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The role of combined laser scanning and video techniques in monitoring wave-by-wave swash zone processes

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ABSTRACT

Simulating swash zone morphodynamics remains one of the major weaknesses of beach evolution models. One of the reasons is the limited availability of data on morphological changes at the temporal scales of individual swash events. This paper sets out to present a new hybrid system, consisting of 2D/3D laser scanners and several video cameras, which was designed to monitor swash zone topographic change on a wave-by-wave basis. A methodology is proposed consisting of sensor calibration and several data processing steps, allowing a fusion of different sensors. Such an approach can improve the performance of several field/laboratory, optical technique applications for nearshore hydro- and morpho-dynamic measurements. Digital Elevation Models from a 3D scanner were used in the extrinsic camera calibration procedure and reduced the geo-rectification errors from $0.035\text{ m} < \text{RMSE} < 0.071\text{ m}$ to $0.008\text{ m} < \text{RMSE} < 0.013\text{ m}$. The 2D scanner provided instantaneous measurements of the water and dry beach surface elevation along a 10 m cross-shore section, and comparison with ultrasonic sensor measurements resulted in RMS errors within the $1.7\text{ cm} < \text{RMSE} < 3.2\text{ cm}$ range. The combination of 2D scanner and video data (i) reduced geo-rectification errors by more than one order of magnitude; and (ii) made 2D laser point cloud processing easier and more robust. The hybrid monitoring system recorded the morphological change of a replenished beach-face on a wave-by-wave basis, during large-scale, physical modeling experiments and the observations showed that individual swash events could result in elevation changes up to $dz = \pm 10$ cm. The sediment transport direction and intensity of the monitored swash events was relatively balanced and sediment transport rates ranged between $-3.5\text{ kg m}^{-1}\text{ s}^{-1} > Q_t > 3.5\text{ kg m}^{-1}\text{ s}^{-1}$. Extreme transport swash events became rarer as the morphology was reaching equilibrium.

1. Introduction

Coastal morphological change takes place at various temporal scales (e.g. Larson and Kraus, 1995; Masselink et al., 2009), requiring very intensive monitoring in order to reach a solid understanding of the related processes and factors. The swash zone in particular is the area where subtle changes take place during each swash event and there is consensus that monitoring on a wave-by-wave basis is fundamental to understand and quantify the different factors contributing to the overall morphodynamic behavior (Blenkinsopp et al., 2011; Brocchini and Baldock, 2008; Cáceres and Alsina, 2012). As a result, there have been several efforts to monitor the water level and beach topography during swash events, using pore pressure sensors buried few cm below the bed (e.g. Baldock, 2009; Baldock et al., 2008), ultrasonic sensors (e.g. Blenkinsopp et al., 2011; Turner et al., 2008) and even laser scanners (Blenkinsopp et al., 2010; Brodie, 2010; Park et al., 2011).

Given the energetic conditions in the nearshore zone, the coastal community has shown a growing interest on non-intrusive approaches like video monitoring (Holman and Stanley, 2007; Pearre and Puleo, 2009; Vousdoukas, 2012; Vousdoukas et al., 2009, 2012b), marine radar (Bell, 1999; Flampouris et al., 2008; McNinch, 2007; Ruessink et al., 2002), satellite images (Wall et al., 2008), airborne LIDAR surveys (Coleman et al., 2011; Wedding et al., 2008) and even, Small Unmanned Aerial Vehicles (Dugan et al., 2001; Vousdoukas et al., 2011b). However, the above approaches lack either the spatial and/or temporal resolution to monitor swash zone morphodynamics, with the exception of stereo-vision which has been applied successfully both under field (Holland and Holman, 1997) and laboratory conditions (Astruc et al., 2012); it does however come with high computational costs.

Terrestrial 3D Laser Scanning (TLS) has been an approach for several engineering applications in different fields (e.g. Hentschel et al., 2007; Lecking and Wagner, 2011; Wagner, 2006), was more recently adopted for coastal research and is becoming the method of choice for beach

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surveying (e.g. Pietro et al., 2008; van Gaalen et al., 2011). Laser scanning devices typically consist of a transmitter generating a laser beam, which is deflected by a mirror to the desired direction; with the mirror rotating around one axis to guide the laser beam along a plane (2D measurements) and an additional rotation axis makes the sampling area three-dimensional. The laser beam is then travelling through the propagation medium, hits the surface and is either reflected, absorbed or transmitted, depending on the reflecting surface and the return signal is measured by a receiver. The laser signal is known for its ability to stay coherent after travelling long distances and the range measurement is typically based on either the Time-of-Flight (ToF), or the Phase Shift (PS) measurement principle. In the former, single pulses are transmitted and since they are travelling with a known velocity, the time lag between transmission and reception is considered to estimate range, according to the following equation (Vosselmann and Maas, 2010):

$$\rho = \frac{c \cdot \tau}{2 \cdot n} \tag{1}$$

where ρ is the range, τ the time delay for one round trip, c the speed of light (299792458 m/s in vacuum) and n the refractive index depending on propagation medium, for air equal to $n = 1.00025$. ToF devices allow measurements at ranges reaching several km, with accuracy around 1 cm.

PS based measurements are based on the recorded phase difference between emitted and recorded laser beam wavelength and for that reason continuous laser pulses are transmitted. Since the range would be limited by the time interval between two identical points on the wave, several modulated phases are used to accurately determine the range over long distances and most devices can measure ranges up to 80 m with accuracy of few mm (San José Alonso et al., 2012).

