

Laser Scanning vs Digital Photogrammetry

Introduction

Laser scanning and digital photogrammetry are two different approaches that are often used to obtain the same result — a 3D model of a real-world scene.

Laser scanners operate by firing pulses of laser light in a known direction and waiting for the reflection. By measuring the direction the laser was fired in and the time it takes for the light to return, the scanner can determine the 3D location of the surface that the laser reflected off. By firing off a large number of pulses in a regular pattern (typically several thousand per second) the scanner is able to create a Digital Terrain Model (DTM) of the scene.

Digital photogrammetry, on the other hand, operates on images of a scene captured from different locations using a standard digital camera, creating one or more “stereo pairs”, in much the same way the human visual system works. Once the positions of the cameras are known¹, the 3D location of any point in the scene can be determined by locating that point in both images. By automatically locating common points in both images (also typically several thousand per second, depending on the speed of the PC) the digital photogrammetric system is also able to build up a DTM of the scene.

The different methods used by these two techniques result in differences in accuracy, range, speed, cost, and suitable application areas.

Accuracy

Data in the real world always contains errors. It is important to understand and accurately characterise this error, not only to ensure that the accuracy required for the application is being met, but also to ensure that time and money is not wasted providing data that is more accurate than required.

Laser Scanners

Laser scanner manufacturers publish a number of accuracy specifications for their products, including angular accuracy and beam divergence. Due to the nature of the operation of laser scanners, some of the factors affecting accuracy are largely independent of distance (e.g. the range accuracy), while others are roughly proportional to distance (e.g. the size of the beam footprint and the angular accuracy).

Derek Lichti and Stuart Gordon from Curtin University in Western Australia have successfully developed error models for scanners that take into account all of the relevant specifications and tested these models in real-world scenarios [1,2]. Their results show that the actual accuracy of the generated data can be significantly worse than expected from looking at the published specifications:

“...this demonstration shows that complete error modelling is necessary to rigorously quantify data quality. It is also likely that an inexperienced operator, perhaps lacking a geomatics background and unaware of the intricacies of error propagation, would quote the advertised coordinate precision (or, range precision, or whatever metric appears on the TLS [terrestrial laser scanner] sales brochure) as a quality indicator for the entire site.”

Wolfgang Boehler and Andreas Marbs from the University of Applied Sciences in Mainz, Germany, have also been testing the real-life accuracy of scanners using a standard test bench they have set up to allow scanners to be compared [3]. They have found that even the published specifications themselves must be treated with caution:

“The accuracy specifications given by laser scanner producers in their publications and pamphlets are not comparable. Experience shows that sometimes these should not be trusted and that the accuracy of these instruments which are built in small series varies from instrument to instrument

¹ This is generally determined automatically by the software from the images themselves rather than by direct measurement.

and depends on the individual calibration and the care that has been taken in handling the instrument since.

“Every point cloud produced by a laser scanner contains a considerable number of points that show gross errors. If the point cloud is delivered as a result of surveying, a quality guarantee, as possible for other surveying instruments, methods, and results, cannot be given.”

Ignoring bad points and inaccurate specifications, some of the factors that determine the accuracy of the data obtained from a laser scanner are:

1. The accuracy of the distance measurement derived from the laser beam itself. This tends to be fairly constant over the entire range of distances that the laser scanner supports, although there is a small distance-related component². The Riegl LMS Z420i advertises a value of ± 10 mm [5], while the I-Site 4400LR advertises a value of ± 50 mm [6].
2. The divergence of the laser beam as it travels from the scanner to the surface. This presents two problems:
 - (i) If the surface is not smooth and perpendicular to the scanner, this will result in multiple “returns” arriving at the scanner that must be combined in some way (e.g. by averaging them), and so the resulting 3D point is an “average” distance of the surface within the area covered by the beam. (“Average” is in quotes because variation in surface reflectance within the beam footprint means brighter areas will have more influence on the final value than darker areas if an average is attempted.)
 - (ii) The scanner assigns a 3D co-ordinate to the point using the direction the beam was fired in; however, the point(s) that reflected the beam could lie anywhere within the footprint. (In fact, a highly reflective surface *outside* the nominal beam footprint could be responsible for the detected reflection because the footprint is not a hard boundary; rather, the beam falls off in intensity as the radius increases, and so the footprint diameter is usually defined as the cone containing 86% of the total beam power [1].)

