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Spherical target-based calibration of terrestrial laser scanner intensity. Application to colour information computation

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ABSTRACT

Terrestrial Laser Scanning (TLS) acquires for each scanned point its position and an intensity. Intensity of TLS is based on a measure of the electronic signal strength which is obtained by converting and amplifying the backscattered optical power of the emitted signal. In this paper, theoretical radar equation is established and particular attention is given to the necessary assumptions. A low-cost intensity calibration method is proposed that provides measurements insensitive to range and incidence angle. This process is data driven without simplifying assumption about radiometrical properties of the spherical calibration target. For the commercial device considered, the laser wavelength is 532 nm. It enables us to measure green levels. Intensity is interpreted for each point of 3D clouds in terms of green level in sRGB colour space viewed under CIE standard illuminant D65. Applications are realized on a data set acquired at Amiens cathedral. There is no more shading or multi-exposure effects compared with high-resolution camera colourisation.

1. Introduction

Terrestrial Laser Scanning (TLS) acquires for each scanned point of a scene its range and angular measurements at this point, leading to coordinates and, an additional attribute, inaccurately called intensity. Such usage leads to confusion with radiometric and photometric terminologies. Indeed the latter intensity is based on a measure of the electronic signal strength which is obtained by converting and amplifying the backscattered optical power of the emitted signal (Pfeifer et al., 2007). Due to the difficulty of its interpretation, that intensity is used in specific applications. For light detection and ranging (LIDAR), practical applications are data registration, feature extraction, classification, surface analysis, segmentation, and object detection and recognition (Kashani et al., 2015). However according to Kashani et al. (2015) there is no standard approach for correction or calibration implemented across manufacturers. Dias et al. (2002) demonstrate that both camera intensity and laser range data can be registered and combined into a long-range 3D system.

In Eitel et al. (2010) the green laser return intensity value was strongly correlated with wet-chemically determined chlorophyll a and b content of two tree species. According to Gaulton et al. (2013) sensitivities to range, incidence angle and scattering area of the target within the laser beam are factors that make exploiting single-wavelength laser scanner intensity difficult for leaf biochemical properties setting. Therefore, they propose the use of dual-wavelength laser scanning systems. One of this paper's contributions is to propose a calibration process for TLS intensity that provides measurements insensitive to both range and incidence angle.

Indeed TLS intensity depends on various factors: the laser scanning device itself (mechanic and electronic elements), incidence angle, range, roughness of surface, surface composition and moisture content (Carrea et al., 2016; Kashani et al., 2015), to mention the most obvious factors only. Instrumental factors affect the range effect on intensity and their influences are different for various TLS devices, so they must be studied individually for each instrument (Krooks et al., 2013). Application of our intensity calibration process deals with green single-wavelength laser and colour information computation at each measured point.

The set of 3D scene points measured by the TLS constitutes a point cloud that describes well the geometry of the scene. But colour is needed to better understand the point cloud, at least for visualisation. Thus, TLS devices may be equipped with a digital camera that scans the environment, after the laser scanning process, taking images to give a colour to each 3D point. The latter colourisation depends first on accurate extrinsic calibration between the laser scanner and the camera, i.e. camera's interior orientation and relative orientation of camera and TLS instrument must be precisely known. Then, camera settings (exposure time, white balance, gain) and image resolution have an obvious impact on the colourisation quality. Furthermore, the dynamics of the camera colour measurement is generally low, easily dealing to shadows and over or under-exposed images, thus colouring the

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3D points with a low quality. Finally, the sequential process of laser scanning followed by the camera scanning may lead to inconsistency between the geometry and colours, mainly due to occlusions, if people, objects, or even the device itself, moved between the two steps.

The intensity being measured for each 3D point, it is not influenced by resolution, extrinsic calibration and occlusions issues encountered with the addition of a camera to the TLS. Furthermore, since the simultaneous collection of both range and intensity is based on a monochromatic pulsed laser, global or local illuminations from external sources have little impact on the intensity, thus avoiding the over and under-exposition issues. One may note that the colour dynamics issue is currently dealt considering HDRi (High Dynamic Range imaging, see Mantiuk et al. (2015)). However, HDRi does not solve the other issues as extrinsic calibration. It even emphasises the sequential acquisition effect, since it needs several camera scans with different exposure settings, thus leading to even more potential occlusions, and increases the acquisition time length. Finally, the resolution issue, that may be highly irregular in some scenes, as heritage buildings with many detailed sculptures at various ranges, would never be solved, or only at the price of, at most, one image acquisition per 3D point, thus exponentially increasing the acquisition time.

The part of the 3D point cloud colour that is recovered by the method described in this paper depends on the laser scanner wavelength. For the Leica ScanStation C10 device considered in this work, the laser wavelength is 532 nm. This choice of laser wavelength enables us to measure the green level of each 3D point from the TLS data. The contributions of this work are twofold:

1. Correction of the intensity, i.e. eliminate the effects of both range and incidence angle on intensity, by a point-to-point linear comparison between the intensity of a 3D point in a cloud and in the case of a spherical target (same range and same incidence angle), acquired in a calibration process.
2. Green level computation, i.e. transforming the corrected intensity in the standard Red-Green-Blue (sRGB) thanks to colour calibration with a colour checker.

