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COMBINATION OF PHOTOGRAMMETRY AND TERRESTRIAL LASERSCANNING – POTENTIALS AND LIMITATIONS. PART 1: OVERVIEW AND PERFORMANCE FEATURES

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1. Introduction

Photogrammetry and laserscanning are highly developed and reliable 3D measuring principles that are established as standard methods in a variety of application areas. Especially in industrial and terrestrial tasks more and more applications are developed that address new challenges in optical 3D metrology. In particular, the combination of laser-based measuring methods with image-based recording and processing tools create an interesting and promising potential.

The topic has recently been discussed by several authors with different points of view. Comprehensive overviews about the combination of photogrammetry and laserscanning are presented by, as examples, Kersten et al. (2006), Przybilla (2005) or Jansa et al. (2004). This paper tries to give an up-to-date overview with particular interest to aspects of industrial metrology, discussing also potential and limitations.

Basically photogrammetry is used in practice since about 150 years. Digital photogrammetry was developed since around 1985, and is available in operational systems since about 1990. The consequent use of the digital image has led to a fundamental change in photogrammetry (Ackermann 1995). Besides higher image quality and data rate, improved measuring accuracy, better price-performance ration etc. new possibilities are offered by integration of photogrammetry into online and real-time processes, e.g. for industrial production control.

Since the 1990ies 3D laserscanning has been deployed in practice by airborne systems (LIDAR, Airborne Laserscanning ALS) (Ackermann 1999). Today digital terrain models (DTM), city and landscape models are usually generated by ALS. Since about ten years terrestrial laserscanning (TLS) is available as an operational method in practice. Major application areas are the modeling of buildings, historical landmarks, lines and driving surfaces, industrial plants etc., i.e. large volume objects consisting of free-form surfaces (overviews given by Vosselman & Maas 2010, Staiger 2005). Even modern motorized and reflectorless tacheometers can be classified as (simple) 3D laserscanners (Scherer 2007). However, for industrial applications fringe projection systems (white light scanners) and laser-line projectors are mainly used. For high accurate single point measurements usually laser tracker and laser radar systems are applied that, in principle, can also be used as (slow) scanning instruments for free-form surfaces.

The presented measuring methods can be combined to use the strength of each method. By laser projection of lines or points and image acquisition by one or more cameras arbitrary surfaces with diffuse reflection properties can be measured. Using single cameras approaches the projection unit must be calibrated and oriented in order to solve the triangulation problem. Using two or more synchronized cameras the laser projection device is only used to provide a unique texture (see section 3.1).

Fringe projection systems and other surface measuring sensors can be oriented in 3D space. This can be done either by mechanical positioning devices (robot, measuring arm, Fig. 1), by control points on the object surface, which are calibrated by photogrammetric means, or by using a synchronized camera system that tracks the surface measurement sensor continuously (Fig. 2).

Laserscanners and tacheometers can be equipped with digital cameras in order to acquire true color images of the measured object or for image processing, e.g. the automatic measurement of targets or surface reconstruction by stereo image processing.

Finally, 3D point clouds created by laserscanning can be combined with image information in different ways, e.g. for visualization, for identification and measurements of object points, for orthophoto generation or for registration purposes. The following sections start with a summary of the characteristics of both methods including a discussion of their weaknesses and strengths. It is followed by an overview of typical system approaches and algorithmic solutions. Exemplary applications are finally presented which could only be successfully solved by a combined processing of laserscanning and image data.

Performance features

In order to discuss hybrid system concept of photogrammetry and laserscanning it is necessary to evaluate each performance features, strengths and weaknesses. Table 1 summarizes some of the major technical specifications and features of both methods, assuming typical values.