The I-Site 4400LR advertises a beam divergence of 1.4 mrad [6], or about 290 arc-seconds, which equates to a footprint of 700 mm at a distance of 500 m, and nearly 1 m at its maximum range of 700 m. The Riegl LMS Z420i advertises a beam divergence of 0.25 mrad [5], or 125 mm at 500 m and 250 mm at its maximum range of 1,000 m.

For many scanners, the divergence of the laser beam is the single largest factor contributing to the overall accuracy that can be achieved and a significant limit on the “resolution” (detail) of the surface model.

3. The accuracy of the angular measurements of the scanner. Like the beam’s divergence, the resulting error is proportional to distance. The I-Site 4400LR advertises an angular accuracy of $\pm 0.04^\circ$, or 144 arc-seconds, which equates to an accuracy of ± 350 mm at a distance of 500 m, while the Riegl LMS Z420i is advertised to have an “angular resolution”³ of $\pm 0.002^\circ$ vertically (7 arc-seconds) and $\pm 0.0025^\circ$ horizontally (9 arc-seconds), or about ± 20 mm at 500 m.
4. The accuracy of the registration of the 3D data in the appropriate co-ordinate system. The error associated with this depends both on the accuracy of the surveyed points used for orientation and the approach used to orient the scanner — i.e. directly, by centring and levelling it over a known point and back-sighting to a known location, or indirectly, by measuring the location of control points in the scan area and performing a resection. Using the first method, the accuracy of the levelling and back-sighting facilities are critically important [1], while with the second method, the geometry of the control points and the method used to observe them determines the registration accuracy [2]. The inclination sensors available for the Riegl LMS Z420i are advertised to have a vertical accuracy of $\pm 0.05^\circ$ [7], which translates into a vertical accuracy of ± 400 mm at 500 m — quite a significant source of error for this scanner. Lowering this value would seem to require extensive post-processing of the data to “fit” the point clouds to each other.

Digital Photogrammetry

There are three main factors that determine the accuracy of the data obtained using digital photogrammetry:

² There are actually quite a lot of factors affecting range accuracy [4], including temperature, pressure, humidity, signal-to-noise ratios, CO₂ concentrations, turbulence, etc., but vendors typically only supply a single value.

³ Note: Not accuracy! Nowhere does the actual *accuracy* of the angular measurements seem to be specified. Without this it is actually impossible to know how accurate the final data is.

1. The area, on the ground, covered by one pixel in the image. The data generated is generally accurate to about $1/3^{\text{rd}}$ of a pixel in the plane parallel to the image. (The “planimetric” accuracy.) The size of the pixel on the ground is determined by the focal length of the lens used and the distance from the camera to the pit wall. After deciding on a desired pixel size and preferred working distance, the user can then choose a lens that will give the desired result. (Conversely, given a lens and a desired pixel size, the user can calculate what distance the images need to be captured from in order to achieve it.) A Canon EOS 1Ds Mark II, for example, with a 28 mm lens from a distance of 100 m, will give pixels that are $26 \text{ mm} \times 26 \text{ mm}$ at the pit wall and a planimetric accuracy of about 10 mm. The same pixel size, and therefore the same results, can be achieved from a distance of 180 m with a 50 mm lens, or 360 m with a 100 mm lens, or 715 m with a 200 mm lens, and so on. The distance record for a 3DM Analyst user mapping pit walls for geotechnical analysis to date is a $30 \text{ mm} \times 30 \text{ mm}$ ground pixel size from 2.8 km away using a 300 mm lens with a $1.7 \times$ adapter on a Nikon D2x, while the accuracy record is held by a dentist measuring denture wear with a $10 \mu\text{m} \times 10 \mu\text{m}$ ground pixel size using a 160 mm macro lens from 160 mm away, achieving depth accuracies of $15 \mu\text{m}$ and planimetric accuracies of $5 \mu\text{m}$.
2. The relationship between the distance between the cameras (the “base”) and the distance from the cameras to the pit wall, known as the base-to-distance ratio. At a base-to-distance ratio of 1:1, the depth accuracy of the 3D data will be the same as the planimetric accuracy. At a ratio of 1:2, it will be half as accurate. Typical ratios range from 1:2 through to 1:5, with the user generally free to choose a convenient ratio that matches their accuracy requirement.
3. The accuracy of the registration of the 3D data in the appropriate co-ordinate system. This is primarily dependent on the accuracy of the surveyed data (control points and/or camera stations) used for orientations — the actual observation of the control points in the software generally doesn’t add a measurable amount of error.

