GEOMATICS I

Terrestrial laser scanning systems

CONTENTS

The notes on the Terrestrial laser scanner give the basic information to understand the main components and to plan a metric survey by using mainly this technique.

GEOMATICS I

ERAMCA
Co-funded by the Erasmus+ Programme of the European Union
Environmental Risk Assessment and Mitigation on Cultural Heritage assets in Central Asia
ERASMUS+ CBHE Project nr. 609574

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1. Introduction

Risk assessment is the process where hazards are identified, analyzed, or evaluated for the risk associated with those hazard, to determine appropriate ways to eliminate or control the hazard threat practical terms, a risk assessment is a thorough look at a workplace, building or environment to identify those elements, situations, processes,. etc that may cause harm, particularly to people.

After identification, an evaluation is made of how likely and severe the risk is, which helps in deciding what measures should be in place to prevent or control the harm from happen.

The Risk Assessment process can be summarized as follows (Fig. 1):

- Risk identification and assessment: determining and analyzing the potential, origin, characteristics, and behavior of the hazard – e.g., frequency of occurrence/magnitude of consequences
- Potential Risk Treatments :
  - Reduction: planning and implementation of structural interventions (e.g., dams, dikes) or non-structural measures like disaster legislation
  - Early warning: provision of timely and practical information, through identified institutions, that allow individuals exposed to a hazard to take action to avoid or reduce their risk and prepare for effective response
  - Disaster preparedness and emergency management: activities and measures taken in advance to ensure adequate response to the impact of a hazard, including measures related to timely and effective warnings as well as to evacuation and emergency planning
  - Recovery/Reconstruction: decisions and actions taken in the post-disaster phase with a view to restoring the living conditions of the affected population.

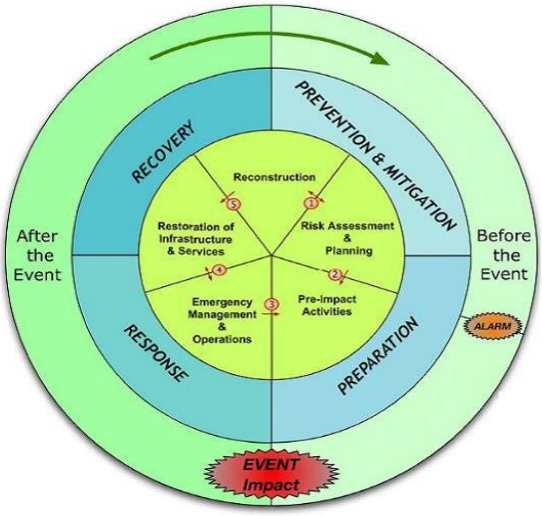


Figure 1 – Risk Management Cycle

Proper risk assessment or risk management requires up to date information, a possible rapid response, accurate data and a possibility to check data for change in a certain time-span. This is exactly what laser scanners do best.

Laser scanners are used for risk assessment in a wide variety of applications:

- Analysing the structural state of a building in danger of collapse

- Assessing possible deformations of structures over time due to external or internal forces
- Detecting possible flooding zones by analyzing the topographical terrain
- Simulation of landslides or earthquakes
- Condition assessment and safety analysis of roads and bridges
- Documenting disaster areas when disaster has already occurred; this includes building collapses, roadway defects, structural failures, damaged vehicles; collision areas, including roadways, shipping docks, parking lots and stairways; the remnants of building fires; interference checks with new designs and as-built scan databases
- Recording crime scenes (comparison of damage profiles, no disturbance of the evidence, incorporates the environment, quick clearance of the scene)
- Surveying high-traffic areas without shutdowns or risk to a survey crew
- Conducting remote and accurate measurements of rock faces (danger of rock falling)
- Tsunami simulation
- GIS mapping: location of people affected and critical infrastructures such as hospitals or fire departments.

1.1 What is Laser Scanning?

Laser Scanning describes a method where a surface is sampled or scanned using laser technology. It analyzes a real-world or object environment to collect data on its shape and possibly its appearance (e.g. color). The collected data can then be used to construct digital, two-dimensional drawings or three-dimensional models useful for various applications.

The advantage of laser scanning is that it can record huge numbers of points with high accuracy in a relatively short time. It period a photograph with depth information. Laser scanners are line-of-sight instruments, so to ensure complete coverage of a structure multiple scan positions are required.

1.2 Static and dynamic laser scanning

Current laser scanner technology can be divided into two categories: static and dynamic.

When the scanner is kept in a fixed position during the data acquisition, it is called static laser scanning. The advantages of using this method are the high precision and its relatively high point density. All static laser scanning can be seen as terrestrial laser scanning; however, not all terrestrial laser scanning can be categorized as static laser scanning.

In cases of dynamic laser scanning, the scanner is mounted on a mobile platform. These systems require different positioning systems such as INS and GPS, making the system more complex and expensive. Examples of dynamic laser scanning are scanning from an airplane (airborne laser scanning), scanning moving car, or an unmanned aerial vehicle (UAV).

These notes focus on static laser scanning.

1.3 Applications of laser scanning

In the early stages, laser scanning was short-range and mainly used in the automotive and industrial design process to facilitate the Computer-Aided Design (CAD) process. This helped in the mass production of consumer products.

However, since technology keeps evolving, other potential fields are exploited. Mid-range scanners were developed for the petrochemical industry. Due to the complexity of plants, which were only documented as 2D drawings, laser scanning led to the full 3D management of sites.

Because the obvious advantages of laser scanning like: non-contact measurement, high accuracy, long range, fast data acquisition, etc., other disciplines like cultural heritage, architecture, urban development, forensics, and the entertainment industry are starting to steadily adopt this technology (see Fig. 2)

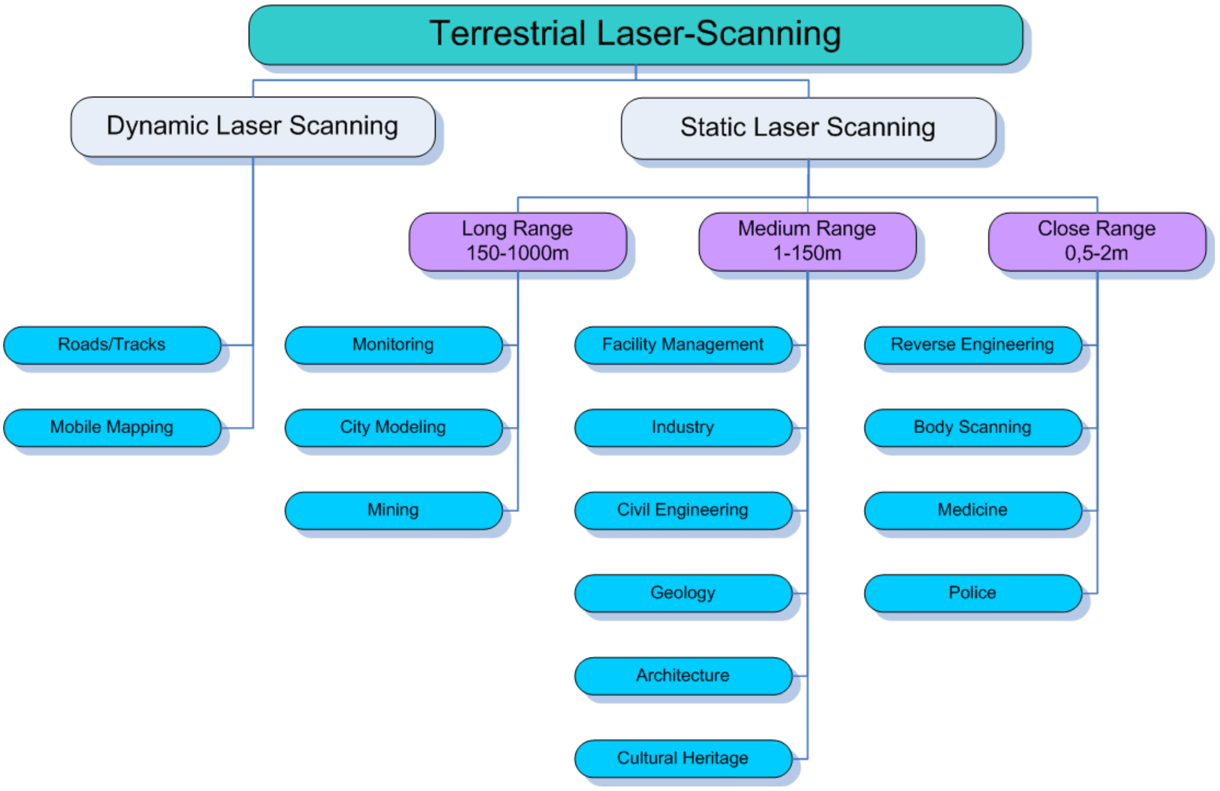


Figure 2 – Laser scanner applications

2. Principles of laser scanning

2.1 The electromagnetic spectrum and light

The electromagnetic spectrum is more familiar to you than might be thought. The microwave you use to heat your food and the cell phones you use, use parts of the electromagnetic spectrum. The reason we see objects, is because they emit, reflect or transmit a part of the visible part of the spectrum that we call light. This visible part of the electromagnetic spectrum consists of the colors that we see in a rainbow - from reds and oranges, through blues and purples.

Each of these colors actually corresponds to a different wavelength of light. We can see this if we pass white light through a glass prism - the violet light is bent ("refracted") more than the red, because it has a shorter wavelength - and we see a rainbow of colors.

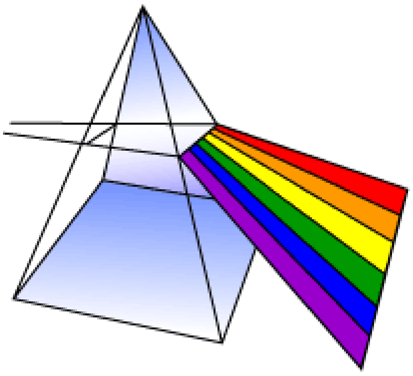


Figure 3 – Prism converting white light into its different colors

Waves in the electromagnetic spectrum vary in size from very long radio waves (the size of buildings), to very short gamma-rays smaller than the size of the nucleus of an atom.

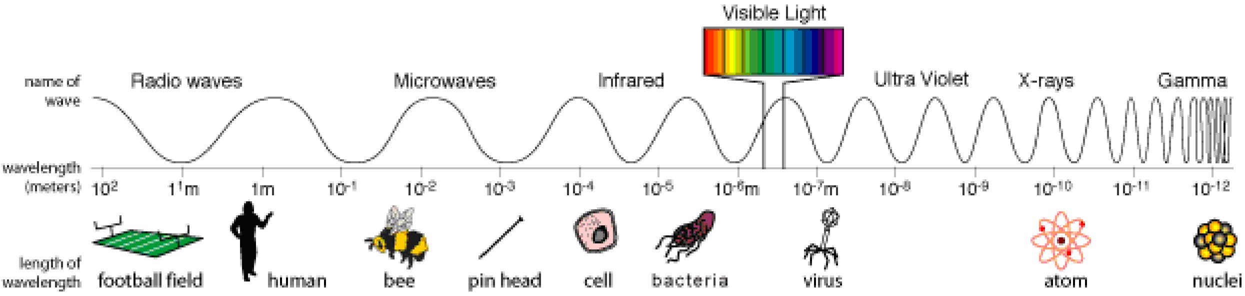


Figure 4 – The electromagnetic spectrum

The electromagnetic spectrum can be expressed in terms of its energy, its wavelength or its frequency. These quantities are related according to the following equations:

$$wavespeed\ (c) = frequency(f) \cdot wavelenght(\lambda)$$

and

$$energy(E) = h \cdot frequency(f) = \frac{h \cdot wavespeed(c)}{wavelenght(\lambda)}$$

where:

c is the speed of light (299,792,458 m/s)

h is Planck's constant (6.626069.10-34 J·s).

So, high-frequency electromagnetic waves have short wavelengths and high energy; and vice-versa, low-frequency waves have long wavelengths and low energy.

2.2 Lasers

A device that is able to generate a wave of light using only a very narrow band of the spectrum is called a laser. A typical laser emits light in a narrow, low-divergence beam with a well-defined wavelength (corresponding to a particular colour if the laser is operating in the visible spectrum). This is in contrast to a light source such as the incandescent light bulb, which emits into a large solid angle and over a wide spectrum of wavelengths. These properties can be summarized in the term coherence.

Lasers are actually similar to transistors, they generate or amplify light, just as transistors generate and amplify electronic signals at audio, radio or microwave frequencies. The word laser is an acronym for Light Amplification by Stimulated Emission of Radiation. The first working laser was demonstrated in May 1960 by Theodore Maiman at Hughes Research Laboratories.

Lasers are used in everyday life, especially in optical storage devices such as compact disc and DVD players, in which the laser scans the surface of the disc for data retrieval. Other common applications of lasers are bar code readers and laser pointers. In industry, lasers are used for cutting steel and other metals and for inscribing patterns such as the letters on computer keyboards. Lasers are also used for military and medical applications.

2.3 Important properties of laser light

Laser light is simply light generated with a laser device. Such light has some very special properties, which distinguish it from light from other origins:

- Laser light is generated in the form of a laser beam. Such a laser beam has a high (sometimes extremely high) degree of spatial coherence, therefore it propagates dominantly in a well-defined direction with moderate beam divergence. The term coherence means that the electric signal at different locations across the beam profile oscillates with a rigid phase relationship. This coherence is the reason why a laser beam can propagate over long distances and can be focused to very small spots.
- Laser light also has a high degree of temporal coherence (in most cases), which is equivalent to a long coherence length. Long coherence lengths imply a rigid phase relationship over relatively long time intervals, which correspond to large propagation distances (often many kilometres).
- Combining a large temporal coherence with a large coherence time or coherence length results in a narrow spectral bandwidth (or line width). This means that visible laser beams have a certain pure colour, e.g. red, green or blue, but not white or magenta For instance, most lasers used in close range and mid-range measuring devices have a wavelength of 1064 nm (near infrared) or 532 nm (green laser). It should be noted that a large coherence length introduces a tendency for the phenomenon of laser speckle, i.e., a characteristic granular pattern which can be observed. This effect can be noticed for instance when a laser beam hits a metallic surface.
- In most cases, laser light is linearly polarized. This means that the electric field oscillates in a particular spatial direction.

Depending on the application, laser light can have other remarkable properties:

- Laser light may be visible, but most lasers actually emit in other spectral regions, in particular the near infrared region, which human eyes cannot perceive.
- Laser light is not always continuous, but may be delivered in the form of short or ultra-short

pulses. As a consequence, the peak power can be extremely high.

Because of its coherence properties, laser beams stay in focus when projected on a distant scene. Another fundamental property of (laser) light waves is their velocity of propagation. Light waves travel with a finite and constant velocity in a certain medium. Because of these properties, laser light is highly suited to the measurement of objects. How this is done will be explained in the following paragraphs.

2.4 Laser safety

Lasers are used in a wide variety of applications including, scientific, military, medical, and commercial fields; all developed since the invention of the laser in 1958. The coherency, high monochromatic, and ability to reach extreme powers are all properties that allow for these specialized applications. Therefore, laser light should be handled with extreme caution, and an understanding of laser types becomes necessary.

To enable users to determine the potential risk, all lasers and devices that use lasers are labeled with a classification, depending on the wavelength and power of the energy the laser produces. The European Standard [3] provides information on laser classes and precautions. It outlines seven classes of lasers:

- Class 1 lasers are safe under reasonably foreseeable conditions of operation, including the use of optical instruments for intra-beam viewing.
- Class 1M lasers are safe under reasonably foreseeable conditions of operation but may be hazardous if optics are employed within the beam.
- Class 2 lasers normally evoke a blink reflex that protects the eye; this reaction is expected to provide adequate protection under reasonably foreseeable conditions, including the use of optical instruments for intra-beam viewing.
- Class 2M lasers normally evoke a blink reflex that protects the eye, this reaction is expected to provide adequate protection under reasonably foreseeable conditions. However, viewing of the output may be more hazardous if the user employs optics within the beam.
- Class 3R lasers are potentially hazardous where direct intra-beam viewing is involved, although the risk is lower than that for Class 3B lasers.
- Class 3B lasers are normally hazardous when direct intra-beam exposure occurs, although viewing diffuse reflections is normally safe. This class of laser is generally not suited for survey applications.
- Class 4 lasers will cause eye or skin damage if viewed directly. Lasers of this class are also capable of producing hazardous reflections. This class of laser is not suited for survey applications.

