Automation in Construction 94 (2018) 127–134

Contents lists available at ScienceDirect

Automation in Construction

journal homepage: www.elsevier.com/locate/autcon

Terrestrial laser scanning harnessed for moisture detection in building materials – Problems and limitations

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ARTICLE INFO

Keywords:
Terrestrial laser scanning
Non-destructive testing
Moisture
Building materials
Intensity
Surface roughness

ABSTRACT

Since the 1980s, Terrestrial laser scanning is successfully adopted in geodesy for contact-free measurements. Collecting dense point-clouds by using TLS is proven as increasingly useful in several other quasi-geodetic, structural, and civil engineering applications. In the study, the newest trend of harnessing TLS is discussed in association with assessing the properties of a scanned object as opposed to its geometrical location. The most promising area of the aforementioned application of TLS is moisture detection in buildings and structures. The present study involved a thorough research programme dedicated to this topic as described in previous publications. Different scanners utilizing visible green and infrared laser beam were harnessed in the research programme. Such aspects of scanning porous construction materials as roughness, colour and presence of water are analysed. Based on the experience, the possibilities and limitations of harnessing TLS for moisture detection in building materials are discussed in the study.

1. Introduction

Terrestrial Laser Scanner (TLS) is an instrument that uses a laser beam for remote non-destructive measurements. It conducts multiple measurements during a scan and acquires data sets. With respect to each single scanned point, the TLS instrument collects a set of data comprising of vertical angle (φ), horizontal angle (ϑ), distance (r), and the relative *intensity* of the captured signal. These data sets are harnessed to create 2-D or 3-D digital models. The TLS technology is known and used since the 1980s [1, 2]. The most common application of the models created with the help of TLS are different geodetic measurements. Over time, TLS technology is increasingly used for a few civil engineering applications such as the monitoring of bridges [3, 4], structure deformations [5, 6], landslides [7, 8], dams [9, 10], tunnel deformations [11, 12], and façade analysis [13, 14].

Previous studies proposed harnessing the TLS technique for remote and non-destructive assessment of saturation of building materials [15, 16] and saturation movement in walls [17]. A research programme conducted with the aid of two commercially available geodetic TLS proved the viability of the concept. The previous research programme focused on scanning commonly used European building materials (such as ordinary concrete, cellular concrete, red ceramic, and silicate). The tested specimens were in three states of saturation, namely oven dry, saturated only by air humidity, and fully saturated. The specimens were scanned in an indoor environment by TLS from three different distances representing a typical range for indoor building acquisition. Measurements were conducted in the indoor lab conditions by assuming that key factors including the atmospheric transmission factor (η_{Atm}) the system transmission factor (η_{Sys}), and transmitted signal power (P_E) are constant for all tests. Thus, the only variable factors included reflectance of a material (ρ), incidence angle of laser beam, and the distance between a scanner and an observed point. The impact of the changes in the incidence angle and distance may be eliminated through data standardisation (see works of Sasidharan [18], Tan and Cheng [19]). The results indicated that the proposed methodology of saturation related measurements is valid for different TLS types. Simultaneously, a few practical problems and theoretical limitations of the methodology were noted.

2. Contribution

Previous studies conducted additional tests (scanning rough and smooth plaster surfaces, performing colour identification by TLS) and analysis (based both on new and old results) to address specific problems that were encountered during previous research programmes [15–17]. The aim of the current study involves discussing both theoretical and practical aspects of TLS saturation measurements. The measurements are affected by three key factors that can enable or disable effective and reliable moisture detection in building materials. The TLS is an apparatus that is solely dedicated for 3-D distance scans

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https://doi.org/10.1016/j.autcon.2018.06.010
Received 18 April 2018; Received in revised form 9 June 2018; Accepted 18 June 2018
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and is prone to misconducting measurements focused on other properties of scanned objects. In the authors' opinion, harnessing TLS for moisture detection in building materials exhibits significant technical potential and potentially constitutes a viable solution for several nondestructive tests in civil engineering. Given the aforementioned facts, previous studies thoroughly discuss the theoretical background of TLS technology by focussing on the reflection characteristics of a laser beam. This original discussion made it possible to address the problem of surface roughness, colour, and presence of water. The effect of colour and roughness on the absorption and dispersion of the laser signal were described in several studies [20–23]. The analysis of value of intensity was utilised for water leakage detection in metro tunnels [24], damage mapping in buildings and structures [25–27], and LIDAR data classification for object identification [28, 29]. Nevertheless, there is paucity of extant studies that examine the topic in a comprehensive manner. In authors' opinion, it is possible to improve a TLS apparatus (both in terms of equipment characteristics and associated software) and ensure that it is increasingly constitutes flexible and versatile NDT technology.