Apart from the accuracy of the surveying, which affects both laser scanning and photogrammetry, the accuracy of the 3D data therefore depends on the relationship between the lens focal length and the distance, and the base-to-distance ratio. The user is free to operate from whatever distance is most convenient and simply chooses the lens and the base-to-distance ratio to fit the accuracy requirements of the job. Unlike laser scanners, the planimetric accuracy is typically more accurate than the depth accuracy (it is usually the other way around for laser scanners), and neither depends on the working distance provided appropriate lenses are available (although atmospheric refraction and earth curvature need to be corrected for over larger distances).

Table 1 gives an indication of how accuracies and point cloud densities compare with two different laser scanners and a range of different camera/lens configurations at different distances and different bases, ignoring the error introduced by the registration of the data in the 3D co-ordinate system. Note that even from twice as far away, it is not difficult to meet even the depth accuracy of the best long-range scanner on the market and far exceed the planimetric accuracy of that scanner with a camera and lens combination that costs less than $1/10^{\text{th}}$ of the price of the scanner. If less detail and accuracy are required, shorter focal length lenses and/or greater distances can be used to increase the ground pixel size and reduce the number of images required — the accuracy and density of the final data is entirely up to the user.

Range

The effective range of a laser scanner depends largely on its ability to detect the reflected light. This also depends on the reflectivity of the surface, so darker surfaces have lower maximum ranges than lighter surfaces. The maximum distances specified typically include a statement on the assumed reflectivity of the surface.

The specified maximum range of the I-Site 4400LR, for example, is 150 m for black coal (5–10% reflectivity), 600 m for rock and concrete (40–50% reflectivity), and up to 700 m for “higher reflectivity surfaces”. The Riegl LMS Z420i is specified as having a maximum range of 350 m (10% reflectivity) up to 1,000 m (80% reflectivity). (Note that these ranges can also be reduced by high ambient light levels; i.e. the range is greater on overcast days than it is on bright, sunny days⁴. Due to the lowering of the signal-to-noise ratio (i.e. the strength of the laser beam relative to the background light levels) this can also have a significant impact on the accuracy of the distance measurement [4].)

Typical operating ranges for many scanners in the mining environment are often in the 100 m to 600 m range. For larger pits, this often means placing the scanner on the pit floor when scanning pit walls, which may also make it impossible to scan the upper benches and even the tops of the lower benches.

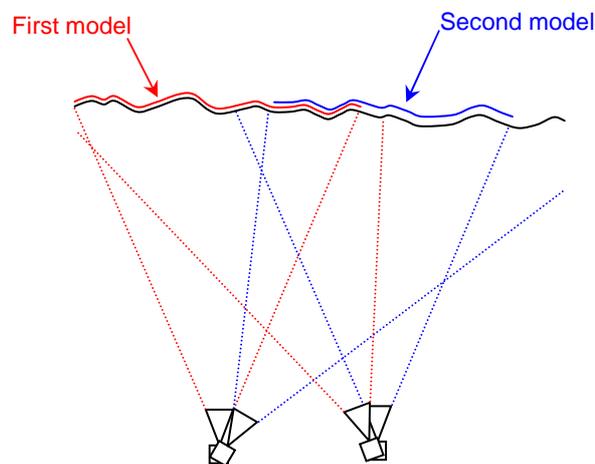
⁴ “In bright sunlight, the operational range is considerably shorter than under an overcast sky.” [5]