Table 1

Performance features of photogrammetry and laserscanning

	Photogrammetry	Laserscanning
Sensors	CCD, CMOS	angle and distance measurement
Wave lengths	400 – 700 nm (RGB) 700 – 1100 nm (NIR)	monochromatic e.g. 532 nm, 780 nm
Measurement volume	camera view (depending on focal length and configuration)	camera view hybrid view panorama view
Distance range	any (depending on configuration)	ca. 5 – 100 m (phase) ca. 10 – 800 m (pulse)
Accuracy	depending on scale 1:10000 – 1:100000	depending on distance 1:2000 – 1:20000
Resolution	depending on scale	depending on distance and angle
Measuring frequency	up to 2000 Hz per frame	up to 10^6 Hz (points per second)
Stationary object	yes	yes
Moving object	yes	limited
Moving platform	yes	with additional sensors
Point measurement	yes	with targets
Surface measurement	with sufficient texture	yes

3D Coordinates

Photogrammetry allows for the measurement of 2D and 3D object coordinates by visual or digital image interpretation and image analysis of the imaged object patterns. Three-dimensional coordinates are generated either by stereo or multi-image photogrammetry, or by combining monoscopic measurements with given object geometries (e.g. a DTM or 3D point cloud), also denoted as monoplotting. Known camera calibration (interior orientation) and image orientation (exterior orientation) are required for accurate 3D coordinate determination. The actual coordinate calculation is usually given by intersection in space or bundle adjustment. In photogrammetry, accuracy and reliability depend on image configuration (number and position of images in space) and on identification and correspondence analysis of imaged structures (textures). The accuracy in lateral direction can differ from depth accuracy significantly (see section 2.3, overviews in Kraus 2004 and Luhmann 2010).

In contrast, 3D laserscanning is based on a polar method where spatial direction (horizontal and vertical angle) and distance are measured for each scan point. Measurement accuracy is mainly a function of angular and range measurement quality, whereby the latter one is influenced by the characteristics of object material (reflectance properties) and atmosphere (e.g. refraction). See Sternberg et al. (2005) and Vosselman & Maas (2010) for further information.

With photogrammetry plane or known object surfaces can be measured even in a single image. In all other cases at least two, but in principle an unlimited number of images can be used. The images are oriented by corresponding tie points while the object coordinate system is defined by(few) control points. Using TLS multiple stations are always required if the object cannot be observed by a single standpoint, e.g. due to occlusions. The registration of individual 3D point clouds is solved either by control points or by matching of object features, e.g. based on ICP methods (overview in Staiger & Weber 2007).

Sensor characteristics

One of the most important features of photogrammetry is the simultaneous area-based recording of one or more images that archive the state of the object for time of exposure. Nowadays CCD and CMOS sensors are available with up to 60 Mpixel whereby even up to 250 Mpixel can be acquired with special aerial cameras. The recording of a complete image area allows for image acquisition from moving platforms looking at moving or changing objects. In special cases (e.g. panorama cameras, aerial image scanners) scanning imaging systems are used that are normally not suited for dynamic conditions.

In contrast, laserscanning systems record an object always by sequential scanning. Usually object and measuring system must be stable with respect to each other for the time of measurement. If a laserscanner is operated from a moving platform (e.g. ALS, mobile mapping), each single scan must be oriented in space, for example by synchronous GPS/INS systems, tilt or acceleration sensors (e.g. Schwarz & El-Sheimy 2004, Kutterer 2010).

Photogrammetric images are usually recorded in the complete visual spectrum up to near infrared (ca. 1000 nm), hence they consist of a high degree of radiometric information. Radiometric image quality is basically depending on illumination conditions. In contrast, laser-based system work in monochromatic mode only. Applied laser wave lengths are available in the visual range (e.g. 630 nm) and in the near infrared range (e.g. 780 nm) as well.

Resolution and accuracy

In the first instance the geometric resolution of both methods is a function of measuring distance or scale. For photogrammetric systems the lateral structural resolution is defined by pixel size of the imaging sensor and imaging

$$\Delta X = mb \cdot \Delta x \cdot pix. \quad (1)$$

In accordance to the Shannon sampling theorem at least two pixels are required to resolve an object element. In fact even smaller objects (e.g. thin linear features) can be detected if they are smaller than 1 pixel but provide sufficient contrast. In addition the term resolution is also used for the ability of a system to detect motion or change of position of an object significantly. In this case resolution and accuracy are correlated. The lateral geometric resolution of a modern digital camera (pixel size ca. 5µm, 4000 x 3000 pixels) that is imaging a 10 m object in full format, results to ca. 2.5 mm per pixel. Using a 20mm lens this is equivalent with an angular resolution of ca. 0.25 mrad. Assuming a subpixel measuring accuracy of 1/10 to 1/20 pixel, the accuracy of a spatial direction amounts to ca. 0.012 bis 0.025 mrad, e.g. in the order of 1 mgon.