3. Theoretical background

Terrestrial laser scanning operates on the same principle as Light Detection and Ranging (LiDAR) also known as Airborne Laser Scanner (ALS). The LiDAR/ALS measurements are based on a general laser range equation that is defined as follows [19, 30, 31]:

$$P_R = \frac{P_T D^2 \sigma}{4\pi R^4 \beta_t^2} \eta_{Atm} \eta_{Sys} \tag{1}$$

where:

P_R – received signal power [W], P_T – transmitter power [W], σ – effective target cross section [m^2], R – system range to target [m], D – receiver aperture diameter [m], β_t – the laser beam width [−], η_{Atm} – atmospheric transmission factor [−],η_{Sys} – system transmission factor [−]

The relation between the laser beam width (β_t), aperture illumination constant (K_a), wavelength of the laser light (λ), and aperture diameter (D) is given in Eq. (2) [32, 33]:

$$\beta_t = \frac{K_a \lambda}{D} \tag{2}$$

With respect to the analysis of Eq. (2), it is observed that infrared laser rangefinders exhibit higher beam width than those emitting visible light [33]. The effective target cross-section (also known as backscattering cross-section), σ, is defined by Eq. (3) as follows [31, 32]:

$$\sigma = \frac{4\pi}{\Omega} \rho A_S \tag{3}$$

where:

Ω - scattering solid angle of the target [sr], ρ - target reflectance [−], A_S - target area [m^2]

In case of TLS civil engineering measurements, the reflecting surface exceeds the laser footprint when compared with that of ALS measurements. The scanned object is subsequently termed an extended target. The phenomenon affects the general laser range Eq. (1). The function value of inverse range $1/r^4$ is replaced in the laser range equation with the value $1/r^2$ [32, 34, 35]. The equation is further simplified based on the Lambertian properties of a target. With respect to a perfect Lambertian target, the backscatter power mainly depends on a target reflectivity ρ, angle of incidence Θ, and range to the target R as given in Eq. (4) [36].

$$P_R = \frac{\pi P_T \rho}{4R^2} \eta_{Atm} \eta_{Sys} \cos(\Theta) \tag{4}$$

Although the value of the target reflectivity ρ is affected by multiple factors, the most important include roughness, colour, and saturation of the scanned surface [15, 20, 21]. Unfortunately, the physical significance of the aforementioned factors is typically not adequately addressed by both manufacturers and researchers [33].The importance of all three factors and their effect on TLS civil engineering measurements is discussed in the following parts of the study.

4. Roughness

The roughness of the scanned surface is a key factor for the scattering of a laser beam. The power of a signal received and registered by TLS depends on the scattering characteristics of the surface. When the scanned surface is extremely smooth, it exhibits mirror-like characteristics. This phenomenon is known as specular scattering or specular reflection. In case of a rough surface, the reflection is diffused, and the energy of the incident beam is scattered as the cosine of the angle of reflection (Lambert's law). Most surfaces reflect laser beam as a mixture of both models. The proportion of both types of reflection is associated with the relation between the roughness of the surface (Δh), wavelength (λ), and incidence angle of a laser beam (Θ). Subsequently, a surface can be “rough” for a wavelength and “smooth” for another wavelength [37]. In case of most building materials, a Lambertian scattering that defines an ideal porous surface is observed. The ideal porous surface is defined by the Rayleigh Criterion and Fraunhofer Criterion [38]. The Rayleigh Criterion (Eq. (5)) and Fraunhofer Criterion (Eq. (6)) are valid for the reflected wavefront phase shift $\Delta\varphi$ that is lower than π/2 and π/8 respectively.

$$\Delta h < \frac{\lambda}{8\cos(\Theta)} \tag{5}$$

$$\Delta h < \frac{\lambda}{32\cos(\Theta)} \tag{6}$$

The graphic interpretation of both criterions is shown in Fig. 1.

The reflected wavefront phase shift $\Delta\varphi$ (i.e., the phase difference between two rays scattered from separate points on the surface) is defined as follows:

$$\Delta\phi = 2\Delta h \frac{2\pi}{\lambda} \cos\Theta \tag{7}$$

where:

Δh – scale of the surface roughness, λ – wavelength, Θ – incident angle of the laser beam

During the research programme described in [15, 17], two impulse TLS instruments were used, namely Leica ScanStation C10 and Riegl VZ 400 generating green light beam (λ = 532 nm) and infrared beam (λ = ~800 nm) respectively. By using the Rayleigh Criterion, an ideal porous surface can be easily defined for both TLS. We assume the perpendicular incident of a laser beam ($\theta = 0^g, \cos(0^g) = 1$), and therefore the scale of the surface roughness Δh corresponds to 66.5 nm

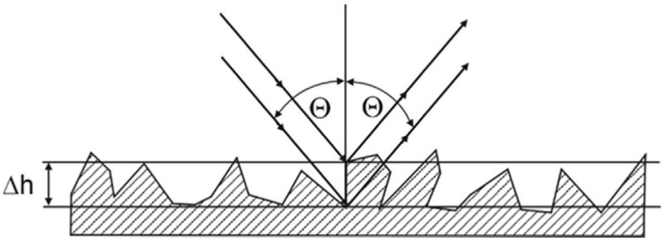

Fig. 1. Reflection of a laser beam on a rough surface.

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