ASSESSMENT OF AIRBORNE LIDAR AND IMAGING TECHNOLOGY FOR PIPELINE MAPPING AND SAFETY APPLICATIONS

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ABSTRACT

Safe pipeline transportation of energy resources is a major concern for the public. Since a pipeline has been built and buried, geologic hazards, corrosions and third-party damages all pose cumulative internal and environmental risks to the pipeline's integrity. As today's pipeline engineering and operation become more reliant on geospatial data for safety in the pipeline's life cycle of design, construction, maintenance, and emergency response of pipeline facilities, the rapid and cost-affordable acquisition of terrain data along the pipeline corridor becomes increasingly critical. This paper addresses the use of airborne lidar and imaging technology for pipeline mapping and pipeline safety applications. We aim to improve the safe and secure transmission of gas and liquid energy in pipeline system by assessing the potential benefits of airborne lidar technology. It is concluded that airborne lidar could be an effective technology to assist pipeline risk management to assure safety in design, construction, operation, maintenance, and emergency response of pipeline facilities. Industrial and scientific advances in lidar systems and data processing techniques are opening new technological opportunities to develop an increased capability to accomplish the pipeline mapping and safety applications. The potential integration with other imaging sensors is expected to put lidar data acquisition and application on a new level with far reaching prospects.

INTRODUCTION

Demand for gas is being driven by growing worldwide demand for gas-fired electric power generation, and to a lesser extent by growing industrial, commercial and residential demand. Natural gas projects continue to dominate construction and engineering work. The pipeline network operating in the United States consists of approximately 1.9 million miles of natural gas and hazardous liquid pipelines operated by more than 3,000 operating companies. Of these 1.9 million miles, 302,000 miles are natural gas transmission pipelines operated by 1,220 operators and 155,000 miles are hazardous liquid transmission pipelines operated by 220 operators. In addition to transmission pipelines, there are 94 liquefied natural gas facilities operating in the United States. This vast network's inception began in the early 1900's and has continued to expand each year to meet the growing energy needs and product requirements of the United States (http://www.bts.gov/gis/reference/npms_chall.html; http://www.npms.rspa.dot.gov/). Estimated miles of natural gas, crude oil and refined products pipelines underway or planned for construction outside the U.S. and Canada total 122,276 km. Current construction mileage is 17,564 km, which is above last year's figure (15,214 km) due to ongoing projects all over the world. In addition, natural gas distribution pipeline systems (Figure 1) are being built, expanded, replaced, and planned worldwide. Some of the larger gas distribution projects are underway or planned (http://www.pipe-line.com/).

Although pipelines are the best way to transport gas and energy resources, major excavation damage and natural disasters such as hurricanes and floods stress an emergency response organization’s abilities to plan and response. High-quality location maps are vital for safety reasons and in order to monitor any ground movement around the pipelines. The pipeline owners and operators are under increasing pressure to produce accurate maps of pipeline routes. In some cases, they are also required by law.

Airborne lidar is an aircraft-mounted laser system designed to measure the 3-D coordinates of Earth’s surface. It has been proven to be an effective technology for acquiring terrain surface data with high accuracy. The lidar may provide a supplemental technology to pipeline risk management to assure safety in design, construction, testing, operation, maintenance, and emergency response of pipeline facilities. It provides rapid 3-D data collection of long, linear objects such as pipeline corridors, roads, railway tracks, waterways, coastal zone or power lines. It is easier to obtain many terrain parameters (e.g., slope) and to generate 3-D flythrough using these data. Since lidar systems have a narrower swath in comparison to optical sensors, they are more cost-effective in capturing information needed for above applications.

When the lidar is combined with a digital photograph, the client has the added value of an image geo-referenced to the laser data set. By combining traditional photogrammetric mapping services with advanced data collection and processing techniques, new technologies help pipeline monitors solve problems and make the decisions. Lidar data also could facilitate the planning of new lines and deciding safe routes for placement of a pipeline by considering the terrain parameters such as slope.

Figure 1. Pipeline constrction at hilly area (http://osfm.fire.ca.gov/gishead.html)

Pipeline Mapping

Pipeline maps are generated to construct a pipeline and to visualize the relationship among objects. Gas and pipeline industry needs precise information when planning and designing the most efficient and economical pipeline routes. Accurate terrain measurements can quickly assess the feasibility of construction in certain areas such as valleys between mountains or hills. It can also reveal the type of terrain, whether it is rocky, heavily vegetated or contains a body of water.

In general, operators develop pipeline or facility information at the time of the original siting and construction of the system. This information is updated when the pipeline or facility is rehabilitated, modified, rerouted, or when additional pipelines are laid in the same right-of-way. The format, accuracy, and utility of the data that are based on each operator's specific business and operating needs as well as historical data collection techniques. Consequently, pipeline locational data within the pipeline or facility operator files exists in a number of varying (paper or electronic data) and vary widely with respect to scale and level of detail. These formats are dependent upon the original survey technique used to capture the data.

