Moisture detection in heritage buildings by 3D laser scanning

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Moisture is one of the main factors in the deterioration of heritage buildings, causing mould, unwanted parasites, and the decanting of salts, which, in turn, aggravate such degradation. The existence of moisture not only affects the building aesthetically, but is also evidence of bad conservation conditions. It is thus extremely important to verify and assess the extent of the moisture, even though it may not be confirmed by mere visual inspection. This article describes an innovative and straightforward procedure to automatically show where moisture appears, as well as the affected area. The procedure is based on the use of 3D laser scanner surveying data for documentation purposes of historic buildings. Data are processed off-line in order to analyse the laser reflectivity level. The method is not intrusive, allows large areas to be covered in a short time, and does not interact with the materials, which makes it optimal for application to these special buildings. Hence, professionals of the conservation sector will have objective and comprehensive information on moisture damage, helping them to take decisions on the action to be undertaken. The results achieved in the Cathedral of Ciudad Rodrigo (Spain) are shown to demonstrate the utility of the proposed method.

Keywords: Moisture detection, Multi-point humidity measurement, Moisture optical measurement systems, 3D laser scanning, Index of reflectivity, Surface reflectivity measurement

Research objective

The present work is aimed at defining a novel, practical method for obtaining 3D digital models that clearly show where moisture appears, and also where it is likely to appear, in heritage buildings. Alternative methods in use are improved, and decision making on the corrective and preventive conservation measures to be adopted by cultural heritage owners or managing organizations will be facilitated. In addition, the competitiveness of related conservation and restoration enterprises will be encouraged.

To this end, an applied research approach is proposed, which combines state-of-the-art 3D data acquisition, with a tailored computational algorithm for managing the reflectivity index provided by laser scanning devices. Hence, a useful unique digital model, including geometrical, colour, and reflectivity information of complex shaped objects, could be readily obtained, thereby favouring not only the cataloguing, but also revealing the moisture content and extension of the original sites.

Introduction

In the construction sector in general, and in the conservation of cultural heritage in particular, moisture detection is carried out by direct visual inspection of walls, baseboards, vaults, and covers, reviewing of pipes, or removing of furniture. Once detected, the humidity content in specific points is measured at the discretion of the expert, using hygrometers or thermo-hygrometers, of which there exists a wide commercial range. Currently, there are no other specific devices for on-site moisture assessment. Wireless temperature and humidity acquisition systems are increasingly used to display real-time curves, but these systems are focussed on environmental monitoring (Yuan, 2010; Zong & Liu, 2012).

Thermography-based techniques, useful in the cases of limited areas (due to the small size of the 2D infrared images), could be used for the qualitative detection

Time, expenditure, and areas to be cleared up can be clearly defined by the proposed method, which has been implemented through a practical tool for handling 3D point clouds, giving support to current and further automatic procedures.

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and location of moisture by skilled operators. However, given that the differences found in the infrared images may correspond to other phenomena than humidity (i.e., temperature differences, air bridges, biofilms, and others), their transcription into images that clearly shows dampness requires the development of complex computer vision applications (Lagüela et al., 2011). This includes considering the regular further corrections to obtain thermal quantitative values, mainly distance to the object, material emissivity, apparent reflected temperature, relative humidity, and atmospheric temperature. Thus, the deployment of additional highly specialized equipment is required (Lehmann et al., 2013).

3D imaging-based systems are in the development stage, but can only be applied in very localized areas and for specific pathologies derived from moisture (Martinho et al., 2012). On the other hand, laser range scanners mainly operate in the visible spectrum, allowing spatial (X, Y, Z) and colour (R, G, B) coordinates to be obtained, as well as, in some cases, the reflectivity index (L) of all those points that are recorded when digitizing a surface (Dias et al., 2003; Arayici, 2007; English Heritage, 2007; Bryan et al., 2009).

The reflectivity index is the fraction of the incident radiation that is reflected by a surface at a given point. The light intensity emitted by the laser scanner is taken as the unit value, then the total amount of light reflected by the material is less than or equal to that value. For example, a mirror (perfect reflector) or a perfect white, have a level of reflectivity of unit value, which means that they reflect 100% of the received intensity. Anyone who has used a time of flight (TOF) or phase shift (PS) scanner has noticed that the reflectivity returned by the scanner can be used to recover some information which goes beyond the geometrical properties, to the point of seeing features invisible to the naked eye (old apertures in walls that have been filled and plastered over, invisible changes of substrate materials, hidden cracks, etc.).

Materials with rough and absorbing surfaces are darker when wet because they reflect less light. Considering this issue, already described by Angstrom (1925), the reflectivity index will be specifically used in this paper for the detection of moisture in historic buildings as an alternative context of application to the latest use of laser scanners for the detection of vegetation moisture content (Neta et al., 2011; Gaulton et al., 2013). Hence, a ‘free addition’ to the typical use of 3D scanners for cultural heritage documentation purposes, will be dealt with. No additional equipment is needed to obtain valuable information on this regard.