Photogrammetric resolution and accuracy in viewing direction can only be determined if the object is observed with at least two cameras providing 3D measurements. In this case it must be distinguished between simple stereo configurations and multi-image setups, e.g. allaround configurations. For stereo images the distance accuracy decreases quadratically with distance as a function of imaging scale, base-to-height ratio and parallax accuracy (eq. 2). For multi-image configurations equal accuracy can be achieved for all coordinate axes as a function of imaging scale, image measurement accuracy and a design factor *q* that models the design of the image network and other effects (eq. 3). Nowadays the typical accuracy in close-range photogrammetry lies between 1:10000 and 1:100000 of the object dimension with respect to the standardized length measuring error according to VDI 2634 (Luhmann & Robson 2008).

$$S_{XY} = m_b \cdot s_{x'y'}, \quad S_Z = m_b \cdot \frac{h}{b} \cdot s_{px} = \frac{h^2}{b \cdot c} \cdot s_{px},$$
$$S_{XYZ} = q \cdot m_b \cdot s_{x'y'}. \quad (2)$$

The geometric resolution of a laser scanner depends on scanning frequency, beam divergence at the object, angular resolution and distance measurement resolution. Thus the signal of a single scanning spot is given by the integral of reflection of the area that is covered by the laser beam. Typically beam divergence of the laser is in the order of 0.25 mrad, i.e. in 10 m distance it is about 2.5 mm, in 100 m distance about 25 mm^2. Assuming an angular resolution of ca. 0.05 mrad the resulting resolution in object space is about 0.5 mm for 10 m distance and 5 mm in 100 m distance, respectively. In addition, the minimal distance of two adjacent scanning points is a function of scanning frequency and scanning step width, hence it increases linearly with distance range. Depth measurement accuracy is mainly a function of the range metering accuracy and can be estimated between 0.5 mm (phase difference) and 5 mm (pulse) in a distance of 10 – 50 m. Investigations about resolution and measuring accuracy are reported by, as examples, Kersten et al. (2009), Mechelke et al. (2007), Böhler (2005), Schäfer & Schulz (2005), Böhler & Marbs (2004), Mulsow et al. (2004).

Fig. 3 displays example calculations of theoretical precision in photogrammetry and laserscanning for an object point in a distance of about 40 m, thus a distance where the combination of both methods is reasonable. Three approaches are discussed: a) a simple stereo image pair (base line 5 m, image measuring accuracy ½ pixel) for the measurement of a non-targeted object (e.g. building façade); b) a multiimage set with target points as it typically occurs in industrial applications (design factor 0.7, image measuring accuracy 1/10 pixel); c) a laserscan measurement with an angular resolution of 0.05 mrad and a distance measurement accuracy of 5 mm.

Typical values, individual devices can show different values *S*/40000. Since the industrial multi-image approach provides highest accuracy, TLS and stereophotogrammetry cover a similar accuracy performance. However, the photogrammetric accuracy for a stereo image pair depends on the base-to-height ratio and image scale as a square function, leading to an error of about 10 mm in a distance of 20 m for this example. Consequently, TLS is most advantageous in distances larger than 15-20 m.

Geometric and radiometric resolution is most important for the detectability of object features. Hence natural features like object edge can only be reconstructed from 3D point clouds if a computational interpolation of adjacent object patches is performed, e.g. intersection of two planes. In contrast the photographic image shows object edges correctly but depending on illumination characteristics. In addition 3D point clouds consist of only no or limited information about object features that can are not formed by variations of the object surface, e.g. small gaps, dirt spots or coloured features. In general the photographic RGB image can be interpreted much easier than a 3D point cloud even in the case where the intensity of the reflected laser beam is recorded (see Fig. 4, Fig. 5).