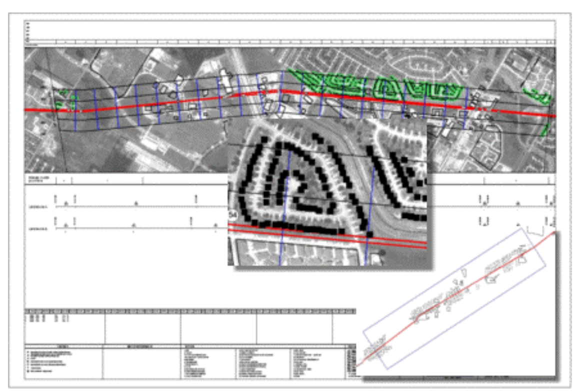

Figure 2.
This sheet is a combination of aerial imagery, map overlays, and schematic drawings (GeoFields, 2001).

Today, the changing regulatory climate combined with the government's need to have access to reasonably accurate pipeline locational data has required the Department of Transportation, Office of Pipeline Safety (OPS), to search for optimum cost-effective approaches in creating a national pipeline mapping system. The major challenge facing the OPS is to create a mapping system for the thousands of miles of existing infrastructure as well as for any future transmission pipeline systems and liquefied natural gas facilities that operators may construct. Figure 2 shows a sheet combing aerial imagery, map overlays, and schematic drawings that inventory pipeline operating pressures and the surrounding factors that influence maximum operating pressures. It serves the additional purpose of reporting compliance with OPS standards for reporting the maximum allowable operating pressure and its correlation to population density (GeoFields, 2001).

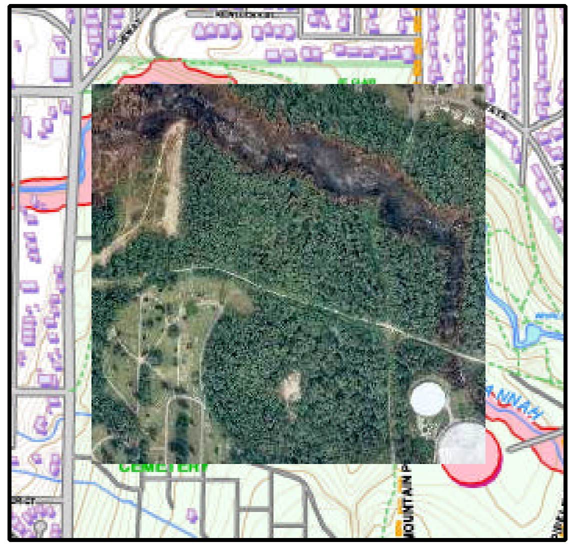

Figure 3.
Map of Bellingham pipeline explosion with aerial photograph overlaid on the basemap of incident area (COB, 2001)

Transportation Safety

Pipeline safety problem starts before the actual construction begins and exists in the all life cycle of a pipeline since it has been built and been placed into services. Since a pipeline has been built and buried, geologic hazards, corrosions and third-party damages all pose cumulative internal and environmental risks to the pipeline's integrity. Excavation damage is the single greatest cause of pipeline failures with all other underground utilities being equally vulnerable. There are hundreds of natural gas and hazardous liquid pipeline accidents each year happened in US (http://ops.dot.gov/stats.htm), resulting huge injuries and property loss. In Figure 3, the Bellingham pipeline explosion is delineated by aerial photograph overlaid on the basemap of the incident area.

Safe pipeline transportation of energy resources is a major concern for the public and the pipeline industry. The Pipeline Safety Act of 1992 requires that Research and Special Programs Administration (RSPA) adopt rules requiring pipeline operators to identify facilities located in unusually sensitive areas and high-density population areas, to maintain maps and records detailing that information, and to provide those maps to federal and state officials upon request. The Department of Transportation's Office of Pipeline Safety (OPS) currently does not have access to a reasonably accurate and national depiction of natural gas and hazardous liquid transmission pipelines and liquefied natural gas facilities operating in the United States. To ensure the safe, reliable, and environmentally sound operation of the pipeline transportation systems, OPS is working with state agencies and the pipeline industry to create a National Pipeline Mapping System (NPMS) (http://ops.dot.gov/; http://www.bts.gov/gis/reference/npms_content.html). This system is a full-featured geographic information system database that will contain the locations and selected attributes of natural gas transmission lines, hazardous liquid lines, and liquefied natural gas facilities operating in onshore and offshore territories of the United States (http://www.npms.rspa.dot.gov/).

The most widely used methods for pipelines monitoring include foot patrols along the pipeline routes and aerial surveillance using small planes or helicopters. These patrols perform facility inspections, check for construction activity in the vicinity of the pipeline, and maintain the pipelines' right-of-way. Heavily congested areas are inspected and patrolled more frequently. In addition, the pipelines undergo periodic maintenance inspections, including leak surveys, and safety device inspections. So the developments and events that could place high-pressure pipelines, the surroundings of pipelines or security of supplies at risk could be prevented. In a continuing effort to remove the guesswork from pipeline operations and reduce costs, many new techniques have been employed to develop software and hardware systems that analyze pipeline risks and maintenance needs in a scientific fashion.