The colour information, consigned by either coordinates (R, G, B) or photo-texturing, is not currently used in moisture detection. The usefulness of colour information lies in the resulting 3D model being a trustworthy virtual replica of the original site. Colour could be combined with the reflectivity information for accurate identification (Grammatikopoulos et al., 2004; Iwakiri & Kaneko, 2006; Yuksel et al., 2010; Lerma et al., 2011; Zalama et al., 2011).

It should be expressly noted that the comparison between thermography and 3D scanning for moisture detection in heritage buildings is not intended in the present work. This paper is rather aimed at presenting 3D scanning as a valid option for humidity revealing just using the data registered for documentation purposes (accompanied by quantitative validation with thermo-hygrometers, as required in thermography). As a matter of fact, there exist relevant differences that make the techniques not very comparable: thermography is 2D and scanning is 3D; geometric resolutions are radically different (see ‘Methodology’ section); also the area registered from a single position is quite different (much larger in the case of 3D scanning than in the case of thermal images); thermography operates in the far-infrared spectrum and scanning operates in the near-infrared or the visible spectrum (at just a few wavelengths, in the case of PS technology, or even at a single wavelength, in the case of TOF technology); and thermography and 3D scanning are not subject to corrections under the same influencing parameters.

Furthermore, acquiring the 3D information of the target location in one go is rather unusual. It is often necessary to place the laser scanner in different positions (scan-stations), regarding the area to be measured, in order to obtain the corresponding partial point clouds. It is important to previously plan the optimal number of scan-stations, in such a way that they individually cover the largest possible area, and the geometric resolution to be used for each one.

The reflectivity index value (L) acquired at each point depends on two groups of parameters:

1. Scanning associated parameters: (i) the environment lighting; (ii) the distance between the scanner and the digitized surface; and (iii) the angle between the surface normal and the laser incidence direction at the current point of the surface. Therefore, the raw reflectivity value has to be corrected in order to obtain a refined value, useful for moisture detection and assessment.

2. Scanned surface associated parameters: mainly surface material and surface temperature. The influence of these parameters is minimized both by properly identifying each type of material and recording...
3D data under stable and equivalent temperatures for all scan-stations (problem-free in interiors of churches, cathedrals, castles, and palaces of historical value). Consequently, the reflectivity value is refined for each scan-station data, and transcribed to a colour scale that allows an expert to appreciate the relevant variations. These corrected data are ready to be related to the measurements provided by a thermohygrometer upon on-site identifiable points, according to the colour scale, as the only way to obtain quantitative values of humidity for a certain material.

Finally, the alignment of all views is carried out in a straightforward way. The process can be done upon providing an initial solution by matching pairs of common points between overlapping partial clouds, and then applying the Iterative Closest Point (ICP) algorithm by Rusinkiewicz (2005), or a recent variant that uses colour data for an improved convergence (Gómez et al., 2013).

Having simultaneously obtained the three dimensional coordinates (X, Y, Z) and the level of reflectivity (L), not only current but potential emerging moisture can be clearly visible in the space throughout the 3D point cloud that describes the studied immovable asset, which is not the case when using 2D thermography-based techniques. In any case, it is worth remarking that it is not possible to see how moisture varies within the walls with either a laser scanner or thermography, as both are surface registration methods.

Results achieved in significant areas of the Cathedral of Ciudad Rodrigo (Salamanca, Spain) will enlighten this innovative procedure.

**Methodology**

The scanner used in field work was a LEICA HDS-3000, based on TOF technology, with a data acquisition speed of 1800 points/second. The typical geometric resolution used (vertical and horizontal point-to-point measurement spacing) was 0.02 m at 7 m away to the surface, enough to have a proper density of 3D points and a permissible file size. The typical resolution of 2D thermography technique is 0.1 m at 9.2 m due to the Instantaneous Field of View (IFOV) limits. The scanning was performed on shaded areas to minimize environmental thermal effects.

Once the corresponding point clouds are obtained, they are processed to correct the level of reflectivity following the steps described below, and they are then registered in a common framework (PolyWorks 12.0), as described in Section 2. Two recommendations between consecutive scans are followed in this operation: (i) minimum overlap of 10%; and (ii) at least one change of shape or colour on the original surface.

Controlling the ambient lighting is quite difficult, especially when working outdoors. Scanners usually filter out the spectral range different from the laser wavelength (532 nm in our case), but the direct incidence of the sun on the device’s optics must be avoided by placing the scanner in a shaded location (whenever possible), or even scanning at night if colour information is not required. Bearing this caveat in mind, and knowing that the laser provides a higher light intensity than the ambient lighting, further correction by this factor is not required. Moreover, environmental conditions during data acquisition (such as temperature, air flows, etc.) do not affect the digitizing process given that they are taken in the visible spectrum (or even in the near-infrared depending on the scanning device).