Users of laser scanning systems should always be aware of the class of their instrument. In particular, the user should ensure that the correct classification system is being used. (Refer to the IEC standard for more information on laser safety [3]).

Particular precautions and procedures are outlined in the IEC standard for Class 1M, Class 2M and Class 3R laser products used in surveying, alignment and levelling. Those precautions, with relevance to laser scanning are:

- Only qualified and trained persons should be assigned to install, adjust and operate the laser equipment.
- Areas where these lasers are used should be posted with an appropriate laser warning sign.

- Precautions should be taken to ensure that persons do not look into the beam (prolonged intra-beam viewing can be hazardous). Direct viewing of the beam through optical instruments (theodolites, etc) may also be hazardous.
- Precautions should be taken to ensure that the laser beam is not unintentionally directed at mirror-like (specular) surfaces.
- When not in use the laser should be stored in a location where unauthorized personnel cannot gain access.
- In potentially explosive environments (e.g. petrochemical plants, mining), special 'explosion proof' laser equipment should be used. Important properties of explosion proof equipment are: peak power of the laser should be limited, no spark generation, and the maximum temperature of the equipment should be limited.

2.5 Measuring using light

Because of recent developments in computer vision and sensor technology, light has been used in a number of ways to measure objects. These measuring techniques can be divided into two categories: active and passive techniques.

Passive scanners do not emit any kind of radiation themselves but instead, rely on detecting reflected ambient radiation. Most scanners of this type detect visible light because it is a readily available ambient radiation. Other types of radiation, such as infrared could also be used. Passive methods can be very cheap because in most cases they do not need particular hardware other than a digital camera. The problem with these techniques is that they rely on finding correspondences between 2D images, which do not always have unique solutions. For example, repetitive patterns tend to 'fool' the measurement method. The accuracy of these methods depends mostly on the resolution of the imaging system and the density of identifiable features in the image.

In these notes, we will concentrate on active measurement techniques. Active scanners emit some kind of controlled radiation and detect its reflection in order to probe an object or environment. Possible types of radiation used include light, ultrasound, or x-ray. Since these active measurement techniques require a laser transmitter and a receiver, they are mechanically more complex than passive techniques. The main benefits of these systems are:

- They do not require ambient lighting, because they generate their own radiation;
- They provide high-density measurements in a very automated way;
- They are useable on featureless surfaces;
- They have a relatively fast acquisition time (1000 – 500.000 pts/sec).

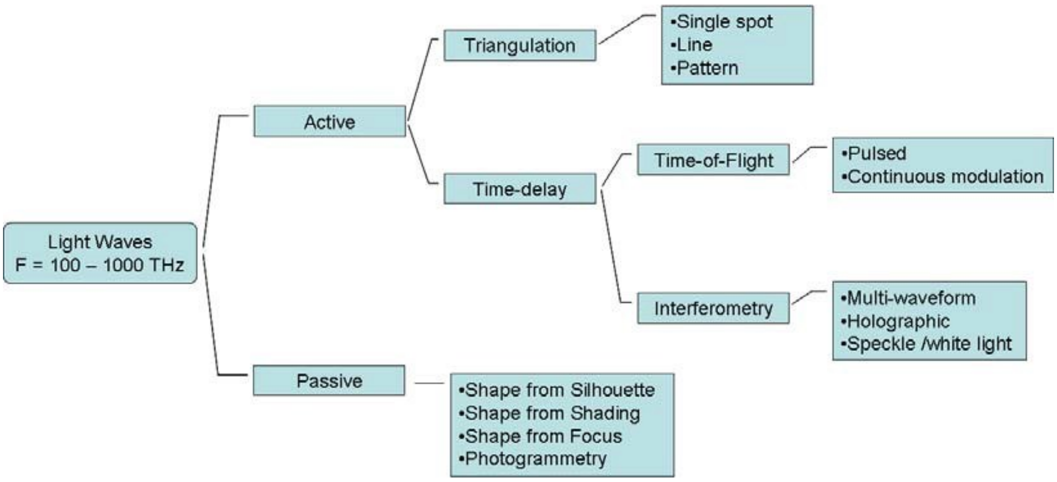


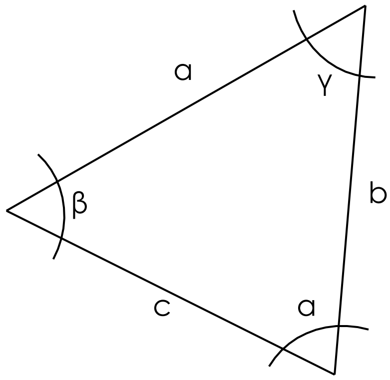
Figure 5 – Categorisation of measuring methods using light

However, some active systems are affected by external light sources, reflectivity, color and roughness. These drawbacks will be discussed at a later point.

A number of active scanners exist, all differing in the way the scanner receives and/or analyses the reflected radiation signal. In the next chapters, these different types of active scanners are described in more detail.

2.5.1 *Triangulation-based based measurement*

Triangles are the basis of many measurement techniques. They were already used for basic geodetic measurements in Ancient Greece and can still be found in modern laser-based 3D cameras. The mathematical basis of the triangle (trigonometry), which is the basis of these triangulation-based measurement techniques, has to be credited to the Greek philosopher Thales (6th century BC).



$$\frac{a}{sin\alpha} = \frac{b}{sin\beta} = \frac{c}{sin\gamma}$$

$$a^2 = b^2 + c^2 - 2bc \cdot cos\alpha$$

$$c = a \cdot cos\beta + b \cdot cos\alpha$$

Figure 6 – Triangulation principle

A triangulation laser scanner uses the same principle to probe the environment. It shines a laser pattern onto the subject and exploits a camera to look for the location of the laser's projection on the object. The laser emitter and the camera are set up under a constant angle, creating a triangle between them and the laser projection on the object, hence the name triangulation. Because of this configuration, the laser projection changes in the camera's field of view depending on the distance to the camera.

Analyzing Figure 7 shows that on the triangle side (D), the distance between the camera and the laser emitter, is known. The angle of the laser emitter (α) is also known. The angle of the camera (β) can be determined by looking at the location of the laser beam in the camera's field of view. These three pieces of information fully determine the shape and size of the triangle and provide the exact depth location of the object being measured.

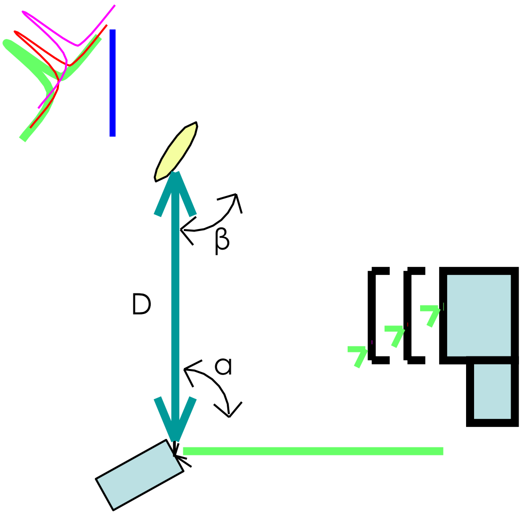


Figure 7 – Triangulation Laser Scanning Principle

It can be shown that, the wider the baseline (D), the less effect errors in pixel coordinates have on the estimate of the depth location. However, the baseline cannot be made very large because then the laser projector and the camera would have a reduced overlapping field of view (FOV) and the laser spot may not be captured in the camera image at all.

As a summary, possible ways to decrease the uncertainty in the depth direction are:

- Decreasing the distance of the object to the scanner → increases shadow effects
- Increasing the triangulation base (D) → also increases shadow effects
- Increasing the lens focal length → reduces the field of view
- Decreasing the measurement uncertainty → more pixels in the camera

In most cases a laser line, instead of a single laser dot, is used and swept across the object to acquire the whole object in 3D. This means that the angle of the laser emitter also changes while sweeping the laser across the object.

Because of the physical limitations of using a wider baseline and the limited field of view of the camera, triangulation scanners are used in applications generally requiring an operating range that is less than 10 meters. Compared to the mid- and long range scanners based on time delay principles (see chapter 2.5.2), triangulation scanners have very high accuracies in the order of microns.

In practice, the active triangulation method was invented to solve the notorious correspondence problem found in passive measuring techniques. The correspondence problem can be stated as follows: given two images I1 and I2 of a scene captured from two different viewpoints, the relative orientation of the cameras and a matching point pair between these images; we can then compute the corresponding 3D point by using the triangulation principle. Thus the correspondence problem consists of finding matching points between different images. The active triangulation method uses laser light to solve this problem by marking the 3D point on the object with the colour of the laser light, so that it can be easily detected in the image.

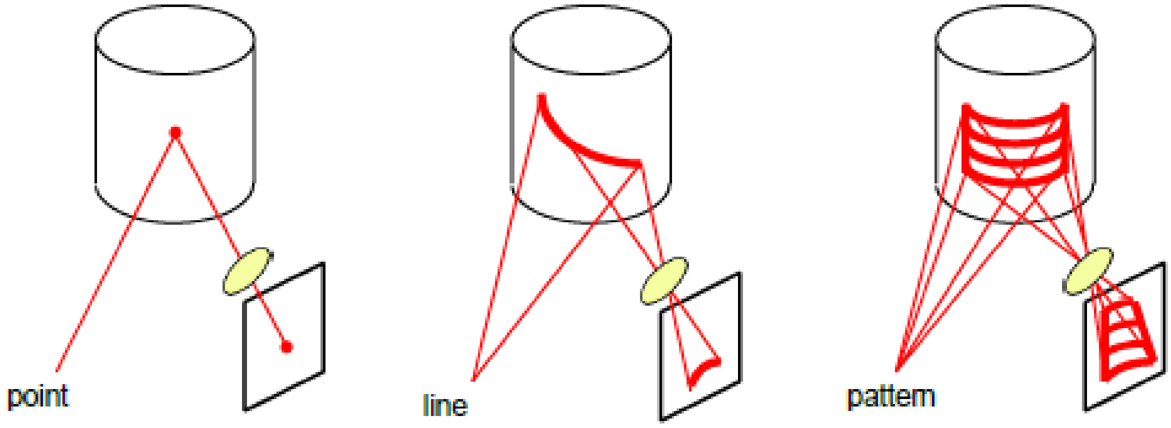


Figure 8 – Different projection techniques used in triangulation scanners

In order to avoid the use of mechanical fixtures, some innovative modifications have been imposed. Instead of moving/rotating the laser emitter to cover the whole object, patterns of points or lines can be projected, which cover the whole object at once. Different patterns are used ranging from regular line patterns to spatially encoded patterns that modulate their frequency or phase in time to provide better accuracy. Note that these spatially encoded patterns require the scan to be to a static object.

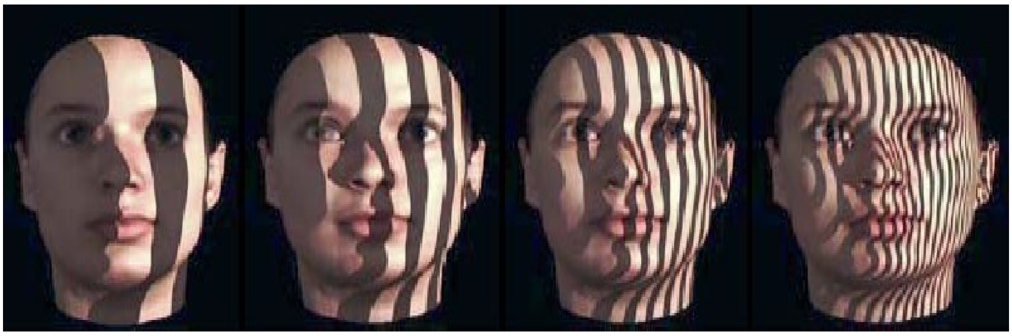


Figure 9 – Regular pattern projection

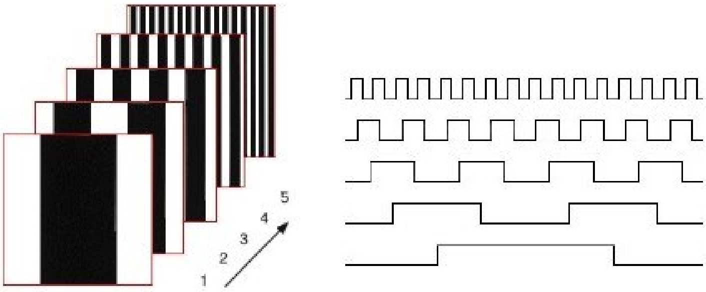


Figure 10 – Binary coded pattern that is phase modulated in time, also called fringe projection

Even more complex patterns based on the Moiré effect are used nowadays to increase the accuracy and robustness of these systems. The Moiré effect is simply the result of two amplitude modulated spatial signals interacting together. This phenomenon can be observed on television when people being interviewed wear striped clothing. A Moiré scanner projects a regular pattern on the object to be scanned while the camera capturing the scene also has an integrated regular pattern. The interference of these two patterns superimposed to each other generates a moiré pattern from which we can determine accurate changes of depth.

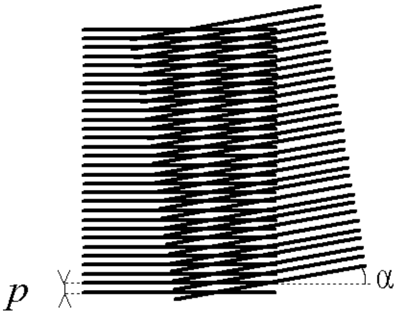


Figure 11 – Moiré pattern formed by two sets of parallel lines, one set inclined at an angle of 5° to the other

As a closing remark on triangulation based scanners, the main challenge in using coded line projection systems is the unique separation of the different directions of projection on objects that have sudden jumps in depth and wide texture differences across their surface.

2.5.2 Time-based measurement

Time-based scanners are active scanners that measure a time frame between two events. In general we have two time-based scanning principles: Pulse based (Time-of-Flight) and Phase based scanners.

Pulse based (time-of-flight) scanners (incoherent detection)

As already mentioned in paragraph 2.3, light waves travel with a finite and constant velocity in a certain medium. Therefore, when the time delay created by light traveling from a source to a reflective target surface and back to the source (round trip) can be measured, the distance to that surface can be evaluated using the following formula:

$$D = \frac{c \cdot t}{2}$$

With c = speed of light in air

t = time between sending and receiving the signal

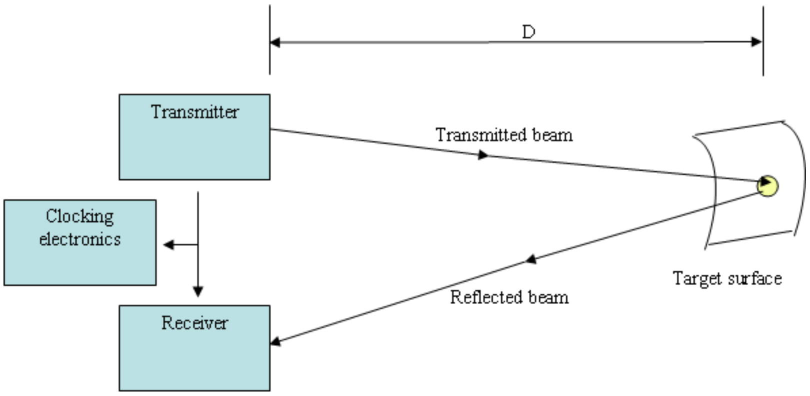


Figure 12 – Time-of-flight laser scanner principle

The currently accepted value for the speed of light in a vacuum is exactly c = 299,792,458 m/s. If the light waves travel in the air then a correction factor equal to the refraction index (depending on the air density) must be applied to c. Taking into account this speed of light, one can calculate it takes 3.33 nanoseconds to travel 1 meter. Therefore, to reach a point accuracy of 1 mm, we need to be able to measure a time delay of about 3.33 picoseconds.