GRI is developing cost-effective ways to enhance pipeline integrity, inspection, and monitoring, as well as new tools and techniques for managing the risks involved in pipeline operations (Willke, 1996). GRI researchers investigated the use of satellite-based technology for pipeline protection. They identified the potential for satellite imagery to detect significant slope motion and ground movements that could threaten nearby pipelines with a less expensive means (Hartdraft, 1998). PIMOS models five types of pipeline defects: external corrosion, internal corrosion, stress corrosion cracking, material/ manufacturing defects, and mechanical damage (Leewis, 1998). Zirnig et al. (2001) studied the natural gas transmission pipeline monitoring combining high-resolution imagery supplied by various spaceborne sensors and the context-oriented evaluation of these data using image processing techniques. EarthData and GeoEngineers developed some pipeline risk assessment tools processing digital ortho-photos from airborne global positioning system (GPS), inertial measurement unites (IMU), light detection and ranging (LIDAR) and the digital camera, and possibly thermal and multi-spectral images (Baker, 2001). The program uses pipeline company data on system design, soil conditions, maintenance history, cathodic protection, and inspection records to determine which pipeline segments are more likely to need maintenance or inspection. A pipeline monitoring project, PRESENSE (Pipeline REmote SENsing for Safety and the Environment) being driven by Advantica Technologies Ltd and the European Gas Research Group GERG with 17 collaborating partners, has gained approval for funding from the European Commission 5th Framework Research and Technology Development programme (Lindsay-Smith, 2001). It aims to further improve the safe and secure transmission of gas in Europe's extensive high-pressure gas mains transmission systems, by assessing the potential benefits of remote monitoring techniques and processes. The project will involve the development of mathematical modeling software, image processing software and the evaluation of detector instrumentation. A remote monitoring system will beam images to earth from satellites in space, mapping the route of a pipeline and identifying key threats to pipeline safety and security.

LIDAR PIPELINE DATA ACQUISITION

Technical overview

Lasers have been used in commercial measuring equipment for more than thirty years and have been remarkably accurate in measuring some very long distance. There are three basic generic types of lidar: range finders, DIAL, and Doppler lidar. Range finder lidar is used to measure the distance from the lidar instrument to a solid or hard target. DIfferential Absorption Lidar (DIAL) is used to measure chemical concentrations (such as ozone, water vapor, and pollutants) in the atmosphere. A DIAL lidar uses two different laser wavelengths that are selected so that one of the wavelengths is absorbed by the molecule of interest whilst the other wavelength is not. The difference in intensity of the two return signals can be used to deduce the concentration of the molecule being investigated. Doppler lidar is used to measure the velocity of a target. When the light transmitted from the lidar hits a target moving towards or away from the lidar, the wavelength of the light reflected/scattered off the target will be changed slightly. This is known as a Doppler shift - hence Doppler Lidar. If the target is moving away from the lidar, the return light will have a longer wavelength (sometimes referred to as a red shift), if moving towards the lidar the return light will be at a shorter wavelength (blue shifted). The target can be either a hard target or an atmospheric target - the atmosphere contains many microscopic dust and aerosol particles that are carried by the wind. These are the targets of interest to us as they are small and light enough to move at the true wind velocity and thus enable a remote measurement of the wind velocity to be made.

The typical airborne lidar (see Figure 4) is a scanning and ranging laser system that produces highly accurate and high-resolution 3-D topographic data. It requires the deployment of an aircraft in much the same way as conventional aerial photogrammetry does. The techno-logy has been in existence for more than 20 years, but the commercial application for topographic maps has developed in the last six years. Today, the entire process of airborne

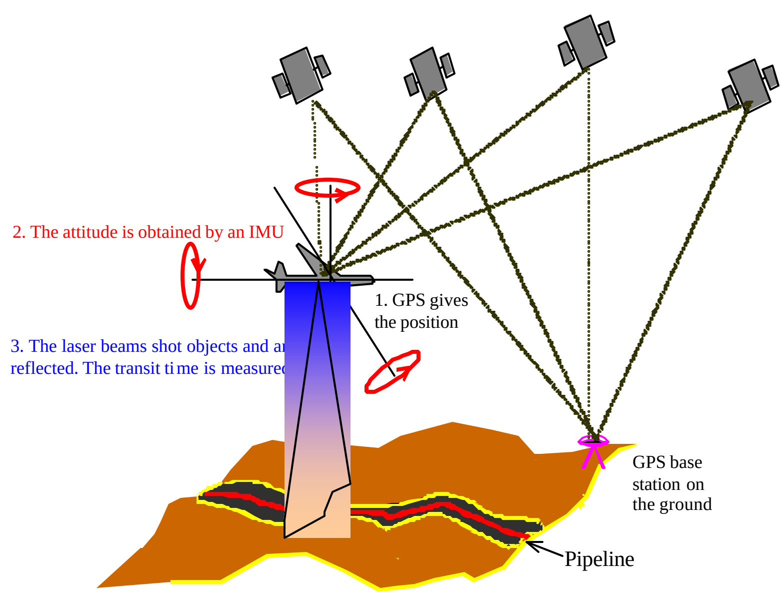

Figure 4.
A typical airborne lidar system (modified from Turton and Jonas, 2000)

