figure that is consistent with the theoretical accuracy previously noted).

Limitations

Although somewhat difficult to visualize without the aid of a computer, the graphic shown in Figure N3 is generated entirely from SideSwipe data collected at ground–level. Further analysis of the graphic reveals that data are missing either side of the 416 overpass. In other words, the black areas represent areas of shadowing. This is entirely consistent with what one would expect to see, but it does nevertheless underline the system's principal limitation.

Current Field Technique

The impact of shadowing can be minimized by adopting appropriate field techniques. Clearly, and once again with reference to Figure N3, if a 3-

dimensional model of the entire overpass had been required the system would have been operated on both RR#6 and Hwy 416.

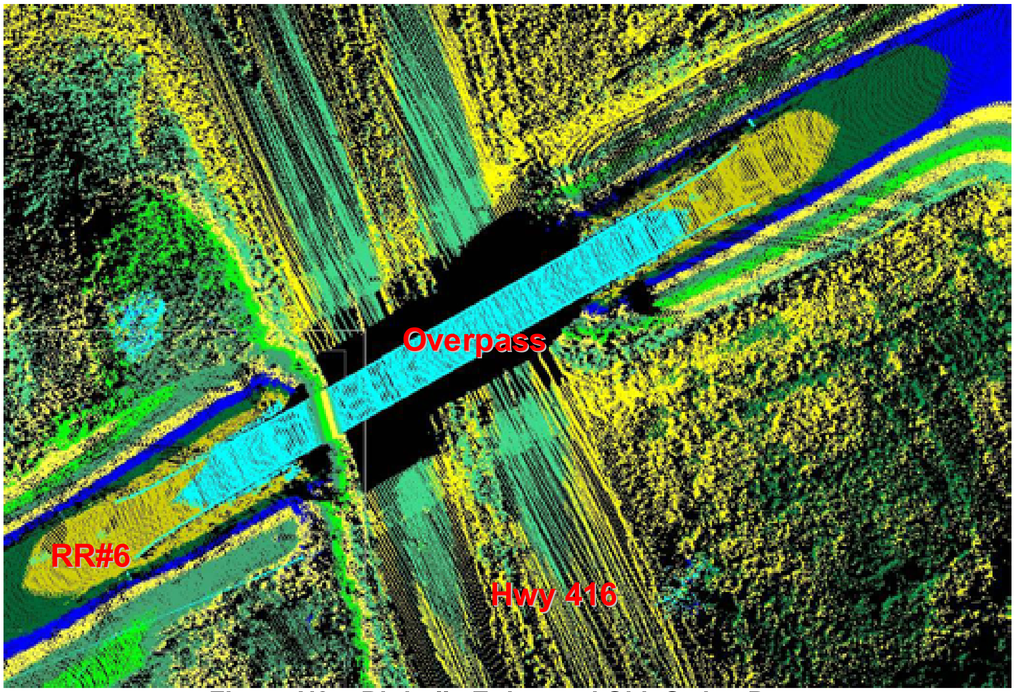

Figure N3 – Digitally Enhanced SideSwipe Data

Forward Pointing Horizontal Scan

Although not previously mentioned in this discussion, the road was first driven with a forward-pointing, horizontally scanning system tilted downwards by about 10° and sweeping a 60° swath. Legal clearance issues dictate that the equipment cannot be mounted more than 4.1m above the surface of the road; all of which equates to a forward reach of approximately 23m coupled to a **horizontal** swath of about 27m. In some situations this might provide sufficient coverage, but it is often the case that more extensive coverage is required (e.g., 30m either side of centerline in Afghanistan) while minimizing the effects of shadowing.

Side Pointing Vertical Scan

Fortunately, the effective swath of the survey can be greatly extended while simultaneously reducing the effects of shadowing. In order to achieve such an outcome the laser is rotated through 90 degrees on its z–axis so that it is side pointing. The laser is then turned through 90 degrees on its x–axis so that it becomes a vertically scanning, side pointing laser. If the laser is once again tilted downwards by about 10°, the resultant vertical swath now extends from approximately 40° below the horizon to approximately 20° above the horizon. Realistically, such a swath intersects the ground some 5m to the side of the vehicle, and extends usefully to about 100m, or until it strikes a reflective surface such as a building.

In Practical Terms

A combination of the two scanning methods outlined above allows an entire road to be mapped in three passes as described and illustrated in Figure N4.

1st Pass — drive along the road performing a forward pointing horizontal scan;

2nd Pass —turn the vehicle around, rotate the laser through 90° about its z–axis, rotate the laser through 90° about its x–axis, and resurvey the road in the opposite direction using a side pointing vertical scan; and finally

3rd Pass — turn the vehicle around, resurvey the road in the original direction, once again performing a side pointing vertical scan.