Pulsed time-of-flight scanners do not use continuous laser beams, but make use of laser pulses. They scan their entire field of view one point at a time by changing the range finder's direction. The view direction of the laser range finder is changed by a deflection unit (see paragraph 2.5.3). Typical pulsed time-of-flight 3D laser scanners can measure up to 2,000~50,000 points every second.

Note that for a non-ambiguous measurement, the time measured (t) should be greater than the pulse width, T_{pulse}. Thus

$$t > Tpulse$$

or

$$d > \frac{1}{2} c \cdot Tpulse$$

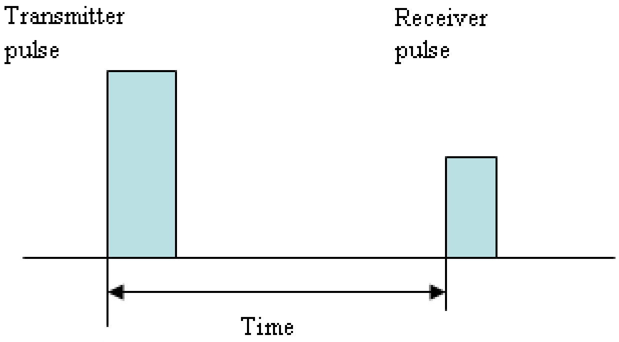


Figure 13 – Laser pulse measurement

To gain a better understanding of these equations, numbers can be used. Setting Tpulse to be 10ps, implies that the maximum accuracy that can be achieved will be d = 1.5mm. Most commercial mid- and long-range systems provide an accuracy of about 6 to 10 mm. Because the accuracy depends on the clocking mechanism, the error of a time-of-flight scanner is almost independent of the distance itself (except for the laser footprint, see chapter 2.6.1).

It is important to notice that the time derivation method for measuring the return pulse depends on the desired time resolution, the counting rate and the required dynamic range of the pulse. Commonly used principles in discriminator design include leading-edge timing (constant amplitude), zero crossing timing (derivation), first-moment timing (integration), and constant fraction timing (search for an instant in the pulse when its height bears a constant ratio to pulse amplitude).

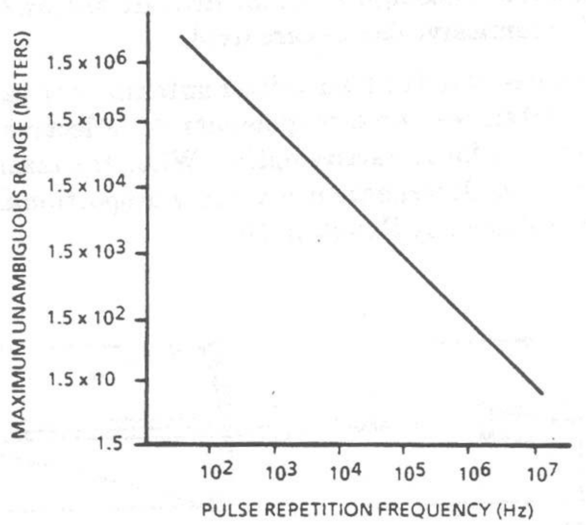


Figure 14 – Maximum unambiguous range versus pulse repetition frequency

In a pulsed time-of-flight system, the maximum pulse repetition frequency is dictated by the fact that the transmitter cannot send another pulse until the echo from the previous one has been received [7]. The purpose of this restriction is to avoid confusion in the pulses arriving at the time interval counter and is called the maximum unambiguous range. The maximum unambiguous range depends on the pulse duration and its frequency.

Three major factors govern the accuracy of a pulsed ranging system [7]:

- Ability to select the same relative position on the transmitted and received pulse to measure the time interval. This is limited by noise, time jitter, signal strength and sensitivity of the threshold detector, and shortness and reproducibility of the transmitter pulse.
- The accuracy with which fixed time delays in the system are known.
- The accuracy of the time interval measurement instrumentation.

The advantage of using pulses for laser ranging is the high concentration of transmitted laser power. This power makes it possible to achieve the required SNR (signal to-noise ratio) needed for high-accuracy measurements at long ranges (up to several hundred meters). The disadvantage is the problem of detecting the exact arrival time of the backscattered laser pulse due to the changeable nature of the optical threshold and atmospheric attenuation.

Phase based

Another time-based measuring principle avoids using high precision clocks by modulating the power of the laser beam. The emitted (incoherent) light is modulated in amplitude and fired onto a surface. The scattered reflection is collected and a circuit measures the phase difference between the sent and received waveforms, hence a time delay.

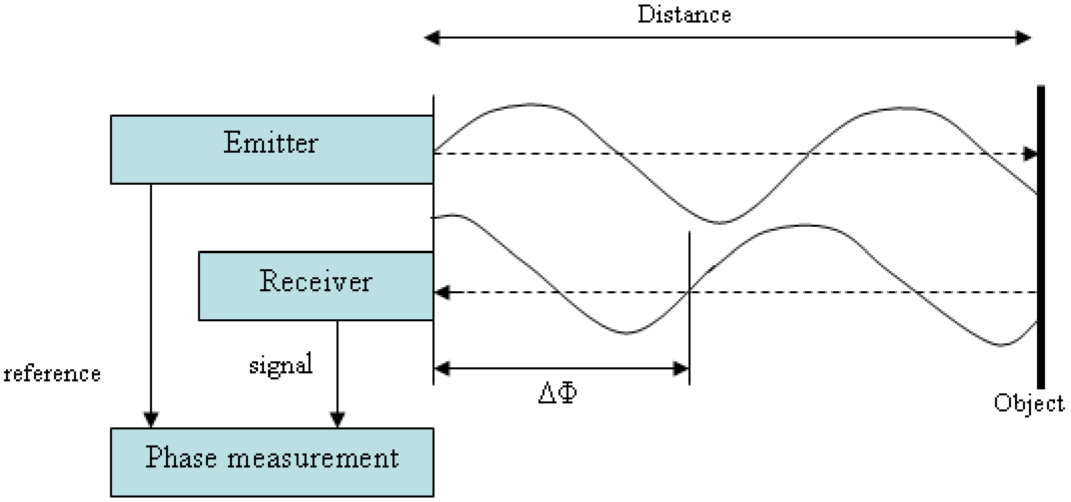


Figure 15 – Phase-based measurement principle

Typical phase-based scanners modulate their signal using sinusoidal modulation, amplitude-based (AM) or frequency-based (FM) modulation, pseudo-noise, or polarization modulation. In the case of a sinusoidal modulated signal, the reflected light is demodulated by means of four sampling points that are triggered by the emitted wave. Out of the four measurements c(τ 0), c(τ1), c(τ 2), and c(τ 3) the phase shift ΔΦ, the offset B, and the amplitude A can be calculated:

$$B = \frac{c(\tau 0) + c(\tau 1) + c(\tau 2) + c(\tau 3)}{4}$$

$$A = \frac{\sqrt{(c(\tau 0) - c(\tau 2))^2 + (c(\tau 1) - c(\tau 3))^2}}{2}$$

$$\Delta\Phi = arctan(c(\tau 0) - c(\tau 2))$$

This phase difference can be related to a time delay similar to that measured in the pulse-based scanners. The relationship between phase difference (ΔΦ), modulation frequency ($f_{modulated}$), and time delay (t), is:

$$t = \frac{\Delta\Phi}{2\pi \cdot f_{modulated}}$$

Then, according to the distance measuring equation of the time-of-flight scanner, the distance to the target is given by

$$D = \frac{c \cdot t}{2} = \frac{c}{4\pi} \cdot \frac{\Delta\Phi}{f_{modulated}}$$

Again numbers may be inserted to get a better feel for these entities. With a frequency of 10MHz and a phase resolution of 0.01 degree (not too difficult with standard electronics), we get a resolution in z of about 0.5 mm.

Continuous beam-modulation scanners also have a maximum unambiguous range, similar to pulsed time-of-flight systems. For these systems, the range is limited to that which causes a phase delay in the sine wave of one complete cycle. The equation for maximum unambiguous range in a continuous wave system is given by:

$$z_{amb} = \frac{c}{2 \cdot f_{modulated}}$$

In the example above, the interval is about 15 m (frequency 10MHz). The range measurement uncertainty is proportional to Z_{amb} and inversely proportional to the Signal-to-Noise Ratio (SNR). To get around the inconvenience of a range ambiguity interval, one can use multiple frequency waveforms in which the target is localized at low frequency (long wavelength) and then the accurate measurement is performed at high frequency. In the latest generation of phase-based scanners,

Two or even three waves with different wavelengths are superimposed. The longest wavelength defines the unique range and the shortest wavelength defines the precision that can be obtained. Generally, phase-based scanners have higher speeds and better resolution but less precision than time-of-flight scanners.

Generally, the accuracy of a phase-based scanner is limited by:

- Frequency of the signal or modulation.
- Accuracy of the phase-measurement loop → Depends on signal strength, noise, ...
- Stability of the modulation oscillator.
- Turbulence in the air through which the measurement is made.
- Variations in the index of refraction of the air.

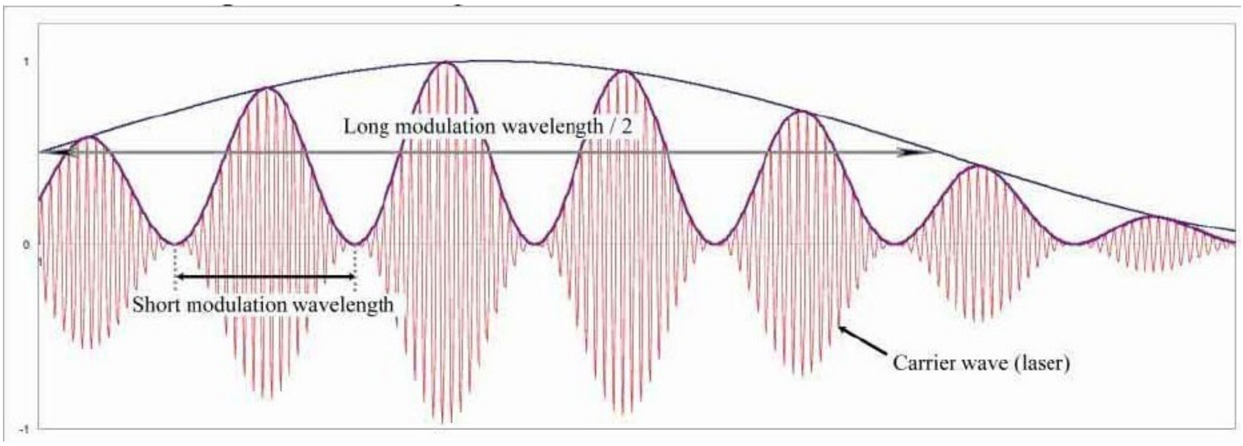


Figure 16 – Schematic drawing of two modulation wavelengths and a carrier wave for phase-based laser ranging

Interferometry (coherent)

Interferometry means using the interference of different light waves to record three-dimensional positions in space. Optical interferometry has been used since the 19th century [7]. Due to the limited intensity and coherence of conventional light sources, the measurements were restricted to distances of only a few centimeters. It was only when lasers were invented that these restrictions could be overcome. Lasers have allowed interferometry to develop into a fast, highly accurate and versatile technique for measuring longer distance.

Interferometric measurement of distance can be highly accurate. It offers a higher degree of precision than the pulsed time-of-flight or beam-modulation telemetry methods. However, it is best suited to measurements made in a controlled atmosphere (for example, indoors) over distances no greater than a few tens of meters.

In an interferometric laser scanner, the laser beam is split using a beam splitter that reflects half the beam in one direction (the reference arm) and transmits the other half (the measurement arm). Both parts of the beam travel along different paths and when the beams are combined together interference fringes are produced. Very small displacements (in the order of a fraction of wavelengths) can be detected (using coherence detection), and longer distances can also be measured with low measurement uncertainty (by counting wavelengths). Many systems have been built on this principle, for example multi-wavelength, holography, and speckle interferometry. These systems have very high accuracy but are also very expensive.

2.5.3 *Beam deflection methods for time-based measurements systems*

To be able to measure multiple points from the same scanner's point of view, the laser beam needs to be deflected. Instead of moving the laser itself, a deflection unit is used. Most deflection units make use of a mirror because they are much lighter and can thus be rotated much faster and with greater accuracy. A number of methods exist to deflect the laser beam towards a specific direction without having to move the scanner itself. In general, three methods are employed for this purpose.

One option is to use an oscillating mirror that allows the movement of the laser along a line. A combination of two mirrors allows for the deflection of the beam in two directions (see Figure 20a). To increase the speed of the deflection unit and reduce the complexity of turning a mirror and then having to turn it back, researchers have come up with a rotating optical reflective prism (see Figure 20b). This principle needs only one direction of rotation and is therefore faster. Recently the use of fiber switches was introduced to make systems more flexible. These systems deflect the laser beam into a circle of optical fibers by means of a rotating mirror (see Figure 20c). The optical fibers then transport the beam in any direction that is required. The advantages of this system are:

- Laser pulse rate is not linked to the viewing angle
- Possible to have a very dense and regular scan pattern
- No calibration required after factory setting
- Forward and side-looking mounting of the laser is possible

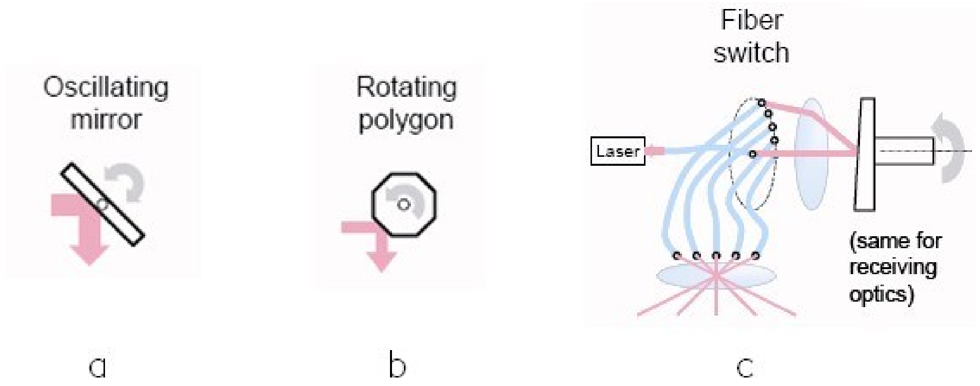


Figure 18 – Beam deflection methods

2.6 Metrological aspects: error analysis

Laser scanner companies publish the accuracies of their laser scanners to illustrate the advantages of their particular product. However, experience shows that sometimes these should not be taken at face value and that the accuracy of the instruments, which are built in limited series, varies from instrument to instrument and depends on the individual calibration and the care that has been taken in the use of the instrument.

Every point cloud produced by a laser scanner contains a considerable number of points that show gross errors. If the delivered product is a point cloud the accuracy of the survey cannot be guaranteed to the same extent as that of a survey by conventional instrumentation. Many researchers have already published papers on accuracy tests with laser scanners (e.g. [11-15]). i3mainz, part of the University of Applied Sciences in Mainz and the Institute of Geodesy and Photogrammetry at the Swiss Federal Institute of Technology Zurich [16] have carried out some exacting work in testing laser scanner accuracy. To be able to systematically describe error sources for laser scanning they are divided into four categories: instrumental, object-related, environmental and methodological errors.