To our knowledge the use of a spherical target is new for intensity calibration of a 3D scanner. Similar TLS intensity linear calibration process by distance information is considered with white discoid targets (Guarneri et al., 2012) placed at different ranges and illuminated by three continuous-wave monochromatic laser sources (Red: 680 nm; Green: 532 nm; Blue: 460 nm). Moreover the spherical geometry of our target provides studies of various incidence angles between 0 and 90 degrees, thus taking into account more precisely the influence of the incidence angle on measured intensity. Practically, it also clearly reduces the acquisition time in the calibration process since the sphere does not need to be rotated to get various incidence angles, contrary to the flat target, obviously. Moreover the calibration process is performed by Minolta spectrophotometer-CM-2600d in Guarneri et al. (2012). Danielis et al. (2015) propose a nonlinear calibration for compensating the input-output characteristics of the optoelectronics system that are specific to the laser scanner prototype considered. In Guarneri et al. (2015) the surfaces are considered almost Lambertian and consequently the power of the back reflected signal is proportional to the product of the reflectance by the cosine of the incidence angle. We don't make the previous restrictive assumption. Furthermore our method allows to work with linear equations in a nonlinear colour space, namely standard RGB colour space. Finally, since considering three wavelengths corresponding to the red, green and blue, Guarneri et al. (2012, 2015), Danielis et al. (2015) get the three colour channels of each scanned 3D point. But they use a specific device called RGB-ITR colour laser scanner prototype with an amplitude-modulation range finding technique. In our work, commercial Leica ScanStation C10 device is considered. Furthermore, our intensity calibration method can straightforwardly be transferred to other devices.

The remaining of the paper is organised as follows. First, the intensity given by the scanner is studied (Section 2): the received signal power is expressed in terms of various parameters for a Lambertian reflector. These results are shown to be both consistent with the simplified radar equation and difficult to use practically. Secondly, based on spherical target-based calibration, interpretation and transformation of intensity to the green level in sRGB colour space are proposed (Section 2). After that, the spherical target-based intensity calibration method is presented and validated (Section 3). Application based on intensity calibration and transformation to the green level in sRGB colour space is proposed. Finally, results for several applications of the contributing method on 3D scans of objects and scenes are presented and discussed in Section 4 before conclusion (Section 5).

2. Terrestrial laser scanner intensity

2.1. Received signal power

In this article, surfaces of studied materials are neither transparent nor highly-reflective.

Raw intensity noted $\mathscr{I}_{raw}$ that is returned by the scanner is proportional to the power ϕ_r (in watt) of the signal received to the detector (Carrea et al., 2016). The following assumptions are made for the content. The laser beam can be considered as infinitely thin without any lateral extension. The point M represents the point of incidence on the target. The laser beam emits the power ϕ_0 that is completely intercepted by the target. Every point on the target is considered to be a Lambertian reflector. $1-\eta(\mathrm{M}, \lambda)$ represents the absorption coefficient of the target at the point M for a specific wavelength λ. The entrance surface of the light receiver is a disk with a diameter D (receiver aperture diameter).

After calculation (see Appendix A), the received signal power $\phi_r$is:

$$\phi_r = \frac{2\eta_{rough}(\mathrm{M})\eta(\mathrm{M}, \lambda)\phi_0}{3}\cos^2(i_t)(1-\cos^3(\theta_{max})) \tag{1}$$

where d is the range between the sensor and the target, i_t is the incidence angle between the laser beam and the target area and $\theta_{max} = \arctan(D/2d)$.

As $d \gg D$, and for the first non-zero order of D/d, the Taylor expansion of the previous result gives:

$$\phi_r = \eta_{rough}(\mathrm{M})\eta(\mathrm{M}, \lambda)\phi_0\frac{D^2\cos^2(i_t)}{4d^2} \tag{2}$$

Under Lambertian assumption, the value $\rho(\mathrm{M}, \lambda) = \eta_{rough}(\mathrm{M})\eta(\mathrm{M}, \lambda)\cos(i_t)$ is often called reflectivity (or directional reflectance) in M for a wavelength λ. Eq. (2) is equivalent, using reflectivity, to the simplified radar equation that is applicable to lidar (Kashani et al., 2015; Jelalian, 1992; Webster, 1999; Höfle and Pfeifer, 2007):

$$\phi_r = \phi_0\rho(\mathrm{M}, \lambda)\frac{D^2\cos(i_t)}{4d^2} \tag{3}$$

The real world is complex and a lot of materials can't be considered as Lambertian reflector. This assumption is very restrictive and scattering phenomenon has been simplified. Other existing models are either overly simplified or only limited to a small number of materials (Kashani et al., 2015). For example Carrea et al. (2016) uses Oren-Nayar reflectance model to take into account a lithological relief with micro-facets.

Moreover empirical data are inconsistent with a law in "K/d^2" where K is a constant according to Fang et al. (2015). Kaasalainen et al. (2011) find that the range effect is strongly dominated by instrumental factors. Indeed, raw intensity depends on electronic signal processing and a linear system transmission factor, called η_{sys}, is often introduced in our previous cited references: $\mathscr{I}_{raw} \propto \eta_{sys}\phi_r$. In reality there are a lot of unknown couplings, not necessary linear, that are dependant on power ϕ_r, range or incidence angle for example.

Finally because of the previous reasons, in this paper, we choose to