**Correction according to scanning angle and distance**

Leaving the reflectivity index independent of the scanning angle requires a detailed knowledge of how the laser is reflected on a rough, flat surface. Some relevant and physically based light reflection models have been proposed by Torrance and Sparrow (1967), Beckmann and Spizzichino (1987), and Nayar et al. (1989).

The latter has been used in the current work because it provides a unified approach. This model considers that the reflected radiation is the compendium of three primary reflection components: diffuse halo, specular halo, and specular peak (Fig. 1).

The size of the halos and the peaks depends mainly on the material and its surface finish. The more rugged a surface is, the smaller the specular components will be. In general, from a certain angle of incidence (\(\phi_i\)), the scanner will capture only the diffuse halo (Fig. 1A). However, in the case of rough materials, for laser incidence directions close to the surface normal, the sum of the diffuse and the specular halos will be captured (Fig. 1B). The inverse square law has to be considered in order to model the influence of the distance on the measured reflectivity index as well.

The reflectivity measured under a given scanning angle and distance has been incorporated into a
A straightforward algorithm consisting of four steps (Fig. 2):

- The normal direction at every point acquired by the scanner is computed. Then, each point is described by: its 3D coordinates (X, Y, Z); the local normal vector regarding the surface (Nx, Ny, Nz); and a gross reflectivity index (L_gross) (Fig. 3A).
- The incidence angle (\( \Phi_{in} \)) of the laser beam with respect to the normal direction is calculated for every point by means of the scalar product (Fig. 3B).
- If the angle calculated in the previous step is under a user-configurable threshold (\( \Phi_{threshold} \)) (Fig. 3C), it can be assumed that the scanner has acquired the diffuse and the specular halos. The specular peak is negligible because of the roughness inherent to the materials which historic buildings are constructed with. Then, the gross reflectivity value is diminished by a user-defined percentage (\( L_{processed} = P_{adjust} \times L_{gross} \)).
  - If the angle were above the threshold, it is considered that the scanner has acquired only the diffuse halo, then the gross reflectivity value can be kept as it is (\( L_{processed} = L_{gross} \)).
- The parameters to be specified by the user are empirically stated. The easiest way to do this is to analyse a view of the scanned surface, studying the variation of the reflectivity index from the centre to the boundaries of a region with the same type of material and similar normal direction.
- The distance between each point and the scanner is computed (Fig. 3D) and the shortest distance (\( d_{min} \)) is taken as the reflectivity reference: \( L_{dmin} \). Then, the processed reflectivity index (\( L_{processed} \)) is multiplied by the ratio between the square of the distance and the square of the shortest distance (\( d^2/d_{min}^2 \)), according to the inverse square law. This makes it possible to correct the dependence between the measured reflectivity and the distance.

The described algorithm has been implemented on a computer using the Point Cloud Library (<http://pointclouds.org/>) for 3D data processing. The programming code is written in C++ to ensure high performance. The environment used is Visual Studio C++ 2008 due to its excellent compiler and debugger tool and the outstanding editing forms.

The corrected reflectivity index is represented in greyscale in Fig. 4A. In order for this data to be analysed in a more visual and intuitive way, a transformation between colour spaces is done to transcribe the greyscale to the RGB space (Agoston, 2005). A statistical study is previously done on the greyscale image histogram (Fig. 4B), so that points far away from the average are filtered out, given that these points are outliers and might hinder the subsequent analysis. Thus, the image shown in Fig. 4C is obtained.

**Correction of the reflectivity index according to histogram**

The transformation from grey to colour fails to take into account the frequency distribution of the reflectivity data. Indeed, the transformation is linear, but this is not the case of the said distribution, as can be seen in the histogram shown in Fig. 4B. This fact results in a loss of information, giving small differences in the reflectivity index that would be masked under the same colour.

A new transformation to unlinearize the colour scale representing the index of reflectivity is required. To this end, the shape of the histogram is explored, and the whole range of reflectivity is automatically
divided into a set of linear segments. Then, a more accurate transformation is achieved (Fig. 5A).

The result can be seen in Fig. 5B. Comparing this to Fig. 4C, it can be observed how the moisture content (related to the change in the reflectivity index) can be clearly appreciated (in blue).

Also, each colour of the scale used can be directly related to the actual values of the humidity content at in situ identifiable points by means of a calibrated digital thermo-hygrometer. In this case, a TESTO 635 plug-in probe (0636 series) was used for testing and analyzing material moisture (resolution 0.1%). This device is manually fastened to each point for obtaining readings after 1 minute stabilizing time. The non-destructive stray field measurement uses the ability of water molecules to dampen and thus change electromagnetic fields. The electric field penetrates the material via the contact plates of the probe and creates a measuring field with a depth of approximately 5 cm. The correct building material is selected in the instrument, for which the corresponding calibration is automatically applied.