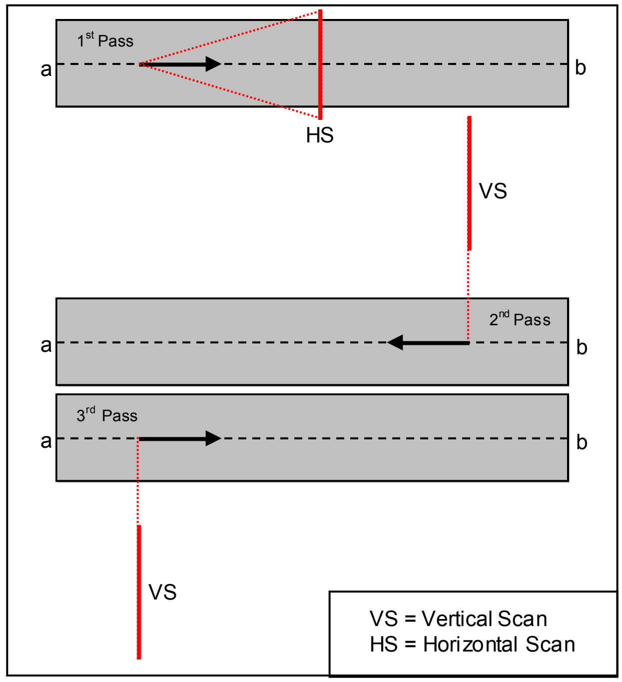

Figure N4 — The Three Pass Survey Approach

The three passes now provide sufficient data in order to map approximately 100m either side of the road's centerline. Although obstructions such as street furniture, buildings, and trees cause shadowing, they are mapped by virtue of the fact that they are "in the way".

Potential SideSwipe Enhancements

The Multi Laser Approach
The current field technique illustrates that there is room for improvement — rather than adopting a three pass approach to the survey, it would be preferable to drive a single pass only. Three lasers (one forward pointing, and two scanning to either side of the vehicle) would facilitate such an approach, but would of course add to the system's overall complexity and cost.

"Spray Painting"
As previously noted, if a 3-dimensional model of the overpass in the test area had been required the system would have been operated on both RR#6 and Hwy 416. Although this would have minimized the degree of shadowing, the interior surfaces of the overpass would not have been captured in their entirety — this would require that the laser be directed upwards. From an engineering point of view this is perfectly feasible as long as the laser platform is mounted on a gimbaled mechanism that can be pointed in any direction. Because the laser is rigidly fixed in space with respect to the system's IMU it would still be able to position the platform correctly, and thus obtain accurate information.

To advance everything several steps further, the gimbaled mechanism could be remotely controlled and if the data processing were performed in real–time the operator would be able to "spray paint" the interior surfaces of the overpass. It is worth noting that this "spray painting" technique could be used in order to collect data in other difficult areas (by driving around a building for example).

GPS Outages

The tightly coupled nature of the system's GPS/IMU means that GPS outages of the order of 15 to 20 seconds can be accommodated without seriously impacting the system's accuracy. If the example of the RR#6 / Hwy 416 overpass is once again considered, and if it is assumed that its underside cannot be thoroughly "spray painted" in 15 to 20 seconds, it is thought that the vehicle could be stopped just short of the overpass (i.e., while maintaining sufficient GPS satellites for positioning) while data are collected using an obliquely pointed laser. If this were repeated from the other side of the overpass (with data being collected while traveling through the overpass, at speed) a complete picture of the overpass' interior surfaces could be acquired.

Some urban canyons and longer tunnels could pose serious challenges, but it is believed that the development of additional field techniques using emerging technologies such as pseudolights may help in this respect.

Conclusions

In response to real–world requirements to provide an accurate surveying system that would capture highway detail in a speedy and cost–effective manner Mosaic Mapping Systems developed its ground–based LIDAR mapping system — called SideSwipe — in record breaking time. The system is already in action in Afghanistan, where it will map almost 600km of road in very demanding conditions.

System tests demonstrate that an accuracy of 4cm r.m.s. can routinely be achieved using the system, although areas of shadowing do inevitably occur from time–to–time. In order to minimize the effects of shadowing and in order to streamline the data collection process a system comprised of three lasers has been discussed as a potential enhancement for the future. It is also thought that real–time "spray painting" of detail via a remotely operated gimbaled mechanism could be implemented.

Relevance to FEMA

On behalf of FEMA, Dewberry is investigating alternative remote sensing technologies to capture 1st floor building elevations and lowest adjacent grades in order to predict flood risks. Because a building essentially presents SideSwipe with a source of shadowing it is, as noted earlier, mapped by virtue of the fact that it is "in the way". Mosaic believes that Dewberry's specific requirements can be met using a very specific mode of "spray painting". SideSwipe's operating costs are trivial compared with those of the helicopter system from which it is derived; also noteworthy is the fact that the helicopter system can be modified for ground use in half a day.