There is a wide range of commercially available laser scanners and the coastal community is gradually becoming aware of the high potential for innovative coastal monitoring techniques and improved data quality. Recent efforts have shown that, apart from the terrestrial LIDARs used for topographic measurements, laser scanning has several unexploited possibilities; e.g. for high-frequency, water surface measurements in the shoaling/surf (Blenkinsopp et al., 2012; Evans, 2010; Harry et al., 2010; Irish et al., 2006; Park et al., 2011) and swash zone (Blenkinsopp et al., 2010; Brodie et al., 2012), and even for monitoring of 2D wave fields (Wübbold et al., 2012).

The present contribution aims to present a new hybrid system, consisting of 2 laser scanners, several video cameras, as well as an array of standard water level gauges. The system was applied to monitor rapid morphological change of a replenished beach-face, during large-scale, physical modeling experiments. Apart from the results related to the rapid berm erosion, the manuscript will discuss the methodology followed to integrate all sensors, and the benefits of the hybrid approach compared to the current state of the art.

2. Materials and methods

2.1. Model setup

Large scale physical experiments were performed at the Large Wave Flume (GWK), in Hannover, with dimensions 300 m (length) × 5 m (width) × 7 m (height). The initial morphology was a linear, sandy profile of 1:15 slope, consisting of 'very well sorted' (Folk, 1980), fine sand with $d_{25} = 210$ μm, $d_{50} = 300$ μm and $d_{84} = 474$ μm. 17 capacitance wires measured water level at 120 Hz and at different positions along the shoaling and surf zone (Fig. 2a). At the swash zone, 8 MASSA M300/95 Ultrasonic sensors were installed every 2 m along the cross-shore direction and 1.7 m above the mean water level (MWL), to provide point measurements of the beach and water elevation at 120 Hz (Fig. 2c, e).

2.2. Hybrid video monitoring–laser scanning system

2.2.1. Hardware and synchronization

The hybrid monitoring system consists of several components, all requiring certain set-up and calibration, in order to generate measurements which can be correlated both in time and space with accuracy below 0.1 s and 1 cm, respectively. A SICK LMS291, 2D ToF laser scanner (called hereafter 2D scanner) was used to record at 8 Hz the beach and water elevation along the swash zone and part of the surf zone (Fig. 2b, d). All data were logged to a PC running the operating system LiRE (Linux Real-time Environment, http://www.rts.uni-hannover.de/lire) which contains the real-time extension Xenomai and the hard real-time protocol stack RTNet (http://www.rtnet.org). The scanner was controlled by the open-source Robotics Applications Constructions Kit (RACK) (Nieto et al., 2010; see also http://developer.berlios.de/projects/rack). The specific 2D scanner model used has a 90° scanning angular range, while the radial range varies from 10 m to 30 m, depending on the laser reflection properties of the target.

Three AVT MANTA G-125, 1.3MP cameras collected imagery at 5 Hz along the swash, surf and part of the shoaling zone. The cameras were controlled by the GS-Vitec Marathon Pro software and were synchronized by a central data-acquisition system through external hardware triggers. All the cameras and the scanner were installed at a fixed location (roof), 12 m above Mean Water Level (MWL), in order to allow for a favorable vantage point and to minimize geo-location errors due to small grazing angles (Fig. 2b–d). For the given model set-up the mean 2D scanner beam footprint was 43 mm and always below 60 mm, while the camera pixel footprint was always below 10 mm. The measurement spot of the MASSA sensors, used for 2D scanner data validation, was one order of magnitude higher, around 300 mm.

In addition, a FARO Focus 3D scanner, based on the PS principle (called hereafter 3D scanner) was used to generate 3D digital elevation models (DEMs) of the experimental set-up with resolution and accuracy below 0.5 cm. Apart from measuring the beach model topography, the DEMs were used to extract accurate information about the locations of the instruments and the ground control points (GCPs) used to geo-rectify the 2D scanner and image data (see section to follow).

Measurements from the several sensors were combined during the calibration and data processing steps of each individual measuring device in order to increase the accuracy of the collected data. The entire processing procedure is described in the paragraphs to follow, while the final outcome is continuous, in 2D-space and time, measurements of the nearshore water surface elevation and of the beach-face topography changes on a wave-by-wave basis (Fig. 1).

2.2.2. 2D scanner calibration

Careful 2D scanner installation ensured that the range measurements were along a vertical plane, parallel to the x- (cross-shore) axis and the acquired range measurements required translation and rotation in order to be converted from the sensor's to the global coordinate system. Translation was necessary only along the x- and z- (vertical) axes, while rotation only around the y- (long-shore) axis, with the y-position of the monitoring transect being $y = 2$ m, implying 2 m from the side wall (Fig. 2b). Such operations, referred as 'scanner calibration' hereafter, took place considering several GCPs, with size one order of magnitude higher than the laser beam footprint and distributed along the scanner's measuring plane. The GCPs were carefully geo-located inside the GWK coordinate system, using the 3D scanner data.

The grazing angle affects the laser beam footprint and 2D scanners have been shown to slightly distort shapes, with planar surfaces appearing slightly convex (Streicher, 2013), therefore an additional calibration step was followed for the scanner. Planar water, dry beach and concrete surfaces were scanned from a similar distance as in the experimental layout and the shape distortion was assessed. Following, empirical correction coefficients were