lidar mapping is highly automated, from flight planning, to data acquisition, to the production of digital surface models. The basic components of a lidar system are a laser scanner and cooling system, a GPS, and an IMU. The laser scanner is mounted in an aircraft and emits laser beams at a high frequency. The scanner records the difference in time between the emission of the laser pulses and the reception of the reflected signal. A mirror is mounted in front of the laser. The mirror rotates and causes the laser pulses to sweep at an angle, back and forth along a line. The position and orientation of the aircraft is determined using a phase differenced kinematic GPS. A GPS is located in the aircraft and several ground stations (differential GPS) are located within the area to be mapped. The orientation of the aircraft is controlled and determined by the IMU. The single most important parameter affecting lidar-derived data accuracy is the specific post-spacing captured in the raw lidar data and the measurement accuracy of the points. The density of points to create an accurate digital surface model (DSM) and resultant contours will vary depending on the terrain. Depending on the system, some laser sensors can record multiple returns, and intensity. The intensity records how much energy is returned from the object. It may enable users to differentiate between different types of surface and may lead to detection of liquid leaking of underground pipelines.

Capabilities and Shortages. Each type of lidar has its special applications and use (Fowler, 2000). Range finder lidar systems are less sensitive to environmental conditions such as shadows, weather, sun angle, leaf on/off condition. Lidar can also work at night without the degradation in performance. The high point sampling densities, and fast turn-around time are among the most attractive characteristics for many terrain-mapping applications. Since lidar systems have a narrower swath in comparison to optical sensors, they are more cost-effective in capturing information needed for corridor or right-of-way mapping. Due to these characteristics, lidar has found applications where ground survey is limited or risky to field crews or aerial photogrammetry is prohibited or not cost effective. Lidar also has its limitations. Range finder lidar cannot collect data in rain, mist, fog, smoke or during snowstorms or high winds. While it can collect data during cloud-covered times, the cloud ceiling must be higher than the aircraft.

Project Planning. The flight plan should be optimized to provide the minimum dataset necessary to meet the final map product accuracies. Some lidar systems require parallel flight lines, and perpendicular flight lines may be advisable or necessary. Flight planning schedules are therefore an important consideration in the applicability of lidar. Flights may take place at night, given that other operating conditions are acceptable. Flights during inclement weather such as high winds, snow, rain, fog, high humidity, or cloud conditions should be avoided. Wet ground and snow-cover conditions should also be avoided, because such conditions may skew laser reflectibility. Because of laser density (i.e., high laser pulse rates), dense foliage and vegetative cover may or may not be a factor for consideration. Density of land cover such as vegetation and structures is an important aspect for consideration during the planning phase of a lidar project. In some cases, lidar has failed to perform as well as expected in vegetated areas, in large part because of "leaf-on" conditions. The contractor should furnish all necessary materials, equipment and consumables, and also supply sufficient supervision, professional, and technical services personnel required to manage, survey, document, and process all aspects associated with airborne laser profiling and digital image data collection. The project area must be investigated with respect to pipeline special requirements, existing geodetic survey control, and governing agency specifications. From this investigation, reasonable ground control stations should be selected to permit reliable post-mission kinematic differential phase processing of the GPS observables. The density and accuracy of data generated by different lidar equipment varies widely and the lidar contractor should have the flexibility to provide a flight plan with the necessary flight passes to create the necessary point densities.

Accuracy and Quality Assurance. The accuracy of lidar data depends on the specific configuration of a lidar system. Laser ranging is very accurate over a wide range of distances, usually within 2~3 centimeters in the normal aircraft operation elevations. The IMU accuracy varies somewhat according to the flying height. The typical carefully set up GPS with adequate ground control stations will provide an accuracy of 5~7 centimeters. When combining all these errors together, the best absolute vertical accuracy that can be guaranteed from current technology is 15 cm RMSE, and the horizontal accuracy is 10 to 100 cm RMSE. Field edit may be employed to provide information for data missing areas or un-reconciled errors in the lidar dataset.