2.6.1 Instrumental errors

Instrumental errors can be both systematic and random and are due to the scanner design. Random errors mainly affect the range measurement precision and the angular location of pulsed time-of-flight rangefinders. Systematic errors may be generated by the non-linearity of the time measurement unit or by temperature drift in the time measurement electronics causing range drift among other errors.

Laser beam propagation

Beam divergence is the laser beam widening with the distance traveled. Beam divergence has a strong influence on the cloud resolution as well as the positional uncertainty of a measured point. The beam divergence can be expressed by the following equation:

$$w(\rho_w) = w_0 \cdot \sqrt{1 + \left(\frac{\lambda . \rho_w}{\pi . w_0^{\;2}} \right)^2}$$

With

ρw = the range relative to the beam waist location

w = radius of the beam

w0 = the minimum beam radius (at the starting point) = beam waist

It is assumed that the laser reflection has a Gaussian shape. For large ranges, the divergence is approximately linear and the beam diameter is expressed as the position that encapsulates 86% of the total beam power within a Gaussian irradiance distribution

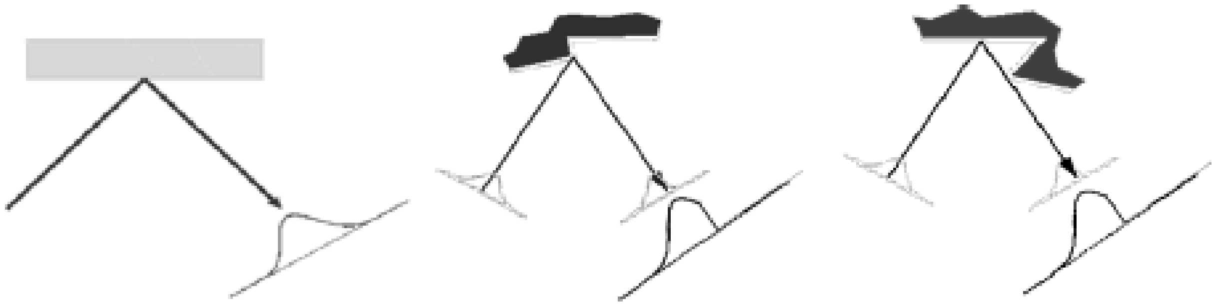


Figure 19 – Ideal reflection, partial illumination, partial occlusion

Practically, this beam divergence has an effect on the angular location of the point measured. The apparent location of the observation is along the centerline of the emitted beam. However, the actual point location lies somewhere in the projected footprint. According to experimental evidence, the beam uncertainty is approximately equal to one-quarter of the laser beam diameter.

Mixed edge problem

One of the most important consequences of beam divergence is the mixed edge problem. When a laser beam hits an edge of an object, the beam is split in two. One part of the beam reflects on the first part of the jump edge, while the other part travels further to hit another surface. The result of this is that the information from one laser pulse that is sent back to the receiver comes from two different locations in space. The coordinates for such a point, relative to the scanner's position, will be calculated based on an average of both returned signals, and will therefore put the point in the wrong place.

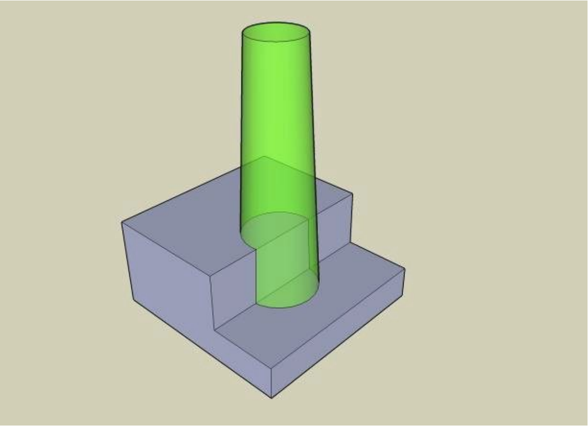


Figure 20 – Mixed edge effect

When using a high resolution scan on an object, the chances of the beam hitting an edge are increased and the resulting data will show noise just behind the edges of the object. Scanners with a smaller beam width help to solve this problem but the range limit remains as the beam width increases over distance.

Range uncertainty

The range uncertainty can be expressed as a function of a number of parameters based on the laser scanner type and its working principle.

For a triangulation scanner, the range uncertainty can be expressed by:

$$\delta_Z \cong \frac{Z^2}{fD}\delta_p$$

Where:

f is the effective position of the laser spot (effective focal length);

D is the triangulation baseline,

δp is the uncertainty in laser position – depends on the type of laser spot sensor, peak detector algorithm, signal-to-noise ratio, and the image laser spot shape.

Z is the distance to the surface

For a time-of-flight scanner, we already know that the range accuracy is dependent on the clocking mechanism. This brings us to the following equation:

$$\frac{\delta_Z \cong c \cdot T_t}{2\sqrt{SNR}}$$

Where

T_t is the pulse rise time.

SNR is the signal-to-noise ratio.

Most mid and long-range terrestrial scanners provide a range uncertainty of about 5mm to 50mm within a range of 50m. In the modeling phase, these errors are minimized by averaging or by fitting primitive shapes to the point cloud.

As already explained, continuous wave-based scanners

A comparison of range uncertainty between different types of laser scanners can be illustrated in a graph as shown to avoid the need for high-speed clocking mechanisms by modulating the laser signal. The range uncertainty in an amplitude-modulated laser scanner depends only on the modulated wavelength and the signal-to-noise ratio and can be described by:

$$\delta_Z = \frac{\lambda_m}{4\pi\sqrt{SNR}}$$

Angular uncertainty

Most laser scanners make use of rotating mirrors to guide the laser signal in a certain direction. A small angle difference can cause a considerable coordinate error when the distance from the scanner increases. The angular accuracy depends on any error in the positioning of the mirrors and the accuracy of the angular measurement device. Since the positions of single points are hard to be verified, few investigations of this problem are known. As described by Boehler et al. [21], errors can be detected by measuring short horizontal and vertical distances between objects (e.g.

spheres) that are located at the same distance from the scanner and comparing those to measurements derived from more accurate surveying methods.

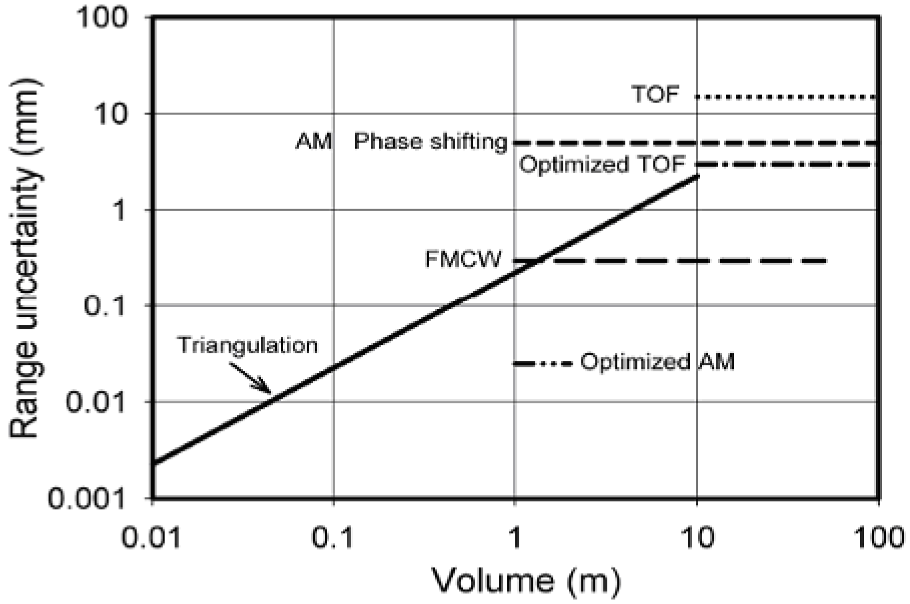


Figure 21 – Range uncertainty for different laser scanner principles

Axes errors in a TLS

In the development of laser scanner calibration procedures, a geometrical model of the scanner is needed. Therefore, we define the following axes:

- Vertical axis: This is the vertical axis that allows the rangefinder to move the laser beam horizontally. Depending on the type of scanner, panoramic or camera-scanner, this is the rotation axis of the scanning head or the axis orthogonal to the axes of the two mutually orthogonal oscillating mirrors;
- Collimation axis: This is the axis that passes through the center of the scanning mirror and the center of the laser spot on the object surface;
- Horizontal axis: This is the rotation axis of the scanning mirror.

Due to manufacturing tolerances, these axes are not perfectly aligned, leading to a collimation error as well as a horizontal axis error.

2.6.2 Object-related errors

Since scanners measure the reflection of the laser beam from a surface, we have to cope with the physical laws of reflection and the optical properties of materials. The surface reflection of monochromatic light normally shows reflected rays in many directions. This type of isotropic (diffuse) reflection (Figure 24) can be described in general by Lambert's cosine law:

$$I_{reflected}(\lambda) = I_i(\lambda).k_d(\lambda).\cos(\theta)$$

With

$I_i(\lambda)$ the incident light intensity as a function of wavelength (color), (is absorbed when travelling through air)

$k_d(\lambda)$ the diffuse reflection coefficient which is also a function of wavelength θ the angle between the incident light and the normal vector to the surface.

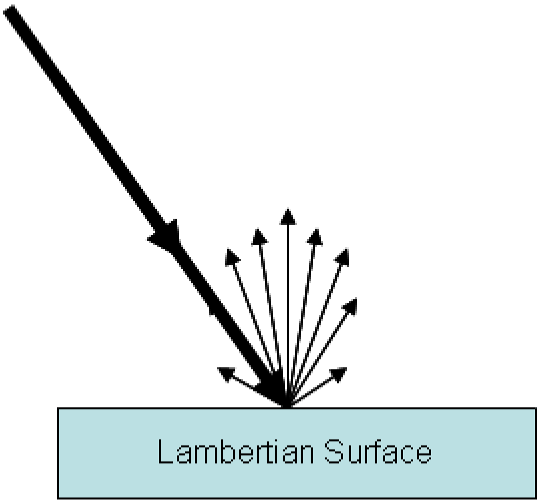


Figure 22 – Lambertian surface reflection

This formula shows us that the laser beam is affected by the absorption of the signal traveling through the air, the reflection of the material being measured, and the angle of incidence between the laser beam and the surface being measured. This means that for very dark (black) surfaces that absorb most of the visible spectrum, the reflected signal will be very weak, hence the pointing accuracy will be corrupted by noise. Surfaces with high reflectance (i.e. bright surfaces) give more reliable and precise range measurements. However, if the object's reflectivity is too high (metal surface, retro-reflective tape …), the laser beam is fully deflected in the mirroring direction and will hit another surface or spread into the open. This deflection results in the point being measured not being the point that the laser is pointing at, but another point or no point at all. This type of noise is called speckle noise.

Recording surfaces of different reflectivity also lead to systematic errors in range, sometimes several times larger than the standard deviation of single range measurement.

As well as reflectance properties of the surface, color properties affect the precision. Significant systematic range discrepancies exist which can be broadly correlated against the color of each surface with respect to the wavelength of the laser used.

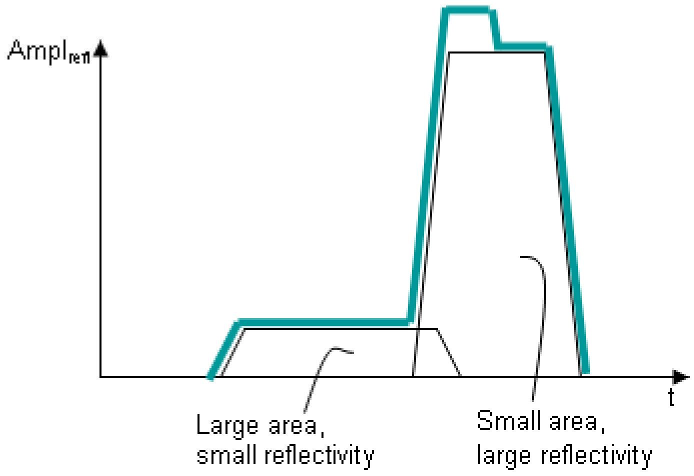


Figure 23 – Signal response when scanning surfaces of different reflectivity

Besides the reflectance effects, a number of materials have a semi-transparent coating that allows the laser beam to refract and reflect in the material itself (i.e. wood, marble, styropor). These effects lead to an addition constant to the distance measurements, which has to be regarded in the computation.

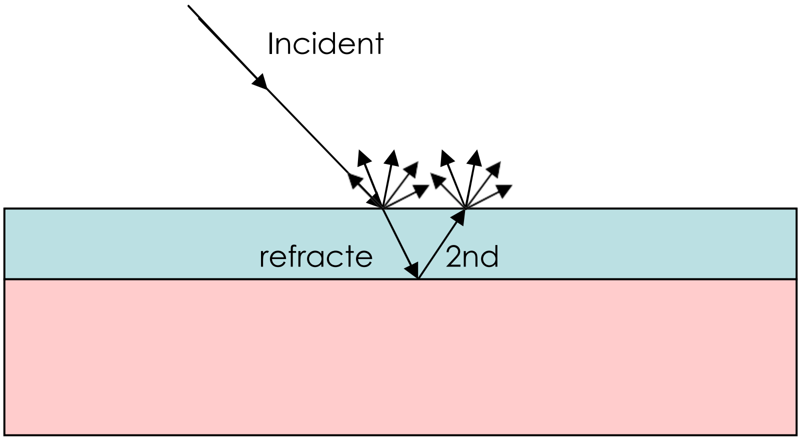


Figure 24 – Refractions effects in inhomogeneous semitransparent materials

2.6.3 Environmental conditions

Temperature

It should be noted that the temperature inside the scanner may be far above the temperature of the surrounding atmosphere due to internal heating or heating resulting from external radiation (i.e. the sun). This external radiation source might heat one side of the tripod or scanner, causing that side to expand, slowly distorting the scanner data.

Not only the equipment temperature, but the temperature of the surface to be scanned is of importance. When scanning a hot target, e.g. in an industrial environment, the background radiation caused by the hot surface reduces the Signal-to-Noise ratio and thus the precision of the range measurements.

Atmosphere

Laser scanners will only function properly when used in a certain temperature range. Even within this range deviations in measurements may be observed, especially in the distance measurement.

As in all laser-based distance measurement operations, natural errors stem primarily from atmospheric variations in temperature, pressure, and humidity which affect the index of refraction and modify the wavelength of electromagnetic energy. This means, that the laser light velocity is strongly dependent on the air density.

Most laser scanning acquisition software provides for correcting this refraction by setting a refraction parameter. In general, the scanners are preset using the ISO standard atmosphere parameter (15°C, 1013,25 hPa). When working under different atmospheric conditions than the standard atmosphere, these parameters need to be adapted. A difference in temperature of 10°C or in air pressure of 35 hPa leads to a scan distance error of 1mm/100m.

In terrestrial cases, this effect may not seriously affect the results for short or medium-range scan distances. For long-range measurements or high-precision scans, it is imperative to apply the correct atmospheric parameters.

When working, for example, in a mountain region, the temperature decrease can be estimated as 0.65°C/100m and the pressure decreases at 10hPa/100m. For a scan station positioned at an altitude of 2000m the scan distance error would then be about 8mm/100m.

Interfering radiation

Since laser scanners operate in a very narrow frequency band, the precision of the range measurement may be influenced by external radiation, for instance from strong external illumination sources. Special optical interference filters can be applied in the receiving unit allowing only the correct frequencies to reach the receiver.

Distortion from motion

Most laser scanners scan at a rate of 2000 to 500,000 samples per second. Although this is very fast, scanning at high resolution can still take 20-30 minutes for some time-of-flight scanners and about 10 minutes for phase scanners. During this time the scanner is susceptible to vibrations in its surroundings causing displacements. We call this distortion from motion.

