Computers and Electronics in Agriculture 134 (2017) 63–78

Contents lists available at ScienceDirect

Computers and Electronics in Agriculture

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

Original papers

Soil surface roughness measurement: A new fully automatic photogrammetric approach applied to agricultural bare fields

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ARTICLE INFO

Article history:
Received 29 August 2016
Received in revised form 7 January 2017
Accepted 12 January 2017
Available online 23 January 2017

Keywords:
Soil surface roughness
Photogrammetry
VisualSfm
3D data

ABSTRACT

This work develops a fully automatic photogrammetric approach for measuring soil surface roughness from pictures taken in the field with a simple digital camera, without geometric constraints. On each site, 13 overlapping photographs of the soil surface were taken from different angles, under the shade of an umbrella. Millimeter accuracy 3D soil models were calculated from these pictures and were used to derive 11 roughness indexes. The whole procedure was implemented in a fully automatic Python program. The system accuracy was determined on artificial models built with polystyrene, the positional and elevation accuracies of which were about 1.5 mm, while the error on the surface area estimation was less than 0.76% of the site surface area. This approach was successfully applied to an agricultural field experiment in which four soil tillage levels have been generated. These levels were correctly identified using two indices for 96% of the 32 measurement sites. These results show that two roughness indices, the surface tortuosity index and the mean value of height, are most efficient to discriminate agricultural soil tillage levels.

1. Introduction

The soil performs many vital functions in the biosphere at the interface between earth, air and water. Its surface acts as an exchange area for water, gas and energy, being also a mechanical barrier to flow and as such subject to water and wind erosions. In agriculture, Soil Surface Roughness (*SSR*) is strongly related to agricultural practices such as tillage and can evolve under the influence of rainfall. SSR is directly or indirectly an important input parameter in many agronomic studies: it is a major parameter for soil erosion models such as the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978) or Sealing and Transfer by Runoff and Erosion (STREAM) (Cerdan et al., 2002) and for water infiltration and storage models (Moldenhauer, 1970); crop simulation models such as Crop Environment REsource Synthesis (CERES) (Jones and Kiniry, 1986) require among soil parameters an albedo factor that is directly linked to roughness (Matthias et al., 2000); modelling gas emissions related to agricultural practices also need SSR parametrization, as for the Volt'air model (Génermont and Cellier, 1997) for ammonia volatilization from slurry applied. Many studies have been conducted to predict soil properties using visible (Vis) and near-infrared reflectance (NIRS) measurements coming from remote sensing data or from field spectroradiometer, (Baumgardner et al., 1986; Ben-Dor, 2002; Viscarra Rossel et al., 2006; Brunet et al., 2007; Vaudour et al., 2013) and some authors have shown the impact of roughness on the spectral measurements (Matthias et al., 2000; Wu et al., 2009) as indeed modelised by the roughness parameter in bidirectional reflectance models (Hapke, 1984; Jacquemoud et al., 1992).

There is therefore a need for developing measurement methods that precisely quantify SSR in agricultural fields, while allowing fast acquisition, in order to obtain enough information to correct roughness effects, especially for spatialized approaches, that require a lot of data.

There exist a number of techniques for measuring SSR that can be classified according to different criteria (Jester and Klik, 2005): the dimensionality of measure (2D/3D), precision (mm/cm), sensor type, and whether the measure is done with contact to the soil surface or not. The roller chain method proposed by Saleh (1993) is a technique with contact to the soil: a chain of known length L_1 is placed along the clods of a soil transect, then the horizontal distance L_2 between the chain ends, when placed on the soil, is measured. The ratio of both lengths defines the chain index (*CI*) (Eq. (1)):

$$CI = \left(1 - \frac{L_2}{L_1}\right) \times 100 \quad (1)$$

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http://dx.doi.org/10.1016/j.compag.2017.01.010
0168-1699/

CI is a tortuosity index comprised between 0 and 100: the higher the index, the higher is soil roughness. With the pin meter method (Hudson, 1993), a ruler containing mobile pins of known length is set parallel to the soil surface, pins "follow" the soil surface and the top height of each pin, which draws the soil surface profile, can be read on a one millimeter graph paper placed on the background of the ruler. In a variant of the pin meter method, pins were replaced by a laser beam. Bertuzzi et al. (1990) described a non-contact optical technique using a laser and a photodiode detector. Gilliot et al. (2012) for their part, designed a prototype using a Leïca DISTO Pro4a™ distance-meter mobile along a rail supported by two tripods. The precision was good (2 mm) but the time of measurement was quite long (15 min for a 50 cm-length profile).

3D methods have also been proposed, from measuring not only a 2D profile but a surface. Systems proposed by Kamphorst and Duval (2001) or by Darboux and Huang (2003) were designed to measure series of successive soil profiles, as to obtain 3D surface data. Although those systems are not easily portable in the field, the surface area that can be scanned at one time is limited and acquisition is quite long. The novel technology of terrestrial laser scanners (TLS) which enables to scan a larger area than classic profile meters (Eitel et al., 2011), is field portable, accurate, but also cost expensive.