Cost Estimation. Pricing for lidar data is a delicate matter due to the variety of data products that can

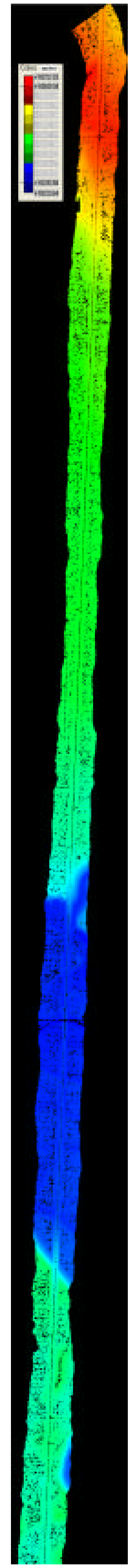

Figure 5. Pipeline

be produced, the deliverables on a given project and the various applications that can be addresses. Each lidar data vendor may have a different pricing strategy. In addition, the numerous configurations that are available with each lidar system add difficulty to the generalized quoteprice. The typical lidar corridor surveys can range in price from US$125 to US$500 per linear kilometer (Schnick and Tao, 2001).

Sample Pipeline Lidar Data

The pipeline lidar data shown in Figure 5 was acquired by AeroScan, and was colored by elevation. Contours with basic elevation interval of 1 meter were generated. The long black strip in the middle of the scene is a groove prepared for burying the pipeline. The data set contains about one hundred and sixty thousand points in an area of 5910 meters long and 424 meters wide. The lidar points have an elevation range from 1023 meters to 1073 meters. It can be easily observed from the profile map along the pipeline that the whole strip is composed of four relatively flat segments with slopes between them.

TERRAIN PARAMETERS AND DEM DERIVATIVES

Terrain Parameters

The terrain parameters are set of information derived from lidar range data. They are based on the difference in elevation between one point in the digital elevation model (DEM) and its neighboring points.

- *Slope*: It is a map of the rate of change, or the first derivative of lidar range data (see Figure 6). What this means in simple terms is that we are performing a neighborhood operation on a DEM in order to get a measure of the steepness of a region of interest. Slope is usually measured in degrees or percent. In either case, the slope value assigned to each point will reflect the overall slope based on the relationship between that point and its neighbors.
- *Aspect*: The aspect value assigned to each point giving the 3-D direction to which that point is oriented. Slope and aspect are usually used together in driving the drainage networks and watersheds.
- *Curvature*: It is a measure of the rate of change of slopes, and is used in landform curvature analysis (convex/concave) and aging of terrain studies (Change detection).

Lidar is an acceptable method of collecting data to derive terrain parameters for the purposes of pipeline mapping and safety applications, if produced in accordance with the product and accuracy specifications.

Lidar DEM Derivatives

The original lidar data and the derived terrain parameters can be used to produce many derivatives. The terrain parameters can help locate steep slopes, which could endanger the pipeline structure and its surrounding environment. The derivations also can identify those segments having the highest risk factors. The intensity data may detect the reflectance difference of some segment from adjacent

Figure 6.
Slope map at a golf site created using ArcView. Note that the darker the steeper

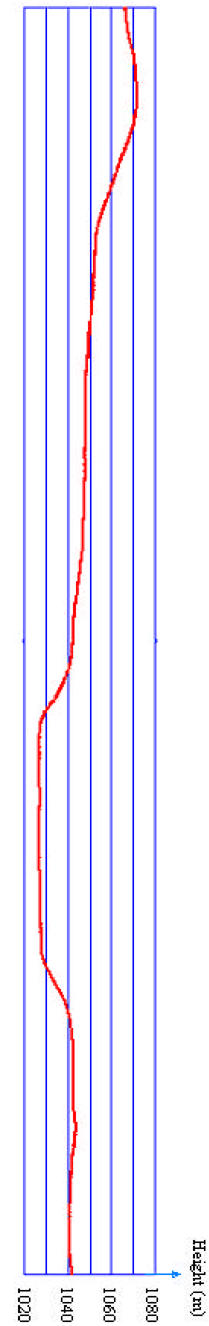

Figure 7.
Profile map along the pipeline created using TerraModeler (TerraSolid)

segments, and identify existing leaks.