Since each point is sampled at a different time, any motion in the subject or the scanner will distort the collected data. Therefore the scanner needs to be mounted on a stable platform to minimize vibrations. The subject itself should also be motionless.

Notice that the scanner can also move due to changes in temperature. For example, if the sun shines on one side of the scanner, the legs of the tripod on that side may expand and slowly distort the scan data (see paragraph 2.6.3.1). The latest scanners, also called scan stations, have a dual axis compensator integrated that compensates for any movement of the scanner during the scan process.

2.6.4 Methodological errors

Methodological errors are errors due to the chosen survey method or the user's experience with this technology. For instance, if the user sets the grid density (resolution) higher than the per- point accuracy of the laser scanner, the scan will be oversampled. By oversampling a scan, extra noise is generated and the required processing time will increase dramatically. Another possible source of error could be the wrong choice of the scanner. By taking a scanner with a maximum range that is near the maximum range of the object to be scanned, these scans will contain less precise measurements and possible noise.

Possible errors generated during the registration or consolidation phase are also categorized under this topic. Depending on the technique used to register multiple point clouds, errors are introduced. These errors occur in indirect registration/geo-referencing as well as in direct registration/geo-referencing.

2.7 State-of-the-artart laser scanner equipment

The current state-of-the-art laser scanners are fully integrated for faster set-ups. They combine the scanner, a control panel, internal storage, and battery in one piece of equipment. Special dual axis compensators are also integrated to automatically level the scanner. Some scanners have mounting devices to attach GPS receivers and/or INS compensators to directly position and orient the scanner in space. To add high-resolution color information to the measured point clouds, some scanners integrate high-quality digital cameras or provide a mounting device.

Laser scanning technology is continuously developing:

- Special targets with integrated GPS receivers overcome the necessity of having to record targets using total stations.
- Hardware-based homogeneous point cloud filtering
- Combining the best of time-of-flight and phase-based scanners into 1 scanner

3. Laser scanning in practice

Using a laser scanner to record a building is not just pressing a button and waiting for the deliverables to come out. It requires a profound knowledge of the equipment and the scanning process. Some of the steps of the scanning process are quite automated while others are still labor intensive. This chapter we will discuss the terrestrial laser scanning process.

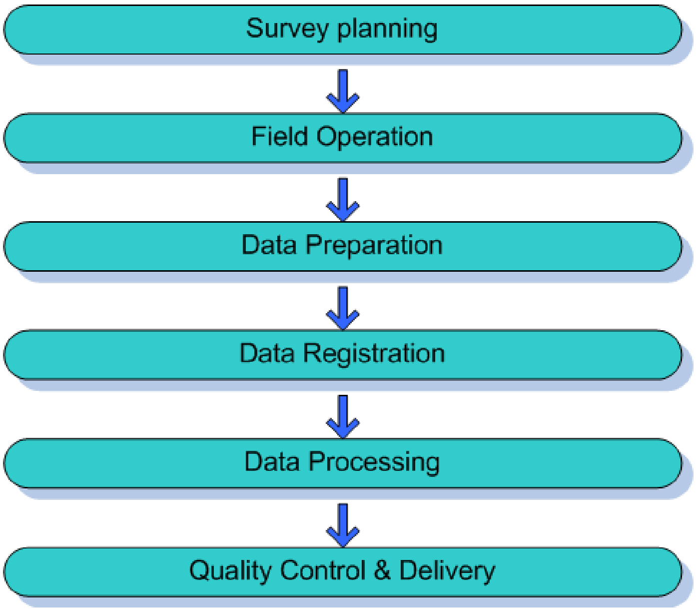


Figure 25 – The terrestrial laser scanner pipeline

3.1 Survey planning[1]

At present, there is no standard procedure for survey planning for terrestrial laser scanning. However, according to the laser scanning users' community, the survey planning should at least contain the following topics (see Figure 26):

- Determining the goals and objectives
- Analyzing the area to be surveyed
- Determining the measuring techniques and equipment
- Data management

3.1.1 *Determine the goals and objectives*

One of the key issues when recording an object, are the client's goals and objectives. To fully understand the client's needs and requests, some questions have to be answered.

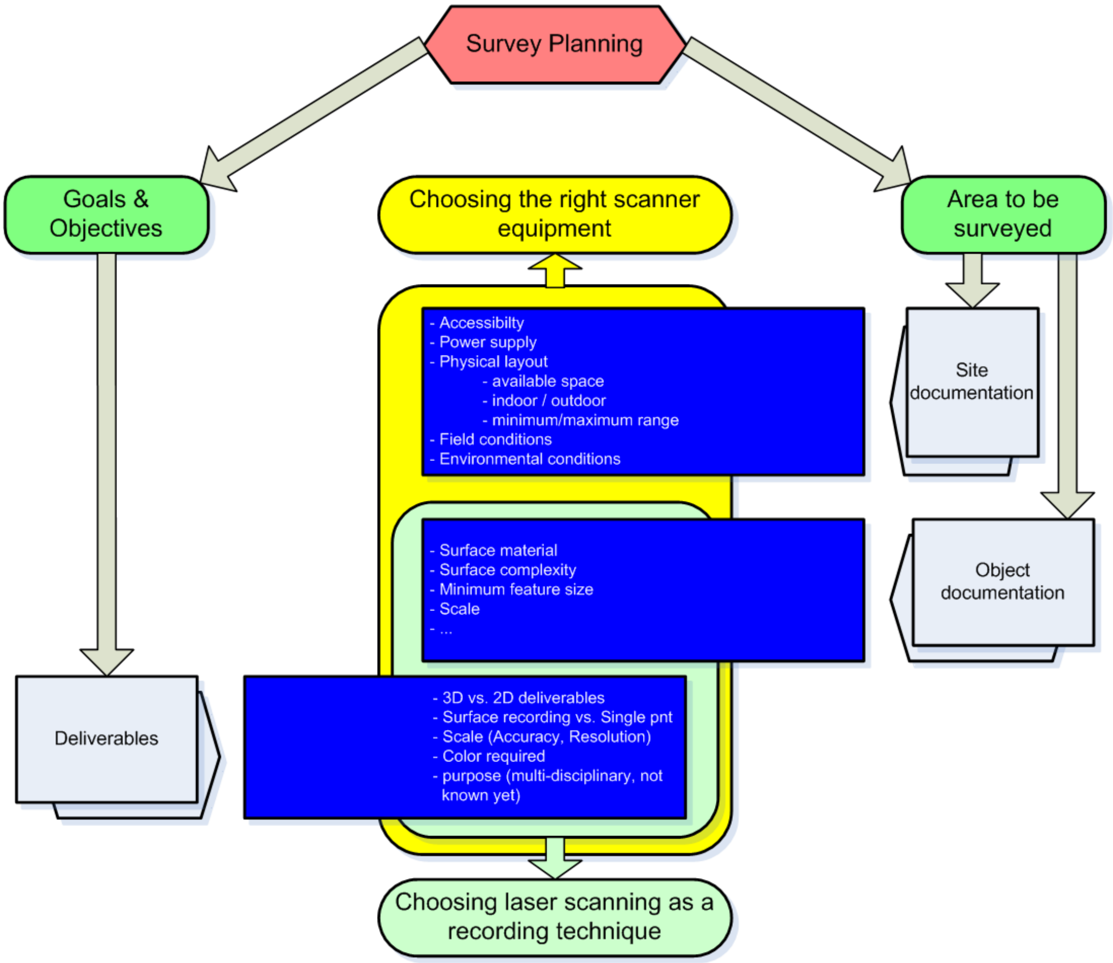


Figure 26 – Survey planning flowchart

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[1] This paragraph could be compared with the notes on Metric Survey planning

- Why does the client want this object to be recorded and what does he/she want to do with the recorded data?
- The reason for recording an object or building can provide insight into the requirements concerning the deliverables and their accuracy. Often the client might think laser scanning is the ideal tool for their problem because they have heard that a competing firm has used a laser scanner. Or, indeed, the other way around, the client might be afraid of using laser scanning to record their building because they are skeptical and rely on using traditional techniques. By listening to the clients requirements, guidance can be offered on the appropriate measurement technique.
- What deliverables are requested?

In close relation to the motivation for recording, we need to define the requested deliverables. These deliverables can range from 2D plans and elevations to 3D models or even 3D animations. In some cases the client may only want the raw point cloud for archiving. Particularly important is the level of detail (minimum feature size) of the deliverables because it helps in determining the expected resolution (i.e. point density).

3.1.2 Analyzing the area to be surveyed

Gathering as much information as possible on the object to be recorded provides insight into the complexity and time required for a certain task. As already mentioned in the previous paragraph, the required resolution and the accuracy of the recording are based on either the scale of the survey area or the minimum feature size that should be recognizable in the final deliverables. Field notes, reports, maps, photographs or video footage of the site can help in determining possible hazards when recording the object, as can previous surveys which may have been created by other means of recording (hand measured, GPS or total station data).

Not only the building itself can provide useful information, but also its surroundings. The site can be scattered with obstructions, limiting the possible laser scanner setup positions, or there might even be time restrictions on entering the site (i.e. recording metro tunnels). Indirectly the possible laser scanner setup positions determine the minimum and maximum range which the scanner should be able to record.

Using all this data, a decision can be made on the proper recording technique and if laser scanning is chosen, the scanner type can be determined. Laser scanning is a highly developed technique, but it is not always the most efficient solution for every problem. Sometimes it is much easier and time-efficient to use another recording technique. Possible reasons to choose laser scanning are:

- Very complex surface structure (organic forms)
- 3D deliverables required
- Requirement for surface measurements instead of individual point measurements
- Data records that can be used by a multi-disciplinary team for different purposes
- Archiving without a priori knowledge of future use
- Access restrictions
- Etc.

3.1.3 Determining optimal scanning locations

Once the site documentation is gathered and laser scanning has been chosen to be the most effective recording technique, the scan and target positions need to be planned.

The optimal locations for the scanning station should be chosen to guarantee maximum coverage and accuracy while minimizing the number of setups. As already mentioned in paragraph 2.6, the accuracy of the measurement depends on footprint diameter from a given scanner setup, indicating that the angle of incidence (see Figure 30) and the range to the object are of great importance when determining the scanner's position. A thorough analysis of determining the optimal configuration of the scanner to achieve the required accuracy is described in [26]. The following list gives a set of prioritized rules that should be kept in mind while determining the optimal position of the scanner.

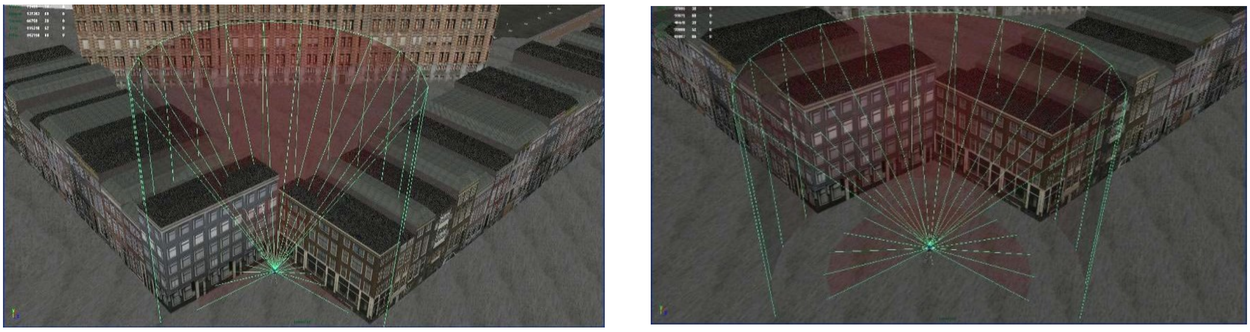


Figure 27 – Bad scanner positioning containing very inclined angles (left) – Good scanner positioning (right)

- Check for positions that provide large area coverage without having obstructions in the line of sight and that produce the least shadows.
- Check if the minimum/maximum range limits of the scanner are fulfilled to reach certain accuracy, the larger the distance to the object, the lower the accuracy and resolution.
- Minimize the appearance of low intersection angles, under sharp angles the laser beam is not so well reflected back to the scanner which results in less accuracy.

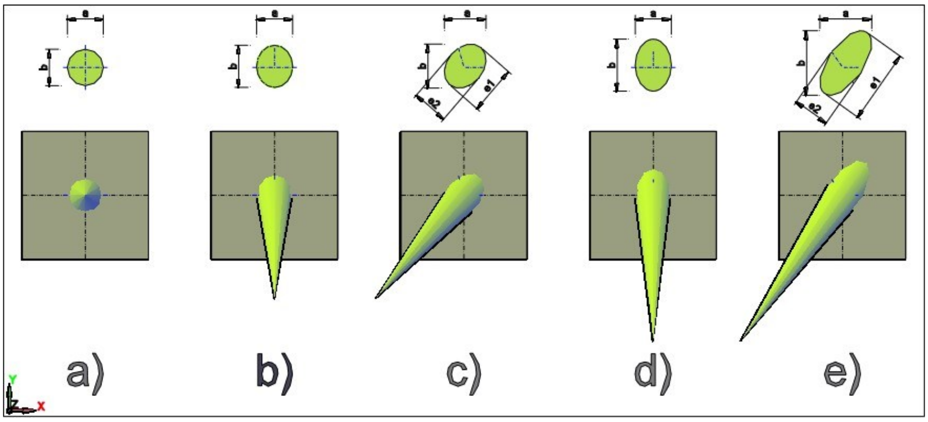


Figure 28 – Laser footprint when scanning under different angles

- Try to decrease the number of scan positions.
- Other important facts that should be taken into account are:
- Health and Safety
- Environment (vibrations, wind…)
- Elevation of the scanner above the ground
- Visibility of artificial or natural targets

3.1.4 Determining the optimal target's location

Next to the optimal scanner locations, the target types and their positions and/or geometric configuration are also important. Targets are mainly used to register scans taken from different scan positions. Currently there is wide variety of target types available: retro-reflective targets, spherical targets, paper targets, prism targets... In the near future, we will even have targets with integrated GPS receivers.

One important remark when using targets is that they need to be widely spread, not only in x and y direction but also in the z direction. This is often forgotten and sometimes all targets are simply placed on the ground.

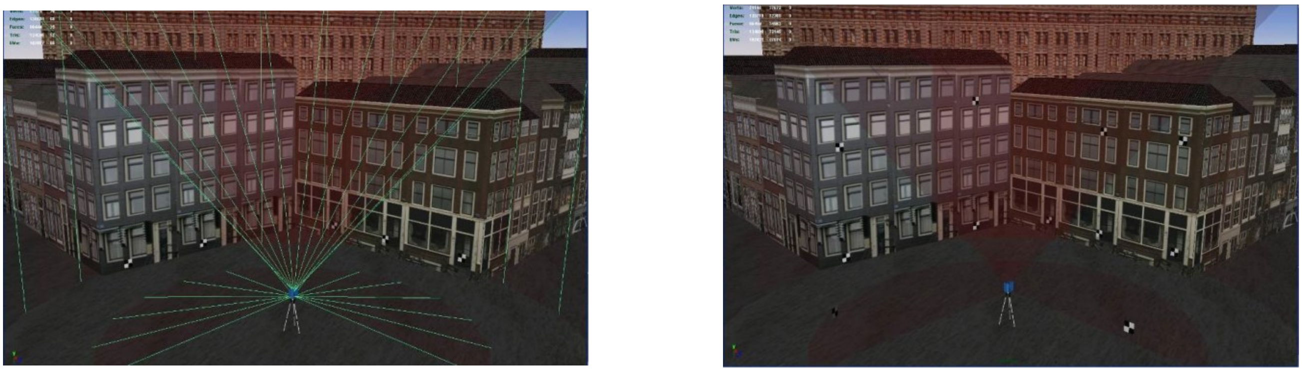


Figure 29 – Bad target configuration (left) – Good target configuration (right)

Some target configurations do not imply a unique solution to the registration process. For instance, if all the targets lie on a line, 1 degree of freedom remains, namely the rotation around that line.