Table 1. Accuracy comparison

	I-Site 4400LR	Riegl LMS Z420i	Nikon D2x + 180mm lens	Nikon D2x + 400mm lens	Nikon D2x + 400mm lens
Distance	600 m	600 m	600 m ⁵	1200 m ⁶	1200 m ⁷
Pixel size	400 mm ⁸	20 mm ⁹	18 mm	17 mm	17 mm
Beam footprint	840 mm	150 mm	N/A	N/A	N/A
Planimetric accuracy	470 mm	46 mm	6 mm	5 mm	5 mm
Depth accuracy	50 mm	10 mm	16 mm	15 mm	10 mm
Overall accuracy	665 mm	65 mm	18 mm	16 mm	12 mm
Point cloud spacing	1,130 mm	42 mm	74 mm	66 mm	66 mm

Photogrammetry is very flexible when it comes to range. The same technique can be used on any scale — from a few centimetres, using a macro lens to achieve point cloud densities in excess of 1,000 points per square millimetre, to astronomical distances, measuring the locations of nearby stars. Photogrammetry is used every day by mapping organisations (including those with ADAM software and hardware) to make maps from aerial photographs (distances in the 6,000 m range) or even satellite images (around 600 km).

This gives a great deal of flexibility to the user — as shown in the previous section, changing to a lens with double the focal length allows an image to be captured from twice as far away with very little effect on the results. BHP Billiton Iron Ore routinely use distances of up to 1,200 m using image fans (Figure 1) with up to 20 images captured from each camera location because it minimises the number of different locations required to capture the pit wall, while Escondida mine in Chile has been mapped with a 3 cm pixel size on the ground from a distance of 2.8 km away, as mentioned in the previous section. Using this technique allows extremely large areas to be captured and modelled very quickly with minimal field work.

**Figure 1. Image fans.**

⁵ Base 200 m.

⁶ Base 400 m.

⁷ Base 600 m.

⁸ The 4400LR uses a line scanner with an 80° vertical field-of-view and 2520 pixels vertically, with a 20 mm Nikon lens. The horizontal pixel size, based on the supplied information, would be about 225 mm at 600 m.

⁹ Using the Nikon D200 with optional 180 mm lens to give the smallest pixel size. Note: The vertical field-of-view of the camera with this lens is only 7.5°, less than 10% of the scanner's vertical field-of-view.

3DM CalibCam, the terrestrial block adjustment package sold as part of 3DM Analyst Mine Mapping Suite, also supports the merging of any number of images captured from the same location to create images of arbitrary size and resolution with any camera (Figure 2). The merged images are colour balanced, have lens distortions removed, and are matched to within $1/10^{\text{th}}$ of a pixel, making them suitable for use in 3DM Analyst if desired. 3DM Analyst supports images of up to 65 megapixels, while 3DM Analyst Professional (used by mapping organisations) supports images in excess of 250 megapixels.



Figure 2. Pair of images captured from the same location merged into a single large image by 3DM CalibCam. Black areas around the image show how far pixels were moved to remove distortions.

Speed

The advent of digital photography has had an enormous impact on photogrammetry.

In the past, after capturing the images, the film had to be processed, and then the 3D data captured manually by an experienced stereoplotter operator, often introducing a delay of several days. Now the 3D data can be ready for use less than 10 minutes after the images are captured, almost completely automatically.