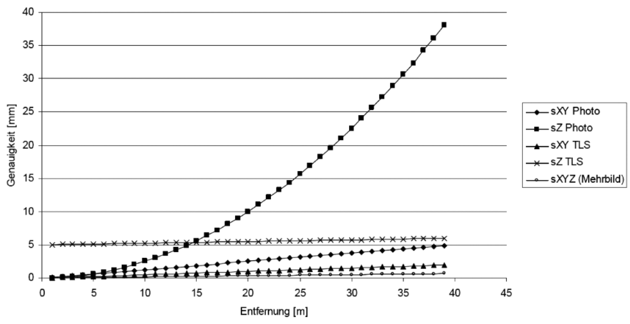

Fig. 3: Example accuracies for photogrammetry and laserscanning stereophotogrammetry: c=20 mm, dx'=2.5μ m, b=5 m multi-image photogrammetry: c=20 mm, dx'=0.5μ m, q=0.7 laserscanning: dα=0.05 mrad, dS=5 mm+S/40000

Fig. 1. Laser profiling sensor on articulating arm (API)

Fig. 2. Camera-based navigation of a surface measuring sensor (NDI, Steinbichler)

Fig. 4. Intensity image (left) vs. colour image (right) for an industrial plant (by Przybilla 2005)

a *b*

Fig. 5. 3D measurement of a sculpture using laserscanning:
a – intensity image; b – superimposition with RGB image

Operational aspects

The pros and cons of both measuring methods should not only be addressed to technical specifications but also on aspects like practical handling, required processing software, invest and maintenance costs, personal requirements and so on.

Basically the costs for photogrammetry cameras and equipment were getting lower in recent years, usually aligned with higher performances. The main reasons are in cheaper digital cameras and the increased use of low-cost programs that offer the full range of photogrammetric processes (camera calibration, bundle adjustment, automated point measurement, CAD functionality) for less than 1000 US$. In addition the existing degree of automation allows system use even by non-skilled personal. With sufficient project planning also short working times on site, high mobility and reduced effort for additional measurements (e.g. control points) is possible.

Investment costs for productive terrestrial laserscanners lie in the order of 80000 to 150000 US$ with strong tendencies to lower prices, e.g. Faro Focus3D for about 30000 US$). Assuming typical amortisation and times of use, a laser scanner costs easily in the range of 1000 US$ per effective working day. In addition more or less large effort has to be taken into account for data processing of unstructured point clouds. The degree of automation in the 3D point cloud processing is still low.

Summary

The first part of this article has given an overview about principle solutions, advantages and disadvantages of photogrammetry and laserscanning in the field of close-range measuring applications. Since every single method shows its own characteristics and benefits, the combination, integration and fusion of photogrammetric image data with terrestrial laserscanning seems to offer a number of additional advantages.

Part 2 of this article will deal with alghorithmic aspects of hybrid systems and potential applications.

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Комбінація фотограмметрії та наземного лазерного сканування – можливості та обмеження. Частина 1. Огляд та експлуатаційні характеристики

Т. Люмен

Описано сучасні розробки та застосування для комбінації цифрової фотограмметрії та наземного лазерного сканування. Обидва методи мають певні переваги, які можуть доповнювати одна одну. Основною перевагою лазерного сканування є можливість вимірювання 3D хмар точок об’єктів, тоді як фотограмметричні методи дешеві у використанні. Розглянуто аспекти точності, вартість системи, комбіновані конфігурації системи з практичними прикладами.

Комбинация фотограмметрии и наземного лазерного сканирования – возможности и ограничения. Часть 1. Обзор и эксплуатационные характеристики

Т. Люмен

Описаны современные разработки и применения для комбинации цифровой фотограмметрии и наземного лазерного сканирования. Оба метода имеют определенные преимущества, которые могут дополнять друг друга. Основным преимуществом лазерного сканирования является возможность измерения 3D облаков точек объектов, тогда как фотограмметрические методы являются дешевыми в использовании. Рассмотрено аспекты точности, стоимость системы, комбинированные конфигурации системы с практическими примерами.

Combination of Photogrammetry and Terrestrial Laserscanning – Potentials and Limitations. Part 1: Overview and Performance Features

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This article discusses recent developments and applications for the combination of digital photogrammetry and terrestrial laser scanning. Both methods provide a number of advantages that can be added to benefit from both. The major strength of laserscanning is the measurement of 3D point clouds of arbitrary objects while photogrammetry offers fast object recording, images as documents and data storage and low costs for equipment. The paper addresses aspects of accuracy, system costs, combined system configurations and applications with a number of practical examples.