Special retro-reflective targets and spherical targets are often provided by scanner developer companies. These targets are designed to reflect most of the laser beam back to the scanner. The scanner can therefore automatically detect these targets and after a fine scanning process, determine the exact center by fitting a primitive shape to the measured point cloud.

Sometimes paper targets are used because they are a lot cheaper than the retro-reflective or spherical targets. On occasions a retro-reflective prism is fixed to the scanner head. Knowing the offset between the deflecting mirror of the scanner and the prism, the scanner's position can be determined by measuring the prism with a total station.

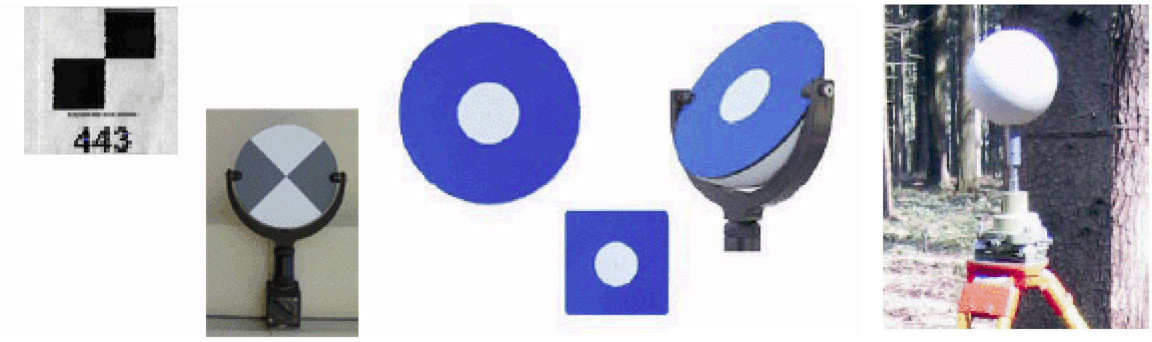


Figure 30 – Artificial target types

Depending on the registration technique used, there should be at least 4 appropriately distributed XYZ control points/targets in each scan. A more detailed explanation of the registration methods and their respective optimal target configurations is described in paragraph 3.5.

3.1.5 Data management

It is important to think about data storage before starting the scanning. For example, using a Leica HDS4500, 1 scan is approximately 140 Mb. On an average scanning day, 20-30 scans can be made, generating a data set of approximately 7 GB. This requires careful planning.

3.2 Field operation

3.2.1 Survey preparation

The survey preparation phase includes the decision-making on the registration technique to be used. These techniques can be subdivided into three categories: registration using 3D re- sectioning of scanned targets, registration by setting the laser scanner over known control points, and registering using cloud-to-cloud constraints (see chapter 3.5 for more details).

3.2.2 Setting up the scanner

Setting up a laser scanner generally follows a similar procedure to that of setting up a total station. The following steps are performed (Figure 31):

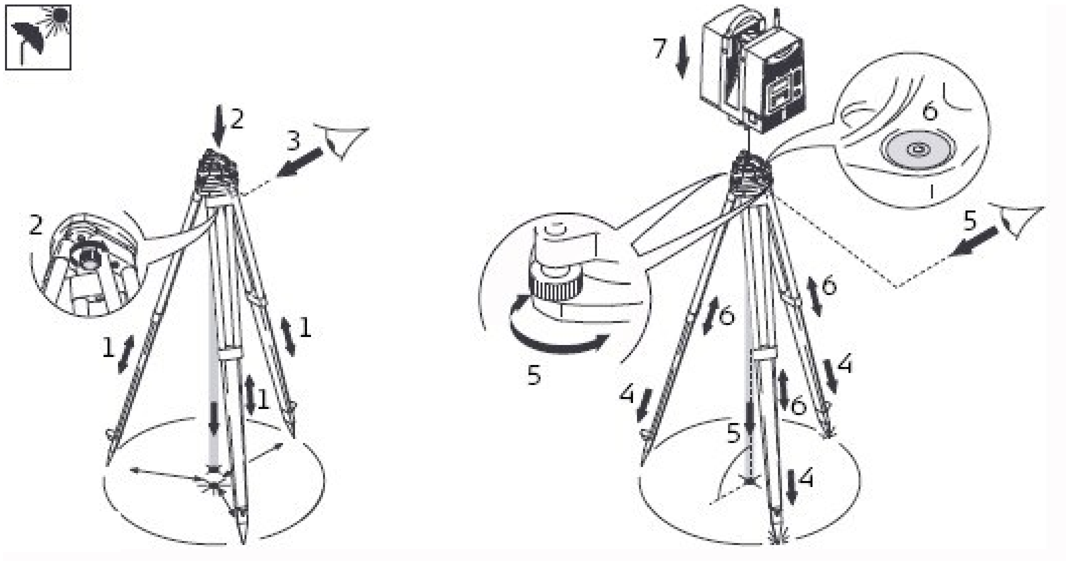


Figure 31 – Setting up the laser scanner

- Set up tripod: Open the tripod and extend the legs. Make sure the tripod is on stable ground. Usually the scanner will be placed at eye height. When the floor area needs to be scanned, an even higher position is beneficial because it provides a better inclination angle.
- Attach the scanner by placing onto the tripod and locking into place.
- Depending on the registration technique, the scanner may be positioned above a known control point.
- Level the scanner: By changing the length of two tripod legs used to position the tripod, level

the top surface of the tripod using the bulls-eye level. The bubble should be within the inner circle. Be as precise as possible. When positioning the scanner above a control point, this procedure should not alter the point you were over in step 3.

3.2.3 Recording the data

Before starting the scanning, the scanning device itself must be connected to a laptop that can receive and store all the points coming from the scanner and control the properties of the scanner. Power can be supplied to the scanner using batteries, a generator, or directly from the main power.

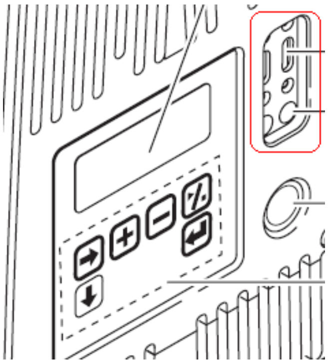


Figure 32 – Fully integrated scan and control on the today's scanners

More recently the TLS can store the data inside a internal or removable hard-disk.

3.2.4 Scanner settings

Once the scan controller software has established the connection to the scanner, the parameters to use in the scan process need to be specified.

Targeting

Although most state-of-the-art scanners can scan a full 360° (Figure 35), this is not always required. Therefore we need to define the area to be scanned. To do this, there are several options.

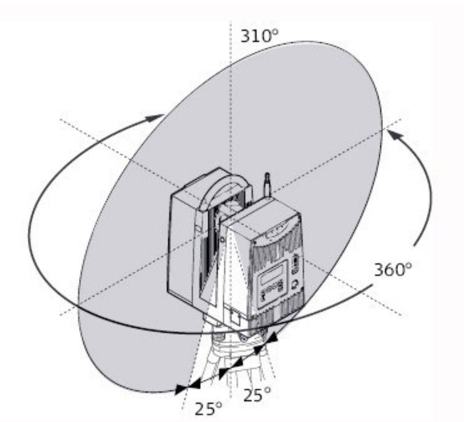


Figure 33 – Field of view of a modern scanner

Some scanners have a minimized control panel on the scanner itself which can define the target area. This is a very rough way of defining the target area, but a very quick method.

Mostly, the targeting area is defined using the scanner control in the software. Using this type of targeting, we first capture an image of the scene that allows the target area to be selected. Scanners nowadays have integrated fixed cameras or even video cameras to show the user what the scanner is seeing. Using the scan control software, the user can then select the target area using a selection box similar to selecting a part of an image in the image processing software.

Most phase-based scanners do not have a camera because of their technical design. However, these scanners can record so many points per second that creating a low-resolution scan only takes as long as another scanner taking pictures. This low-resolution scan can then be used to select the target area.

Resolution

The key question when carrying out a laser scanning project is choosing the correct resolution. The resolution is defined as the distance between two subsequent measured points and thus determines the density of points in the point cloud. Often people mistake accuracy with resolution. Although there is a certain connection between both, they still define different aspects of the laser scanning process.

The resolution is mainly governed by the smallest detail of the surface structure that needs to be recognizable in the final deliverable. Therefore it is also directly related to the scale of the deliverable. In fact, laser scanners overcome the intelligent processing that humans do when analyzing a building (i.e. splitting a building up into planes, lines, and points) by recording a huge set of points with redundant information. For instance, in smooth areas like planes, less points are required to model the object, while in areas with high curvature, many more points are required, sometimes even more than the laser scanner can provide.

It should be noted that the higher the chosen resolution, the more points need to be scanned and thus the longer it will take. Besides the time frame, the dataset storage size increases. The operator should bear in mind that scanning at a higher resolution than the scanner’s single point accuracy in distance measurement can cause oversampling and thus result in more noise in the final dataset.

Since most laser scanners work with constant angle change between two consecutive points (based on polar coordinates), the scanner resolution is defined at a specified distance to the scanner. This distance can be manually entered through the software, or a probe can capture a point distance value and define the resolution at that distance from the scanner. Points scanned further than this distance will have a lower resolution, while points scanned closer have a higher resolution. In general, it is advised to take the probe point at the furthest point to be scanned.

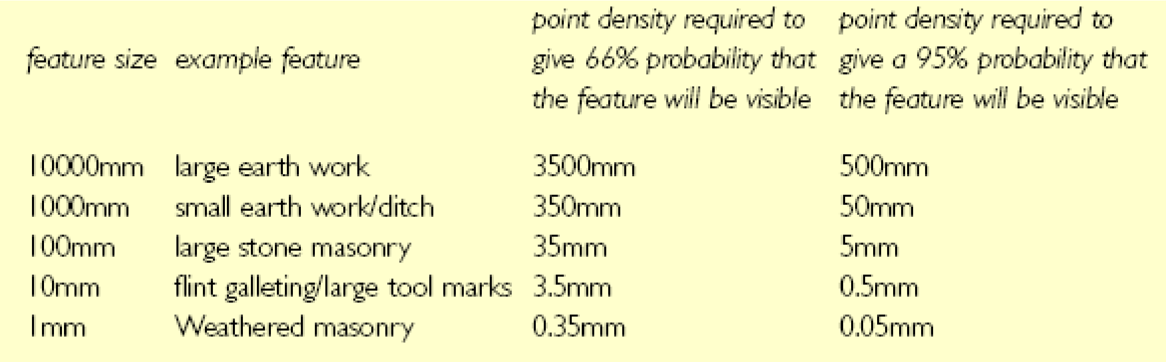
Some scan control software provides quick settings for the resolution, i.e. low, medium, or high resolution. These quick settings set the resolution to a specific value for a certain distance. In the manual of the scanner, tables are provided illustrating the effective resolution at several distances for each setting.

English Heritage, a non-departmental public body of the United Kingdom with substantial expertise in managing the historic environment, created a table that helps a user to determine the appropriate resolution for the project.

This table is generated based on the following formula:

$$Q = 1 - \left(\frac{m}{\lambda} \right)$$

Where Q is the quality of the data, m is the point density (resolution) on the object and λ is the minimum feature size, or the point density required. The value Q, therefore, indicates the level to which the object has been scanned.



feature size	*example feature*	*point density required to give 66% probability that the feature will be visible*	*point density required to give a 95% probability that the feature will be visible*
10000mm	large earth work	3500mm	500mm
1000mm	small earth work/ditch	350mm	50mm
100mm	large stone masonry	35mm	5mm
10mm	flint galleting/large tool marks	3.5mm	0.5mm
1mm	Weathered masonry	0.35mm	0.05mm

Figure 34 – Appropriate point densities (sampling resolution) for various sizes of cultural heritage features

Primary filtering

While scanning, the scan data can be filtered using primary filters, sometimes also called hardware filters. Different options are given: filtering by range, filtering by reflectance value, or a combination of both. Primary filtering can be used to make sure that the data collected is within the range of the scanner's range accuracy limits, or to remove points with low reflectance values because they are probably not accurate enough

3.3 Data acquisition

3.3.1 Scanning the object (building)

Once the field-of-view is determined and the proper resolution is set, the scanning itself can be started. The scanning process is almost fully automated. After pressing the control button in the scan control software or directly on the scanner control, the scanner moves to the starting point and starts collecting points. These points are stored by the laptop or in the internal memory of the scanner itself. When a laptop is connected to the scanner, the points scanned are directly visualized in three dimensions on the screen and provide an overview of the area that has already been scanned. After scanning, it is a good practice to check the scan for unforeseen obstructions that cause occluded areas in the scan data.

In most scan control software, the target and parameter settings can be scripted, so multiple regions can subsequently be scanned with different resolutions. A script can be created to enable specific areas to be scanned at higher resolution whilst the general scan is running, so that better defined features can be used as registration features in the registration process.

Depending on the chosen resolution and the targeted area, the scanning process can take from 5 minutes up to 120 minutes or even more. During this time, the survey notes should be made orin case the sketch of the surroundings hasn't been made during the survey planning, this might be the time to do this. The sketch and survey notes should show/describe the object(s) being scanned, the target positions and their labels and the scan positions. Specific external conditions influencing the scanning and the scanner settings used should also be noted.

Scanning targets

When artificial and/or natural targets are used to register the scans in the registration phase (see paragraph 3.5), these targets should be labeled and measured very precisely.

Because of the limited speed of a time-of-flight scanner, the scanning is done in two phases. At first, the subject is scanned using a resolution that is appropriate to reach the requested deliverables. In a second phase, the targets are fine-scanned (Figure 39) to reach a higher accuracy when determining their center position. However, in public areas, it would be beneficial to first scan the targets and afterward scan the subject to avoid any possible movement of targets.

After finishing the global scan (phase 1), most scan control software provides tools to automatically detect artificial targets in the scan. Since these artificial targets are made from highly reflective material, their reflectance value is much higher than its surroundings. However, since these automated detection tools often give erroneous results, so it is advised to always check the results and make sure no target is missed.

Once the approximate positions of the artificial targets are known, they are scanned with very high resolution (phase 2). The scan control software can then automatically fit a specific target shape to the target and determine its exact centre point.

Sometimes points-of-detail are used instead of or along with artificial targets. A point-of-detail is a geometrical point that is highly distinguishable and can be accurately located due to its shape. These points are also scanned with very high resolution. It is good practice to manually insert the vertex for this natural target and label it on-site to reduce misinterpretation problems at the processing stage.

It is important to note that the latest generation phase-based scanners scan at high speed so that a 360° scan at very high resolution may only take 5 to 10 minutes to complete. The targets are automatically scanned at high resolution, so they do not have to be scanned again afterward. This way of working is of course much faster since the user does not have to identify and fine-scan these targets on-site. However, the labeling of the targets now needs to be done in the office and requires very good field notes and sketches of the site.

3.3.2 Measuring the targets

A part of the scanning process is the recording of the targets with a total station survey instrument. If multiple total station setups are needed, a traverse or resection should be performed to minimize errors in the recording process. Since it is assumed that students working with this tutorial have a background in surveying, this process is not described in detail.

3.3.3 Completeness checking

As already mentioned, it is of great importance to double-check the scan's completeness when the scanning is finished. Realizing a part is missing in the scan data when at the office may lead to an expensive return visit to the site. The second visit might require more time than checking the completeness on-site during the first visit would have taken. When working with a laptop, point splatting can help with this (see paragraph 3.6.1).