The time required in the field remains much the same as before, but this has always been a strong point of photogrammetry — it takes far less time (and manual effort!) to capture an image with a digital camera than it does to set up a laser scanner and perform a scan. It also doesn't require much skill — even a junior surveyor can be taught how to point a camera and capture an image, and if they make a mistake it will be obvious when the images are being processed, so the staff member who is going to be held accountable for the accuracy of the data does not need to be involved with the acquisition of the images. With a laser scanner, however, that same staff member might want to pay close attention to the setting up and operation of the scanner before being willing to stand by the results.

Control points also needn't be a burden — using 3DM CalibCam only a few control points are needed even if large numbers of images are used, and those points can be permanent so they don't need to be placed and surveyed every time; many customers have control points that last *years*.

Mathematically, only three known locations (camera stations and/or control points) are required for the entire project, although we usually recommend more to provide redundancy and improve accuracy. (One aerial project from a customer with 35 images capturing 7 km of pit was adequately controlled using just *seven* points!) Note, also, that control points do *not* need to be placed in dangerous locations — as long as overlapping images can be captured from the controlled area to the uncontrolled area, all of the data in the project can be georeferenced. (In fact, existing images that have already been georeferenced in the past can be used to control new images even if the existing images themselves don't have any control in them.)

The best case scenario for photogrammetry is mapping a large area where the camera can be placed far away so that image fanning can be used — it only takes a few seconds to rotate the camera slightly and capture another few hundred metres of pit wall, while the scanner needs to be moved and set up multiple times. In one recent

example, 178 images were captured from three different locations to map a 2.2 km x 600 m section of a pit wall with a ground pixel size of 5 cm from 1.4 km away. It took just four minutes on average at each camera station to capture the images, and seven minutes on average to pack up at one camera station, travel to the next, and start capturing images again.

Another difference is that with photogrammetry, the time-consuming task of generating 3D data doesn't need to be done in the field — it can be performed back at the office, and even batch-processed and done overnight or in the background while the user gets on with other work. On a 2.4 GHz dual-core PC, 3DM Analyst Mine Mapping Suite can generate between 3,000 and 7,000 points per second; with the 3.0 GHz quad-core PCs now on the market the software can generate 10,000 to 15,000 points per second, and will continue to improve as computers continue to get faster.

Applications

Both photogrammetry and laser scanners can be used for surveying, topological mapping, and stockpile volume measurement.

Laser scanners can have an advantage in very small pits or enclosed areas like buildings because most can scan 360 degrees and pick up the entire area from a single location. Using photogrammetry requires many images to achieve a similar result, because the field of view of each image is typically limited to about 90 degrees, although underground tunnel mapping using 3DM Analyst has shown that even this isn't overly burdensome.

Photogrammetry has a big advantage in large open spaces, however, for the reasons outlined above. It also has an advantage in geotech applications because these often require very fine detail in the images (i.e. a small ground pixel size) so they may be interpreted, requiring the scanner to be placed inconveniently close to the pit wall and requiring many more scans to be performed to capture the entire area (assuming that the depth accuracy of the laser scanner is sufficient, since this is constant and can't be improved by moving the scanner closer).

Photogrammetry also has the advantage of being equally at home with aerial images, terrestrial images of a pit wall, and images underground or even underwater. With cost-effective autonomous UAVs now on the market (e.g. Rotomotion's SR20 and SR100 [8]) able to be pre-programmed with the desired camera co-ordinates and to capture aerial images autonomously, aerial mapping of mining pits and stockpiles has never before been as accessible and as cost-effective as it is now. What used to be an expensive service that was outsourced to professional mapping companies can now be done in-house by existing staff with minimal additional training.

Of course, being a passive user of light rather than an active emitter of light, photogrammetry relies on an external light source to illuminate the scene. For a large open pit this means photogrammetry can only be used in daylight hours; underground and in other small spaces, flashes or other light sources can easily be used. Both photogrammetry and laser scanners have problems when there is too much dust, fog, or rain, although in the case of photogrammetry this is more likely to produce holes in the point cloud than spurious points in mid-air that must be removed.

Ease of Use

Laser scanners are conceptually very similar to total stations, so very little training should be required by most surveyors in order to learn how to use one. (Effectively predicting the *accuracy* of the result, however, can require quite a lot of training.)