- *Contour*: It is the most commonly used alternative representation of the terrain relief. A spill plume at any point on a pipeline could be calculated based on potential release volume and topography at the spill point. This ultimately identifies segments of the pipeline that could determine impact on high consequence areas.
- *Volume Computation*: Based on the contour map, split the ground along the contour planes into a series of horizontal slabs. Each slab being considered as a prismoid with the height equals the contour interval and end areas are the areas enclosed by the contour lines.
- *Profile*: The profile gives a visualization of terrain relief along a linear object, e.g., a pipeline (see Figure 7).
- *Shaded Relief DTM*. The shaded relief image is a powerful tool that is usually used to highlight structure within a digital terrain model (DTM). It simulates how a terrain surface would look if the sun were in different positions (defined as azimuth rotation from North, and elevation above the horizon). A sun shaded layer is normally set up as an intensity layer, so that it can be combined with a Pseudo-color layer to generate a color drape image.
- *Watershed and Drainage network*: A raster DTM contains sufficient information to determine general patterns of drainage and watersheds. Drainage modeling identifies cells located along the steepest downhill path extending from a target area (see Figure 8). To achieve this, the algorithm always chooses the direction of the maximum relief and the search stops at the location where no more downhill path can be found. Considering that each raster point as the centre of a square cell, the direction of flow of water out of this cell will be determined by the elevations of surrounding cells. Water is assumed to flow from each cell to the lowest of its neighbors and, if no neighbor is lower, the cell is a basin. Since in natural systems, small quantities of water generally flow overland, not in channels, we may want to accumulate water as it flows down stream through the cells so that channels being only when a threshold volume is reached.
- *Bald DEM generation and biomass estimation*. There are many algorithms developed for the generation of bald earth DEM from the lidar data (Tao and Hu, 2001). Then the difference data between the original range data and the generated bald DEM can be created. The penetration rate of laser beams mainly depends on the types of trees and season. Multiple returns allow the data to be analyzed and classified as vegetation, while the ground return allows DEMs of the bare ground to be generated and accurate tree heights to be calculated. Thus the derivation of other important parameters like biomass estimation, tree type etc. is possible. Information on tree heights and densities is difficult to collect using traditional methods. Accurate information on the terrain and topography beneath the tree canopy is extremely important to both the forestry industry and natural resource management.

Figure 8.
Drainage map created using TerraModeler (TerraSolid)

Lidar data can be used to produce orthoimage, which has the geometric properties of a map. Orthoimages are generated from aerial or satellite images through a process known as orthorectification. A original un-rectified aerial or satellite images does not show features in their correct locations due to displacements caused by the tilt of the sensor and the relief of the terrain. Orthorectification transforms the central projection of the image into an orthogonal view of the ground, thereby removing the distorting affects of tilt and terrain relief. Thus, orthoimage can be used as maps to make measurements and establish accurate geographic locations of pipelines.

PIPELINE MAPPING AND SAFETY APPLICATIONS

Pipeline Mapping

Because of the narrow scanning swath, airborne lidar is particularly suitable for rapid elevation data collection of pipelines in a cost-effective way.

The alignment sheet is the predominant method of recording pipeline location information for pipelines (see Figure 9). Alignment sheets are general purpose drawings based on a variety of surveying methods, including geographic coordinate system data, slack chain survey, electronic distance measuring, GPS, as well as local landmarks and legal descriptions. Any information that would commonly be used in an operational environment, by the pipeline operators, is depicted on these drawings. This information may be gathered from more detailed sources such as lidar data and synthesized.

There are also some specialty maps. These maps vary in scale and accuracy depending on the use of the map (i.e. strip maps, city maps, county highway maps). The purpose of these maps is to convey locational information about the pipeline system for various purposes including public relations, public awareness, one-call, emergency preparedness and response, and for public education. Sometimes pipeline maps are generated based on the county road system. County maps show the pipeline in relation to existing roads in order to describe the location to the public and assist personnel in accessing the pipeline. Generally, this type of map is produced by transposing location of the pipeline from the alignment sheets to county road maps. Minimal information, such as location and size of the pipelines, is shown on these maps and can be considered analogous to a dictionary of the pipeline (http://www.bts.gov/gis/reference/npms_content.html).

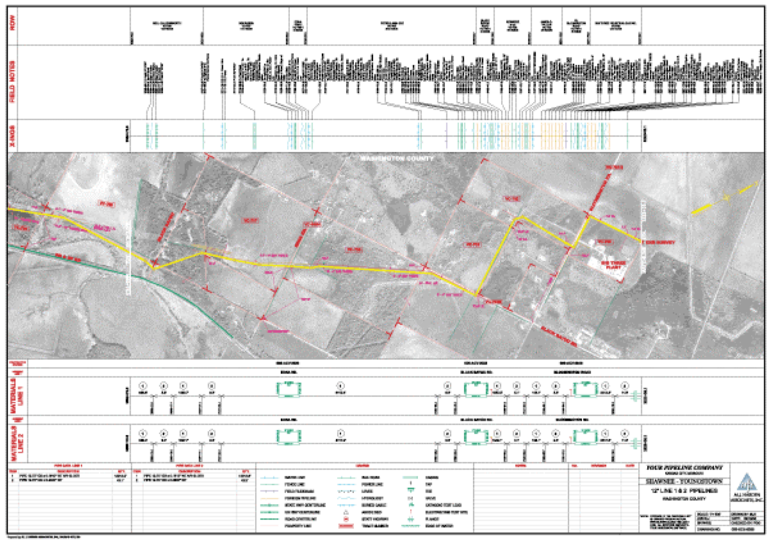

Figure 9.
An alignment sheet (MJHAI, 2002)

Pipeline Safety Applications

Lidar data has great potential in pipeline safety applications. Using the DTM derivative as well as other data sources, we can create a virtual picture to evaluate the pipeline safety rates.