Digital photogrammetry has been widely used for aerial photography. Since the 1980s, photogrammetric techniques have also been used to study SSR from soil photographs (Gascuel-Odoux and Bruneau, 1990), Zribi et al. (2000) following Ivanov et al. (1995) used stereo-photographs to reconstruct 3D numerical soil surface: two digital cameras fixed on the top of a 3 m-height support were used to analyse a 1 m^2-soil surface. Old photogrammetric techniques required specific and expensive metric cameras, necessitating calibrations for determining camera parameters and scene geometry, and imposing geometric constraints while acquiring photographs. Moreover commercial photogrammetric softwares had to be used in order to process pictures which implied some user's expertise on photogrammetry. Warner (1995) has shown that non-metric hand-held 35 mm-camera could be used for photogrammetry on soil surfaces. More recently multiview 3D-reconstruction, a new method derived from stereo-photogrammetry, has greatly simplified the creation of 3D models from photographs. Multiview 3D reconstruction is based on a set of overlapping photographs taken by a cheap high quality digital camera from different points of view and process to automatically determine the scene geometry and camera parameters (Favalli et al., 2012). Besides these photographic techniques, some other indirect techniques exist such as acoustic backscatter (Oelze et al., 2003), multiple view angle infrared spectroscopy (Croft et al., 2012), shadow analysis (García Moreno et al., 2008; Denis et al., 2014), radar imagery (Aubert et al., 2011) or optical/radar pair (Vaudour et al., 2014).

The general objective of this work was therefore to develop an automatic, fast and accurate method for agricultural soil roughness estimation applicable in the field at a high number of sites for spatialized applications. As the acquisition of simple photographs is likely to be fast and well adapted to field constraints, we chose to develop a Multiview 3D-reconstruction technique for the purpose of assessing SSR. We conducted this study in the framework of the Gessol3-Prostock project of the French Ministry of the Environment, dedicated to the spatial prediction of soil organic carbon (SOC) content by means of remote or proxy reflectance data (Vaudour et al., 2012, 2013) which were directly influenced by SSR. Our approach first describes the principles of our photogrammetric multiview 3D-reconstruction method, then evaluates this method accuracy using artificial surfaces of known geometry, and is finally applied to agricultural soils, the surface roughness of which was shaped by known cultural operations.

2. Materials and methods

2.1. Multiview 3D reconstruction

2.1.1. Overall principles

Photogrammetry is a method of determining shape and position of objects from photographic images (Kraus and Waldhäusl, 1998), being either aerial or terrestrial. Considering the simplest case in stereovision, i.e. a pair of cameras having their optical axes mutually parallel (Fig. 1), the camera *L* (left) is horizontally shifted to the camera *R* (right) by a *b* distance (baseline). The observed point *P* is projected onto the image planes IP_L (left) and IP_R (right) respectively to the two points P_L and P_R. O_L and O_R are the projection centers of the two cameras (optical centers) while the triangle O_L *P* O_R defines the equipolar plane. The intersection between the equipolar plane and each image planes defines the two equipolar lines EL_L and EL_R.

For the considered pair of homologous points P_L and P_R, the distance in the image plane between P_L and P_R along the equipolar line is named the disparity (*d*) (Dhond and Aggarwal, 1989) (Eq. (2)).

$$d = x_L - x_R \tag{2}$$

In this simple case, the two images only differ by a translation on the x axis. The direct relation between the depth of the point in the real world (z_W) and the disparity between both images is the base of stereo-analysis using triangulation calculation, enabling 3D-structure determination (Fig. 1). Such relation could be less direct depending on the complexity of the geometric configuration, especially in the case of nonparallel axis, as in the case of equipolar geometry.

The 3D reconstruction by stereovision requires that projection geometry parameters be known. One generally distinguishes two kinds of parameters (Verhoeven et al., 2012): on the one hand, the interior calibration or inner orientation of the camera, such as the focal length for instance and on the other hand, the exterior parameters (six parameters) for the camera pose (position and orientation) in the scene. The Ullman's Structure from Motion (SfM) theorem (Ullman, 1979) originally due to Kruppa, in 1913 (Butterfield, 1997) shows that three-dimensional structure and motion of rigid objects can be inferred from the two-dimensional transformations of their projected positions. This theorem demonstrates the ability to recover the 3D structure of objects from a set of pictures.

The complete 3D reconstruction from a set of images requires the three following steps: (i) key points localisation and features description; (ii) feature matching between the different images; (iii) camera pose and scene structure calculations. The main output of SfM algorithms is a set of 3D points in relative coordinates generally-called a points cloud, for which a geo-registration last step is needed to obtain absolute locations. Feature descriptors need to be invariant between images for the same object in order to be matched. The commonest method used for this purpose, is the Scale Invariant Feature Transform (SIFT) proposed by Lowe (2004), which is based on the scale-space filtering approach (Witkin, 1983).

2.1.2. Softwares for 3D reconstruction

Several software packages are presently available for 3D reconstruction from a set of overlapping images. We tested some of them that are open-source or free of charge. Microsoft's Photosynth (Microsoft, 2010) and Arc3D (KU Leuven, 2012) are web-based services, easy to use but difficult to integrate with other