**Results**

The described methodology was applied in the Cathedral of Ciudad Rodrigo (Salamanca, Spain), using the building as a true-scale test obtaining real-scale information. In particular, it was tested under stable environmental conditions on some areas of the cloister and on some areas adjacent to the Gospel nave, both made of the same type of limestone. In these areas, there are completely dry regions and others visibly affected by humidity.

All the previously described steps have been followed: the planning of scan-stations and resolution; the scanning of the successive views that make up...
the areas under study; the off-line treatment of acquired data (geometry and reflectivity indexes); and finally, the alignment of the views to compose the final 3D model. Skilled operators are not required to interpret the results or making specific environmental and material corrections.

Figure 6 shows the scanning process and the results achieved for the wall between the cloister and the Gospel nave. Moisture is evidenced near the graves and also at the union of the facing with the flooring. A section of the arches of the cloister is shown in Fig. 7, where damp areas are clearly appreciated.
Figure 7  (A) Arches of the cloister (composite orthophoto). (B) 3D model showing the reflectivity index in colour scale. The results in the detection of moisture are revealed by comparing (A) and (B).

Figure 8  Correlation between the values of the corrected reflectivity index and the equivalent humidity rates.
(especially in the buttresses and areas close to the ground). All the damp areas detected with this method were verified on the original site, even those hardly discernible to the observer due to dangerous or bad accessibility. Biological patina (basically mildew), which occasionally appears close to the ground, implies maximum humidity and therefore the lowest reflectivity index. Disturbing effects of crusts, salts, and biology on stone surfaces are due to their rough and absorbing coating (‘darker when wet’ phenomenon: Introduction). They reflect less light and thus the total internal reflection at the liquid–air interface of the thin film of water covering them. This makes them always shown as very wet areas.

Furthermore, the colour scale used allows anticipation of where the next damp patches may appear, which is very important for preservation and conservation work. The association between the scale values of reflectivity and the humidity content are shown in Fig. 7B. Moisture was measured at 74 control points by the thermo-hygrometer using Fig. 7 colour gradation as a reference, and values were obtained ranging from 18.7% to 56.2% (water content in weight percent of dry mass). The corresponding numerical association is given in Fig. 8, showing a clear grouping of values around a defined band that can be approximated using a logarithmic term, also bringing the Angstrom model (see the ‘Introduction’ section) into good agreement with the method proposed in this work.

Conclusions
A new non-destructive moisture inspection method is ready to be used, based on the study of the reflectivity provided by a laser scanner. Humidity can be easily detected and displayed on the same 3D model obtained by documenting a cultural asset. Multiple and global information is provided without the need for additional studies. Although each scanner uses a slightly different probing ray in terms of frequency, size, power, and duration, the proposed method could standardize the measurements of reflectivity regardless of the equipment used.

In direct connection with each type of material, this approach allows humidity values to be shown, measured with a thermo-hygrometer on the corresponding representative points on the 3D map of reflectivity indexes. No further image processing, difficult radiometric, environmental, or material typology corrections are required. A 3D visual representation, also useful for information integration/linking for enhanced analysis, easily manageable on a computer (locally or remotely), and supporting fully digital accessibility for detailed studies (physically impossible/dangerous/unaffordable perspectives) is obtained.

All these aspects together represent a real breakthrough compared to conventional infrared thermography, whose practical utility is the qualitative determination of heat loss on a 2D image for energy efficiency reports, enabling defects in the building envelope to be detected as the source of discomfort for occupants. The point is that thermal defects in the building envelope do not have to be humidity: air infiltration, thermal bridges, lack of insulation, leaks in closed-loop heating systems, or electrical components overheating, etc. Moreover, the obtained measures are weakly affected by environmental conditions during data acquisition due to the scanning devices operating in the visible or near-infrared spectrum.

Hence, an objective criterion to make decisions according to the UNESCO and ICOMOS recommendations and rules for heritage preservation is provided. Heritage conservation related professionals will benefit from new possibilities of digital technologies that are increasingly being applied in the cultural sector. This demonstrates the value of applied research to give rise to new effective methods and cost efficient tools for heritage conservation. The European Union Treaty (The Lisbon Treaty, 2008), in the Article 167 specifies that safeguarding cultural heritage must be treated as a priority for the EU and is the legal basis for protection initiatives including research on cultural heritage.

Two aspects will be examined in detail in future research: (1) the dependence of reflectivity on known moisture content (laboratory testing on samples in dry and wet state will be required, also ensuring a homogeneous distribution of moisture on them); (2) the reflectivity dependence on changes of surface roughness due to the deterioration of cultural heritage materials.

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