Examining the derived terrain parameters, we can create a rating system along the length of the pipeline that would indicate corresponding levels of risk and predicate potential trouble spots or estimate the potential risk posed by vegetation and other features adjacent to pipeline. For example, we may be interested in highlighting any segment of a pipeline whose slope is greater than 30 degrees. To determine the high-risk segments of a pipeline from the viewpoint of natural disasters such as forest fire, we have to take into account some factors, such as sliding and fire risks. The sliding risk is subject to the slope. We can assume that a slope of 90 degrees is most dangerous, and a slope of zero has no danger. The fire risk is defined by the direction of prevailing hot winds, by the slopes that trend up from that direction, and by the vegetation biomass on those slopes. Slopes facing the prevailing wind and having high vegetation biomass are at high risk. Also, steeper slopes are at higher risk, as the flame front can travel quickly up the slope. So the pipeline risks are determined by slope, aspect, and biomass. Putting all these factors together, the risk rates can be estimated for each pipeline segments. We could generate a pseudo-color image of different risk levels according to the risk rates. We also could drape the high-risk rates over the original lidar data, and view the processed result in 3-D.

One specific problem that has garnered significant attention from the pipeline industry is the stress corrosion cracking (SCC). It is described as small cracks that appear on the outside of a pipeline. Over time, the cracks can grow and widen, eventually leading to a leak or rupture of the pipeline. Multiple variables affect stress corrosion cracking phenomena, such as stress level, alloy composition, microstructure, concentration of corrosive species, surface finish, micro-environmental surface effects, temperature, electrochemical potential, etc. The main external cause of SCC problem is moisture being trapped between the outer wall and the protective coating. The predicative models for SCC problem rely on accurate, reliable terrain data to determine soil drainages, which is an important initiating factor for SCC. As well, lidar data can be used to identify areas of slope instability that can place stress on the pipelines, increasing the risk of SCC ruptures. The predication of segments of pipelines at high-risk for internal corrosion could be done simply using slope values. If the slope and terrain data were combined with pipeline information such as gas or liquid type, operating line pressure and wall thickness, quantitative models could be derived to predict the ext ent of corrosion within a pipeline at each segment.

Because the 15 cm measure accuracy of lidar data is likely greater than the extent of erosion, in most cases erosion would not be reliably identifiable. So the suitability of lidar data for monitoring land erosion is limited, except for areas of extreme erosion. Change detection may be successful of the amount of topsoil that is eroded greatly exceeded the standard accuracy of lidar data. A more practical use of lidar data for land erosion monitoring purposes is to establish hydrologic models of the pipeline right-of-ways and the neighboring zones around them. In the past, hydrologic modeling has commonly been done on large areas with low-resolution terrain data. The same established principles can be applied to a small-scale project such as a linear pipeline right-of-way. By accurately modeling the drainage flow of water, soil erosion and deposition could be sketched. Thus zones with a high probability for erosion could be better observed and the effects mitigated. Having an erosion model is useful for future construction projects near the right-of-ways, where terrain changes may alter the drainage.

Terrain stability is an important aspect to monitor for pipeline maintenance. Areas of poor stability – due to the combination of improper soil conditions and steep slopes – can pose a risk to the structural integrity of nearby pipelines. Another concern for pipeline operators is the effect of permafrost on buried pipelines. As the permafrost thaws and refreezes, the ground can settle and potentially create problems for pipelines. Lidar technology could be applied to the terrain stability problems above in a few different ways. One possible application is for the pipeline operator to use slope maps to identify high-slope areas that require more intensive slope monitoring analyses to be conducted. Because of the dense coverage provided by lidar systems, slope shapes conducive to instability could also be identified. Another use of lidar data would be to acquire multiple DSMs and calculate a height change between acquisitions. This is possible because the lidar data is usually accurate enough to detect the change that is being observed. Thus, sinking or uplifting areas of the pipeline corridor could be automatically identified. A third application would be the use of high-resolution ortho-rectified photos or imagery to monitor the surface movement of objects. For this purpose, a high-accuracy DSM produced by lidar is necessary. The slope stability models could also be incorporated into a maintenance scheduling application.

Lidar range data can also be used to help deal with the leak detection issues. The extent of the damage caused by a leaking incident is largely influenced by the surrounding terrain. Terrain data for a given pipeline could be combined with the flow pressure models used in leak detection systems. The influence of hills and slopes could be modeled and incorporated into the system. While many pipeline operators are increasingly using tools like smart pigs and hydrostatic testing to monitor their pipeline integrity, it may not be practical or economical to conduct these tests on every segment of their transmission lines. By combining the predicted risks due to fire, SCC, internal corrosion, surface erosion and terrain stability into one unified model, maintenance supervisors could better prioritize their work schedules to emphasize monitoring of the highest risk zones.