3.4 Data preparation

Back at the office, the data is analysed and compared to the field sketches and notes. It is advisable to start working on a copy of the original scans and keep the originals as a backup. Different types of scanners store the point cloud information in different formats. For archiving purposes, it is important that the file format is easily accessible and recognizable. If it can be accessed directly, without any decoding, it can later be easily converted to any other format readable by an appropriate piece of software. The file format should also contain the data in its most rudimentary format, instead of using the most preferred format for reprocessing.

Always add a meta-data file to the backup files containing the field sketch, field notes and all the data gathered already in the preparation stage of the scanning job.

Before processing the clouds, scans affected by extreme environmental conditions or erroneous scans due to human mistakes are removed from the data set. The scans that are not removed now need to be prioritized according to the 'best views'. The prioritization is done using the field notes and sketches.

In some cases, it is also required to clean some scans before the registration phase. When targets are put very far from the scanner or due to certain environmental conditions, the target fine scans can be cluttered with noise. This noise has to be removed before registering the scans because it will affect the precision of the registration phase.

3.5 Registration and georeferencing

In most cases, the object to be scanned is too large to be scanned from one position only. Therefore, multiple scanning positions are required. Each scan position is defined in a scanner coordinate system. To be able to align different scan positions, it is necessary to know the exact position and orientation of these scanner coordinate systems according to a local/global site coordinate system.

Directly linked to the aligning, or registration, is the geo-referencing of the whole dataset. Geo-referencing means, besides aligning the scans, also geo-referencing the dataset to a fixed coordinate system. The next paragraphs will explain the possibilities for registration and geo-referencing.

These notes categorize the registration techniques into direct and indirect registration or geo-referencing techniques.

3.5.1 Indirect registration and Georeferencing

Indirect registration implies making use of target features (artificial or natural) in the scene itself to align datasets. If geo-referencing is required, the targets themselves should be recorded and transformed into a known coordinate system using recognised surveying methods.

To perform an indirect registration at least three target correspondences between two scans are needed. However, it is always better to have more than three, so that errors can be minimized by performing a least-squares optimization.

Places that are easily accessible do not pose a problem for placing targets. Artificial targets come in a variety of forms. There are special targets from the laser scanner companies made from highly reflective material, but printed paper targets can also be used. When no printer or special targets are available, targets may be improvised by using objects to which an ideal geometrical surface can be fitted. For instance, pieces of a cylindrical tube can be used as targets. Using the scan processing software, an ideal cylinder can be fit to a fine scan of such an object to determine the centre axis with very high precision. If the cylinders are then placed in both a vertical as well as horizontal direction, they can be used to align different scans.

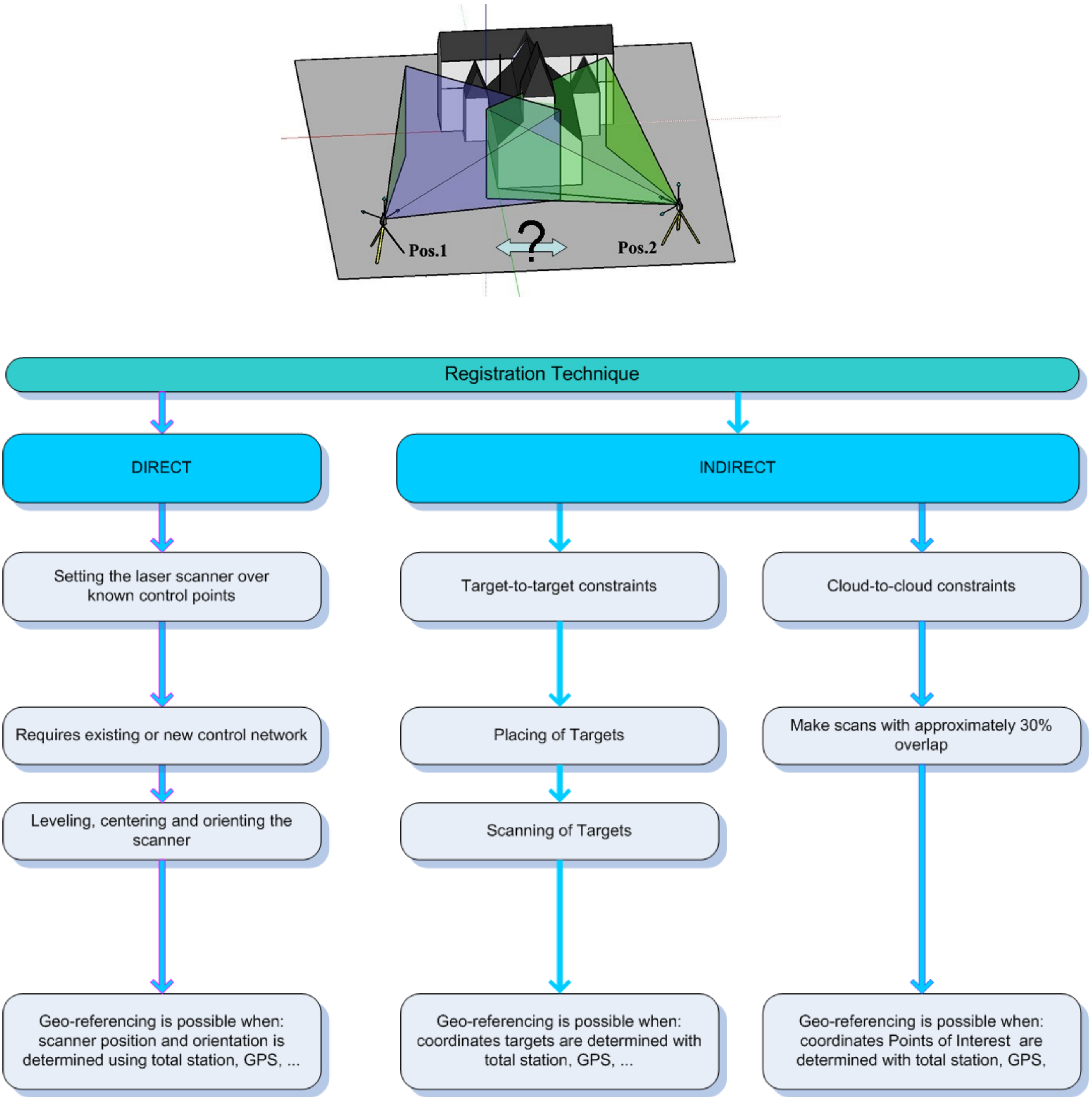


Figure 35 – Registration between two adjacent scans)above) – Registration techniques (belowe)

Target-to-target registration

In areas that are not easily accessible, for instance that are too high to reach, natural targets can be used. Natural targets are points of interest in the structure itself that can be identified with high precision, for instance edges of windows or cornices. As English Heritage states in their publication [28], the registration results obtained using these natural targets are poorer than using the artificial targets. The reason for this is twofold:

- The common features in different point clouds are not composed of identical points, which are, essentially, circles of several mm in diameter, because of the laser beam divergence;
- Identification of common features is rather subjective, especially on very inclined scans.

Cloud-to-cloud registration

Another way of registering two point clouds is by using point cloud overlap. If two point clouds have enough overlap (generally 30 – 40%), a technique called Iterative Closed Point processing or ICP can be used to align both datasets.

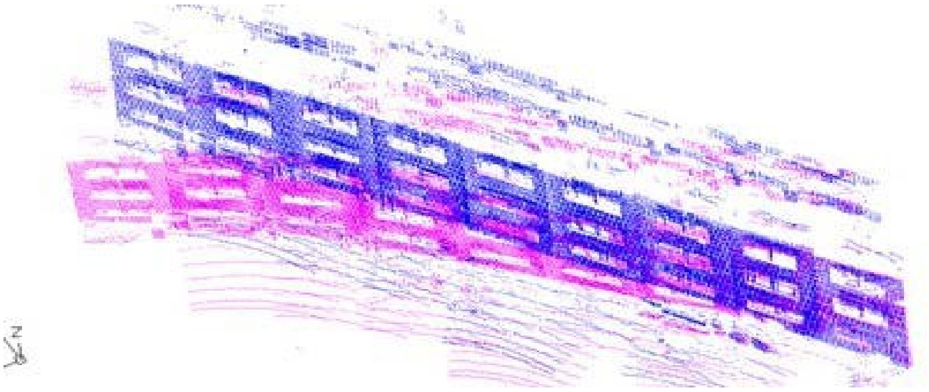


Figure 36 - Error propagation due to cloud-to-cloud registration of multiple façade scans

This technique requires the user to manually pick at least 3 corresponding points in the point clouds. Since these 3 points will never be exactly the same points (see explanation in the previous paragraph), the ICP algorithm iteratively checks the distances between all the points of the point clouds and estimates the transformation to align both sets thus resulting in minimal error.

The rules on target configurations mentioned in the previous paragraph are also applicable to the point configuration in cloud-to-cloud registration.

This registration technique should be used with caution. When scanning long linear structures where multiple setups are required, small errors in each registration pair may propagate and result in large global errors.

Surface-to-surface registration

In 2006, A. Gruen published a new technique to align datasets by matching the surface geometry of two scans. His algorithm estimates the Euclidian distances between surface patches by least squares and tries to minimize this distance iteratively as in the ICP algorithm. This method offers high flexibility for any kind of 3D surface correspondence problem, as well as statistical tools for the analysis of the quality of the final result.

Surface-to-surface registration is especially useful when some of the scans contain substantial quantities of noise. In this case, it is better to first clean and mesh the separate scans so that each scan can be processed using the appropriate settings. When all scans are transformed into surfaces, the surface-to-surface registration can be used to align the different scans.

3.5.2 Direct registration and georeferencing

Direct registration means that the position and orientation of the scanner is directly computed. This can be done in two ways. One example is the laser scanner with some capabilities of a total station, where the scanner can positioned directly over a known point using a laser plummet. The orientation can be determined by scanning only 1 target in the next laser scanner setup position. These laser scanners also have a dual-axis compensator so that they level themselves within certain limits. This levelling imposes a third restriction on the orientation of the scan.

Sometimes, a special reflector is fixed on top of the scanner's vertical rotation axis. The exact position of this reflector to the laser beam centroid can be determined through a calibration procedure. If this position is known the reflector can be measured using a total station as would be done when setting up a closed (or open) polygon for traverse networking. Other ways of determining the scanner's position, is by mounting a GPS receiver to the scanner.

This technique reduces the number of targets to be placed and therefore avoids the quite demanding requirements on the target configuration. The scans also do not need overlap. Taking all these considerations into account, this technique is often faster than using indirect registration.

When geo-referencing is required, the measured reflector position can be transformed into a specific known coordinate system using general surveying techniques.

3.5.3 General aspect of registration and georeferencing

This paragraph describes some advice in care which should be taken when registering datasets or even planning the registration phase. Most of these statements are adopted from a publication by English Heritage [29].

- When performing a registration, make sure the residuals of the global registration process are equal to or better than the geometric precision required by the end deliverable.
- When registration is done solely using resection calculation (indirect), each scan should contain at least 4 appropriately distributed XYZ control points/targets. This over-determines the geometric relationship between the two datasets and therefore a least-squares optimization can be used to minimize errors in the target recordings.
- Always include the residuals of the registration process and the geometric precision of the estimated parameters in the survey report.
- Add illustrative photography/screenshots of irregular features in the scan data caused by cracks or features on the subject that could be misinterpreted as errors in the registration process, and note them in the survey report.
- Do not put artificial targets at places where they obscure important details of the subject. Don't make the targets too large.
- When mounting targets on the surface of the subject, make sure the adhesive does not damage the structure
- Try to avoid the use of natural target points, because they are less accurate than artificial target points.
- The scan control software must be adapted to the type of targets used. Some flat retro-

reflective targets for instance show a Halo effect caused by multiple target returns of the laser energy in the vincity of the target centre. Proper software can reduce the cluster of returns to the target centre e.g. by using intensity-weighting of individual returns [11].

- When artificial targets are scanned under very sharp angles, the automatic target identification tools should not be used, because they give bad results.

3.6 3D point cloud processing

Point cloud processing means the process of transforming the raw registered point cloud into a final deliverable. These deliverables come in a wide variety of formats: cleaned point cloud data, standard 2D drawings (e.g. plans, elevations, cross-sections), fully 3D textured models for walkthrough animations.

Often, scanner companies show impressive videos of point clouds turning into fully textured models in less than one second. However, in reality this process is still very time consuming and is mainly a manual process. In the Figure below, an overview is given of the different steps in the laser scanning process and their grade of automation.

In general, the 3D point cloud processing can be divided into two categories. Deliverables can be extracted straight from the point cloud without further processing, or by first creating a 3D surface model from the point cloud and extracting the deliverables from this surface model. Which method is chosen depends greatly on the required deliverables. For instance, when only a limited number of cross-sections are required, it is better to extract them directly from the point cloud. However, when more sections (+50) are needed, the second method is more efficient because there are automated tools to generate multiple cross-sections from a meshed model. Furthermore, the surface model adds more value and understanding than just a raw registered point cloud.

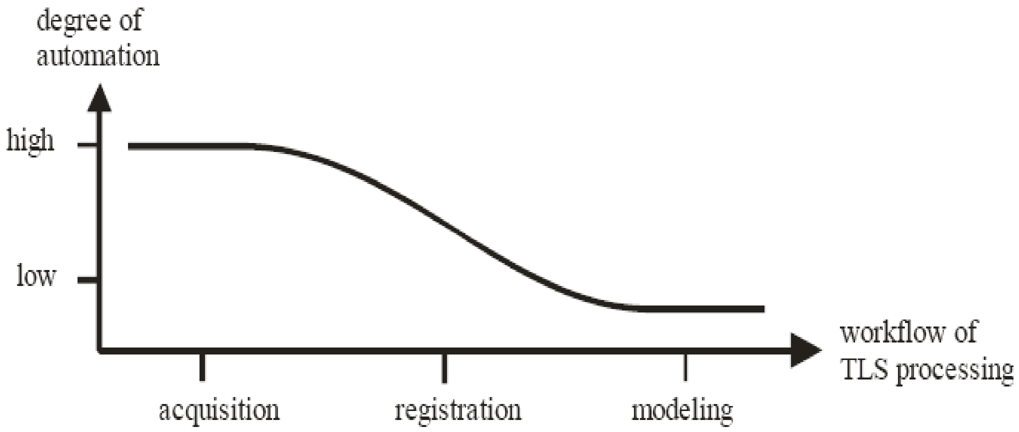


Figure 37 – Automation in terrestrial laser scanning workflow

3.6.1 *Point cloud representations*

The result of a scan acquisition is a huge number of points in space, each having an x, y, z coordinate and usually a laser reflectance value. Some scanners even provide colour information in the form of RGB values.

The point cloud can be represented by drawing all these points on the screen, but this gives a very chaotic impression and a user will have difficulties recognizing structures from the cloud. When every point is given its reflectance value or a colour value, the overall structure becomes understandable.