Photogrammetry is less likely to be familiar to existing personnel. In fact, many surveyors have a fairly negative view of it due to their exposure to it at college many years ago prior to the advent of digital photogrammetry, when everything had to be done manually.

3DM Analyst Mine Mapping Suite has been designed to be used by anybody with very little training. Although we recommend a four or five day training course to ensure as many scenarios as possible can be covered during training, some of our most productive customers — including customers with no background in the spatial sciences — have had no training at all. The theory behind the operation of the software is actually quite simple to grasp — most of the training consists of performing actual projects on the client's mine to ensure they have had plenty of practice by the time the course is over.

If the user does do anything wrong, the software has extensive troubleshooting capabilities that allow it to pinpoint what the problem is and direct the user on the best approach to solve the problem.

Less than half of the customers using our software are actually qualified in the spatial sciences (i.e. surveyors and photogrammetrists). Other users include geologists, engineers, a dentist, and an ROV (remote-control

submarine) operator with no prior experience in the concepts underlying photogrammetry (or surveying, for that matter).

Cost

Laser scanners suitable for mining are very complex instruments and tend to be very expensive — typically four or more times more expensive than a complete 3DM Analyst Mine Mapping Suite solution, with an annual maintenance fee that would pay for another 3DM Analyst suite licence about every two years.

In addition to costing much less, the parts of the digital photogrammetric system that are susceptible to breaking down — the digital camera and the PC used to run the software — represent a relatively small proportion of the overall cost, and are readily available from multiple suppliers. Even having a backup camera is a feasible option in case the camera breaks down at a critical time. One customer on a trip to an overseas site discovered their camera was damaged in transit; they ordered a replacement camera over the Internet and it arrived the next day. They then proceeded to capture their images and calibrated the camera “online” in 3DM CalibCam using those same images; if they weren’t able to for some reason, they could have always taken other images once they returned to the office and calibrated the camera then.

Future Improvement

The performance (both speed and accuracy) of a laser scanner is determined at the time it was manufactured. Any improvements require the manufacturer to physically upgrade components or replace the scanner altogether, generally at considerable cost.

The performance of the digital photogrammetric software, however, is determined by the efficiency of the software and the speed of the PC it is running on. PCs increase in performance all the time — CPU manufacturing is an enormous industry where manufacturers like AMD and Intel literally spend billions of dollars in R&D every year trying to make them go faster, which they then amortise over hundreds of millions of CPUs. Periodically buying a new \$2,000 PC can double the performance of the software instantly. ADAM, too, is continually working to improve the performance of the software — even on the same PC, the speed of 3DM Analyst Mine Mapping Suite nearly doubled from version 2.1 to version 2.2, and more than doubled *again* from version 2.2 to version 2.3! With PC speeds increasing *as well* during that time, the software now runs a factor of 10 times faster on new \$2,000 PC than it did on a new \$2,000 PC just two years ago. If just 10% of the money saved buying 3DM Analyst Mine Mapping Suite instead of a laser scanner was used to purchase a high-end computer, the throughput of the software could *easily* exceed the performance of even the fastest long-range terrestrial laser scanner — and that’s not even taking into account the time normally required to post-process laser scanner data, which can be a factor of ten times longer than the time needed to perform the actual scan itself [9].

Digital cameras also continue to improve rapidly — using a higher resolution camera reduces the time in the field, further boosting productivity.

Conclusion

Both laser scanners and photogrammetric techniques have strengths and weaknesses. In the mining environment, however, photogrammetry has advantages in many areas, including its flexibility due to its inherent accuracy and range characteristics, especially when it comes to large, open-pit mines, as well as its price competitiveness.

With the advent of digital photography and new digital photogrammetric software packages like 3DM Analyst especially designed to work with digital cameras, photogrammetry has reached a new level of convenience, speed, and flexibility that allows its traditional strengths of range and accuracy to be far more accessible than in the past.

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