If a pipeline carrying a toxic gaseous or heavy vapor product should rupture, the public is exposed to a potentially significant threat. During such an incident, emergency response crews would be responsible for planning safe evacuation routes for those who are affected. A valuable tool for emergency planners would be a GIS that incorporated real-time weather information in addition to the basic data layers. Using the weather data, a model could be derived to predict the flow of the toxic emissions. An important part of this model would be the DSM because the terrain of the surrounding land (or buildings in an

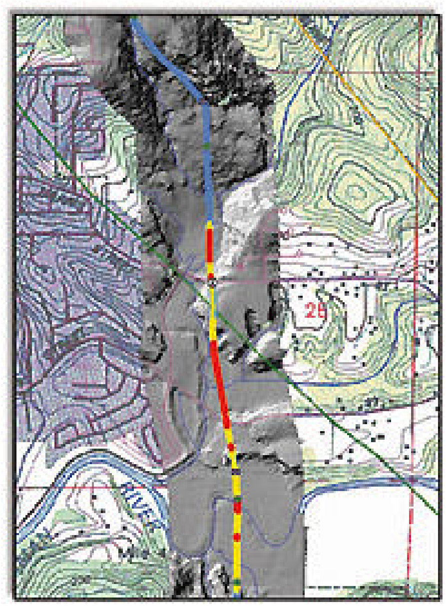

Figure 10.
A pipeline risk-rating map (Baker, 2001)

urban area) would influence the flow of the emissions. Gases eventually settle in low-lying regions or depressions in the ground. Thus, a combination of an accurate DSM and up-to-date wind information could be used to quickly predict and map the riskiest locations once a rupture has taken place.

Instead of utilizing the terrain information, the DIAL may be used to measure trace gas concentrations (McRae, 1996; Philippov, P. et al., 1998). This method is suitable for gas leakage detection during regular aerial patrols with small helicopter. It is based on the Beer-Lambert absorption law and on the absorption properties of the gas to be detected. In order to exclude atmospheric effects and diffuse reflection from the signal, two wavelengths were used for transmission. The first wavelength is absorbed by the gas, while the second is not absorbed and serve as a reference. In order to detect hydrocarbons such as methane or ethane from natural gas leak, the laser must be set to a wavelength at which these gases have appropriate absorption lines.

Lidar data is valuable in mitigating liquid product pipeline hazards. Slope information can be used to predict the volumes of product that would be discharged from a pipeline. An accurate DSM could be combined with other data in a GIS to create a drainage network that accurately represents the flow of liquid products from a ruptured line segment. The drainage network is critical in modeling a product's travel after a rupture. During an incident, emergency planners and response crews could predict where the most products would flow, allowing for the efficient construction of berms or ditches. Areas that have high natural drainage characteristics could be identified from the hydrological model. They could either be classified as spill containment regions or environmentally sensitive areas to be avoided, depending on other information within the GIS, such as land-use or vegetation coverage.

Figure 10 demonstrates a pipeline risk-rating map (Baker, 2001). The pipeline was segmented into three risk categories, the colored sections of this pipeline image depict where a geologic hazard could critically damage the structure. Red areas are high-risk, yellow are medium-risk, and blue are low-risk. This end product was created from a one-foot ground sample distance digital ortho-photo of the underground pipeline, supported by a lidar digital elevation model for identifying potential geo-hazards and by thermal sensor data for determine the exact location of the underground line.

CONCLUDING REMARKS

Safe pipeline transportation of energy resources is a major concern for the public and the pipeline industry. Today, the pipeline owners and operators are under increasing pressure to produce accurate maps of pipeline routes to assure safety in design, construction, operation, maintenance, and emergency response of pipeline facilities. Airborne lidar has been proven to be an effective technology for acquiring elevation data with high accuracy. Because of its narrow scanning swath in comparison to other sensors, airborne lidar is particularly suitable for rapid elevation data collection of pipeline routes in a cost-effective way compared with other elevation data collection systems, and should be considered for accurate pipeline mapping projects.

Lidar data can be used to produce orthoimages combining aerial or satellite images, which can facilitate measuring accurate locations of pipelines. It is easy to obtain many terrain parameters and produce DEM derivatives using lidar data. We can generate bald earth DEMs and estimate biomass in the vicinity of the pipeline routes. The terrain parameters can help locate steep slopes, which could endanger the pipeline structure. The derivatives can identify those segments having the highest risk factors. Putting the above information extracted from lidar data and possible other data sources together, the virtual picture of a risk rating system to evaluate the risk levels of different segments of a pipeline route can be created. This information can also help plan new lines, decide safer routes for placement of a pipeline, and improve the fast response ability in case of an accident.

Airborne lidar has great potential in assisting pipeline risk management and mitigating the hazards. Industrial and scientific advances in lidar systems and data processing techniques are opening new technological opportunities to develop an increased capability to accomplish the pipeline mapping and safety applications. The potential integration with other imaging technologies, such as optical, infrared, and SAR sensors, is expected to help pipeline risk managers solve safety problems and make decisions.

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