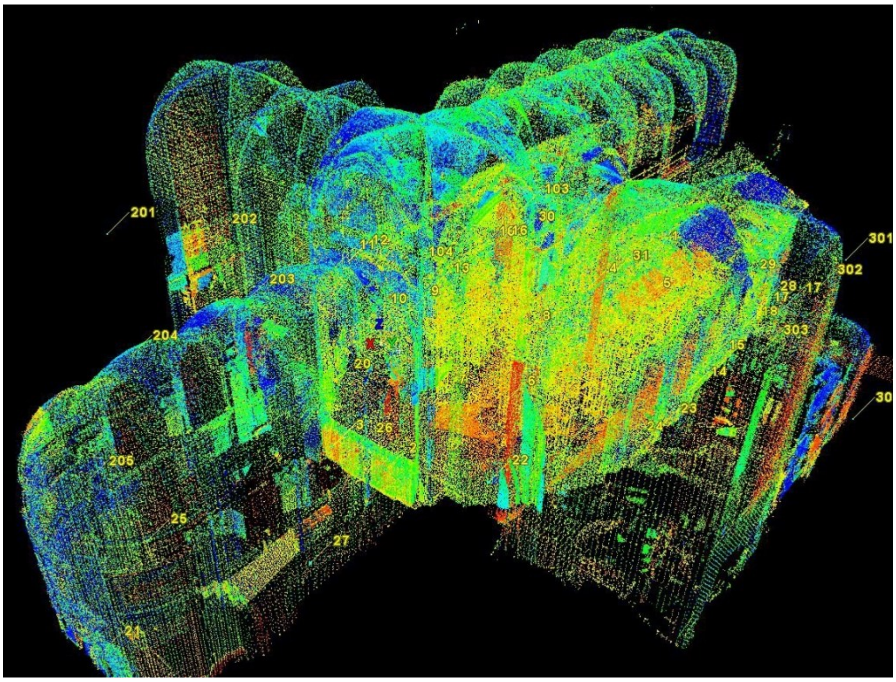


Figure 38 – Unorganized point cloud

Since most laser scanners scan a scene in columns and rows, one way to represent a point cloud is in a very simple way is as a depth map. A depth map is a matrix-like structure (2D) in which each pixel represents the distance of the 3D point to the scanner in the form of a grey value. Because this type of representation incorporates neighbouring information, it is of great use in point cloud processing algorithms and is known as an organized point cloud.

Figure 39 – Depth map

By using complex meshing (triangulation) algorithms, neighbouring points can be connected to form surfaces. This provides a closer representation to reality because surface structures or meshes are not transparent, therefore points lying behind others cannot be seen. By computing the local normal directions of the surface, artificial shading can be used to highlight surface details.

Because the generation of a mesh, especially from an unorganized point cloud, is complex and can take considerable time, there have been attempts to find alternatives to quickly make a coarse representation of the cloud just for viewing and analyzing. As a result, the idea of laser point splatting was launched. Point splatting generates surfels (small surface elements) for each point in the cloud from the raw laser scanner data. Each surfel is represented by a small primitive surface shape (circle, ellipse …) in 3D that inherits its normal computed from its neighbouring points. This results in a very high speed surface representation.

3.6.2 Data improvement

Noise filtering

A first step in the meshing process is removing noisy data from the point cloud. If noise has been introduced due to wind, bad surface reflection, etc. (see chapter 2.6), the mesh will contain triangles connecting these noisy points to correct points. This results in a mesh full of spikes. It is therefore important to remove these noisy points in the first step.

Often, an operator can easily identify parts that are scanned, but are not required in the final deliverable. Therefore, it is advised that this operator performs a first analysis of the point cloud and removes all the unnecessary points from the dataset by hand.

Automatic algorithms that remove noisy points are mainly based on two principles. The first principle is the fact that points that have little or no other points in their direct surroundings, are considers to be outliers. They probably originate from people or other obstacles moving in front of the scanner while scanning is in progress and are not part of the object to be scanned. These points can easily be identified using a limited number of parameter settings and then be removed from the point cloud.

Another noise removal principle is to move points slightly so as to achieve an optimal smoothness of the surface. These algorithms try to locally fit (freeform) planes to the points in the point cloud. When the central point lies very far from the fitted plane, it is moved towards the plane so as to provide more consistency to its neighbours.

Other noise filters exist, some specialized according to scanner type, others removing systematic errors. Of course, care has to be taken when removing noisy points. Features can be lost when over-smoothing the dataset or removing too many points.

Resampling

As mentioned earlier, when creating a mesh, the triangle count is more than double the point count. A meshed version of a phase based point cloud can easily measure up to 20 million triangles. This number of triangles becomes difficult to work with using standard hardware. In general, the number of points needs to be reduced before meshing and this point reduction can be done in two ways.

The easiest way of reducing the number of points, is by deleting one point within every few other points. When based on their 3D spatial position, points can be removed while keeping full coverage of the area. However this technique possibly removes points in areas that contain important features and therefore may remove valuable information.

Another way of removing points is by looking at the surface curvature to determine whether a surface part is smooth or is highly curved. This point cloud resampling technique works intelligently, keeping valuable points in areas of high curvature, while removing points in areas that can easily be represented by fewer points. Using this technique, a proper reduction of the original point cloud size can be achieved without losing valuable features.

3.6.3 Direct 2D modelling from point clouds

Direct 2D modelling from point clouds is a matter of human interpretation. Most available software packages in this domain are plug-ins for CAD packages like AutoCAD or MicroStation. Special interfaces let the user load huge point clouds into these programs to process them using the standard CAD tools. Typical software to perform these tasks are: Leica CloudWorx, Kubit Pointcloud, LFM CAD Link, …)

Cross-sections, plans and elevations can be generated by taking a thin slice of points from the point cloud and projecting all the points onto a plane. Then the user has to manually trace or connect the points creating lines, arcs, etc. The user makes an interpretation about corners and details that are smaller than the scan resolution. This is a precise and difficult task and may take considerable time to complete just one cross-section or plan. The person performing this task must have a proper understanding of the building or structure or have photographic material at their disposal to make the correct interpretations.

In some research centres, academics create algorithms that can automate these tasks. A number of these algorithms have proved to be useful; however they need certain restrictions to generate satisfying results. This means that they cannot be used in a generic way and thus are not yet implemented in commercially available software.

Elevations can be created in two ways. When there is colour information available through photographs, or the laser beam reflection intensity is available, the coloured points can be orthogonally projected to a plane, generating a true ortho-photograph. By tracing this ortho-photograph, an elevation can be made. An important note to make is that the accuracy of the elevation depends highly on the resolution of the scan.

Another way of creating an elevation is by tracing important edges (e.g. window openings, door openings, etc.) in the 3D point cloud and then projecting all these 3D entities into a plane. This technique requires a good geometrical understanding and a capability for recognizing structures in point clouds quickly.

Some software packages allow the user to register external images to the point cloud and use these for mono-plotting. This means that the interpretation is done in the image and the depth information is gathered from the point cloud. The problem with this type of software is that the results should always be double checked, because tracing an edge in an image often is misinterpreted by the software due to missing data and therefore is not generated in its correct position.

3.6.4 Direct 3D modelling from point clouds

When the shape of a 3D object is known beforehand and it can be described by geometric primitives, it can be automatically detected from a point cloud. When fitting these geometric shapes to the point cloud, the algorithm makes an assumption that it is an ideal shape. For instance, a scan of a petrochemical plant can be easily converted into a 3D model, assuming the fact that all pipes have a circular cross-section and the connecting pieces also have a specific shape. Most of these applications are applied to the petrochemical industry.

3.6.5 3D modelling of complex surfaces

In general, the final product of the 3D modelling process is a meshed surface model. By connecting all the points in the point cloud with small triangles, a surface model or mesh is generated. This mesh is an interpolation of the points in three dimensions creating a full surface representation. To create a quality mesh, a number of steps have to be followed:

- Data cleaning (noise reduction, removing outliers…)
- Resampling (see 3.6.2.2)
- Meshing/triangulation
- Hole filling (bridging, merging…)
- Mesh optimizing (decimation…)

Meshing/triangulation

Different algorithms exist to create meshes from point clouds. The connections between points are usually made out of triangles or quadrilaterals. By far the most popular of the triangle and tetrahedral meshing techniques are those utilizing the Delaunay criterion. In recent years, more complex meshing algorithms like the ball pivoting algorithm or the marching cubes algorithm have been developed which are able to triangulate huge datasets withlow memory consumption.

Hole fitting

In recent years, more complex meshing algorithms like the ball pivoting algorithm or the marching cubes algorithm have been developed which are able to triangulate huge datasets with low memory consumption.

Mesh optimisation

Although the point cloud has been reduced during resampling to create lesser triangles in the mesh, it might be necessary to reduce the number of triangles in the mesh in a second step to overcome hardware capabilities. This is called mesh decimation.

Other ways of optimizing the surface description is by approximating it using mathematical surfaces. One of the most commonly used surface types for this task is NURBS (Non Uniform Rational Basis functions). These nurbs are mathematical precise representations of freeform surfaces like those in car bodies, ship hulls or even the human face. They have control points, which direct the surface; however these control points are not necessarily points of the point cloud.

3.6.6 Indirect 2D modelling from point clouds

Indirect 2D modelling means generating 2D drawings from 3D modelled or meshed objects. This technique is useful when multiple cross-sections have to be made, for instance one cross section every 1 centimetre to be able to create a depth contour map.

Indirect modelling requires a 3D modelling phase as described in chapter 3.6.5. Once a surface model has been created it can easily be intersected by planes to create cross-sections. The interpolation of areas in-between the measured points, is automatically done in the meshing phase and does not need to be performed by an operator.

3.6.7 Texture mapping

A texture map (i.e. colour information or other) is mapped to the surface of a shape, or polygon. To correctly place the texture information UV maps are used (see Figure 49). In contrast to x, y and z, which are the coordinates for the original 3D object in the modelling space, "U" and "V" are the coordinates of the transformed object. UV mapping transforms the 3D object/mesh onto a flat image which can then be used to attach textural information. This mesh transformation can also be described as an unfolding or pelting of the 3D shape onto a 2D canvas.

When a model is created as a polygon mesh using a 3D modeller, UV coordinates can be generated for each vertex in the mesh. One way is for the 3D modeller to unfold the triangle mesh at the seams, automatically laying out the triangles on a flat page. A UV map can either be generated automatically by the software application, made manually by the artist, or a combination of both. Commonly used maps are, height maps, normal maps, displacement maps, light maps, specular and bump maps.

Once the UV map is created, the user can paint/colour this UV map and then project it back to the 3D model, making it easier to correctly colourize a 3D model.

Instead of using UV maps, some 3D software packages also have an option to project and bake the texture information onto the surface, usually using orthographic projections, which simplifies the texturing process.

Unfolding is preferred over projections because of minimal texture stretching. Both techniques can be used and mixed in a single 3D model.

In laser scanning, often high resolution photographic information is required for visualization of 3D models. For accurate mapping, the positions of the cameras and the internal camera settings (focal length, lens distortions…) have to be known in relation to the model. Commercial software packages provide algorithms that allow the user to manually select corresponding points between the image and the 3D model to determine these unknown parameters. Given enough correspondence, the position and parameters of the camera can be calculated.

Mainly two different algorithms exist to project photographs onto the 3D model, texture mapping and texture draping. Texture draping can be described as putting the photograph onto a piece of elastic canvas and then pulling it over the 3D model. This implies that areas that do not contain a lot of information or no information at all in the photograph (for instance very oblique surfaces) will be stretched and are therefore not textured correctly. Texture mapping overcomes this problem by first analyzing the visible parts in the image and then only projecting these photo pixels onto the 3D model.

The detail of the texture map is dependent on the resolution, this is mostly defined as power of two (i.e. 512*256, 1024*1024) which is best for graphic memory. The new generation of graphic cards is more capable of handling textures which do not have power of two.

3.7 Quality control and delivery

The quality aspect of surveying using laser scanners needs careful consideration throughout the measurement and processing process. Each time the scanner is set up to capture data (before, during and after) certain elements of the data should be inspected and checked against expected or predicted results. The most technical factors that might have an influence on the quality of the data have been explained, in detail, in 2.6. In addition to these factors, scanner operators should also be checking factors such as sufficient area coverage, even point distribution with required resolution, reference photography with high resolution camera, correct acquisition of reflective scanner targets and acquiring additional check dimensions which would be very useful at further processing steps.

Quality starts with a full understanding of project specification. This understanding allows the correct choice of scanner, correct scan resolution, appropriate registration method and so on. For example, choosing a scanner which has insufficient range, not using enough scan targets and positions, not allowing appropriate overlap (if decided to register your scans using overlapping scans), and most importantly, not using the correct scan resolution will have a direct effect on the quality of the end product when produced from point cloud data.

Adequate on-site documentation ensures the achieving of optimum quality. Supporting sketches, reference photography, check dimensions would be used in later processing steps.

In general, the aim should be to reach a registration accuracy ten times smaller than the accuracy of the required deliverable. Keeping this in mind, there are many other elements that might have an effect on accuracy; so it is always better to aim for the best registration results.

The flowchart in the next page, (Figure 40) gives an overview of quality assurance for laser scanning surveying.

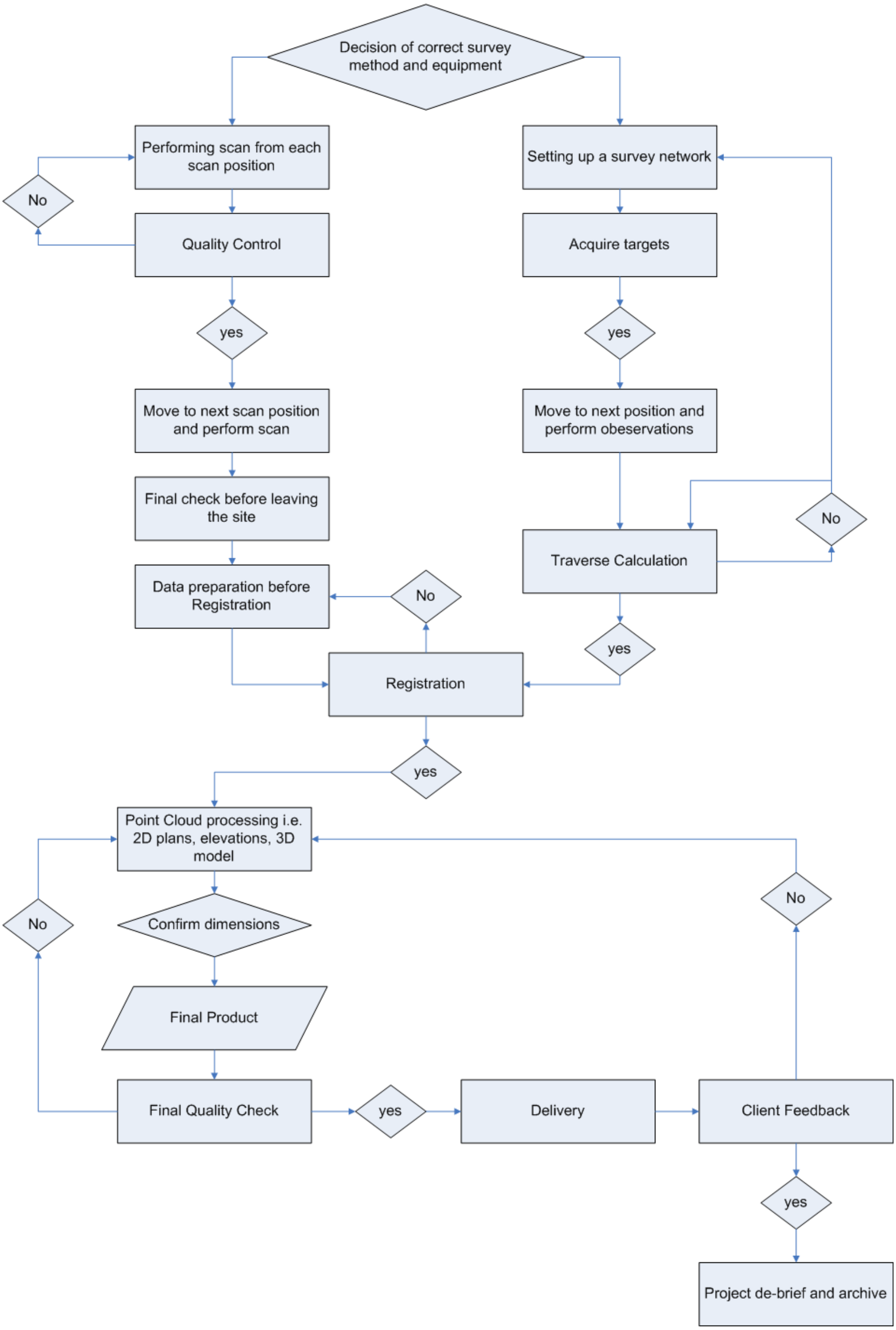


Figure 40 – Quality control flowchart