Journal of Coastal Conservation (2020) 24: 47
https://doi.org/10.1007/s11852-020-00764-6

A comparison of high-end methods for topographic modelling of a coastal dune complex

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Received: 1 May 2019 / Revised: 25 June 2020 / Accepted: 29 June 2020 /

Abstract

In recent years, increasing tourism and development in the coastal dune area of the South East of Ireland have resulted in greater pressure on the environment, resulting in issues including soil erosion, flooding and habitat loss. Topographic mapping across a dune field is important for the development of targeted land management actions that maintain biodiversity and ecological functions. Developments in surveying technology, including LiDAR, terrestrial laser scanners (TLS) and aerial surveying from Remotely Piloted Aircraft Systems (RPAS), have enabled high-resolution and high-accuracy spatial data to be gathered quickly and relatively easily for 3D topographic modelling of a coastal dune complex. To-date, however, the relative efficacies of these three modelling methods, in the context of coastal dune modelling, has not been explored. This paper compares high-end methods based on LiDAR, TLS and RPAS technologies, for the topographic modelling of coastal dune complexes with particular reference to the Brittas-Buckroney dune complex in the South East of Ireland. The results identify the advantages and disadvantages of the respective technologies and highlight the efficacy of RPAS, in particular, for topographic modelling of coastal dune complexes. These results can provide reference information for others when selecting suitable methods for topographic modelling of similar environments.

Keywords Coastal dune complexes · Topographic modelling · LiDAR · Terrestrial laser scanners · Remotely piloted aircraft systems

Introduction

Coastal zones comprise 2% of the earth's land area and are the transition areas between the marine and terrestrial environments (Acosta et al. 2005). Dune complexes are the main structures at these coastal zones (Lucas et al. 2002). They play an essential role in the preservation of ecosystem stability and biological diversity as they provide habitat for special flora and fauna, control soil erosion and flooding, and provide protection for nearby properties from other environmental hazards (Clark 1977; Andrews et al. 2002). Human pressure on coastal zones around the world has increased dramatically in the last 50 years (Curr et al. 2000; Westley and McNeary 2014).

Concern for the increasing threat to coastal dune ecosystems has generated a greater interest in coastal dune conservation and management (MacLeod et al. 2002; Olbert et al. 2017). Accurate 'baseline' topographic mapping, with detailed information concerning the earth's surface, are considered critical to the development of an effective coastal environmental management plan (Acosta et al. 2005). However, high-resolution and high-accuracy topographic modelling is a challenging task which requires a considerable investment in time and resources (McKenna et al. 2005).

Aerial photogrammetry and optical satellite imagery have been used for topographic mapping for various landscapes including coastal ecosystems (Curr et al. 2000). However, a

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single dune complex is typically represented as a long and narrow strip because such mapping is generally produced at national and regional scales (Acosta et al. 2005). There are, notwithstanding, a number of data processing approaches for generating finer-scale mapping from the more traditional sources (Lucas et al. 2002; Timm and McGarigal 2012; Rapinel et al. 2014). Nevertheless, it remains quite difficult to produce, from these sources, topographic mapping with accurate and detailed land cover information for small coastal dune complexes. A considerable limitation of optical satellite imagery, in particular, is the influence of weather, especially cloud-cover which can interfere with the view of the earth's surface (McGovern et al. 2002).

Aircraft-based Light Detection and Ranging (LiDAR) is an alternative resource for 3D topographic models even for a smaller target area e.g. 50–100 ha (Bolivar et al. 1995; Grebby et al. 2014). It is often available from national mapping agencies (NMA's), such as Ordnance Survey Ireland (OSi). OSi quotes spatial resolutions and vertical accuracies in rural areas of 0.5 m and 0.5 m respectively (OSi 2017) and charges c. €250 per square kilometre for the data. LiDAR data can be used to generate both Digital Terrain Models (DTM) and Digital Surface Models (DSM) (Crapoulet et al. 2016). For a study at a coastal dune complex in North Carolina, a LiDAR dataset were used to represent coastal dunes for volumetric change analysis (Woolard and Colby 2002).

Ground surveying methods, including Total Station (TS) and Global Navigation Satellite System (GNSS), are suitable for topographic modelling of smaller target areas (D'iorio et al. 2007; Lee et al. 2013). These on-site, data collection methods provide more ground truth, and up-to-date and accurate information than many alternatives (D'iorio et al. 2007). The distance measurement accuracy of TS is 2 mm + 2 ppm over a distance of about 1 km (Lee et al. 2013). However, the operation and performance of TS in field surveying projects is limited by poor visibility circumstances, such as darkness, rain, snow, thickets or physical occlusions (Schneider and Panich 2008). There are three techniques based on GNSS to enhance the precision of satellite position data. These are Post Processing Kinematic (PPK), Real Time Kinematic (RTK) and Network Real Time Kinematic (NRTK) (Li et al. 2015). The accuracy of GNSS is 10–20 mm (Dow et al. 2009). With lighter equipment and easier operation, these GNSS techniques can save labour and time in collecting the same amount of modelling data as TS (Mieczysław 2013).

In recent years, due to being non-contact, rapid, accurate and complete, Terrestrial Laser Scanning (TLS) has been increasingly used to build three-dimensional models (Parrish et al. 2016). The positioning accuracy of TLS is of the order of millimetres (Staiger 2003). The laser scanner is integrated with a computing device to save the acquired point information and also to control the scanning patterns. The operation of the laser scanner is almost fully automatic which leaves little room for operating error as human influence plays a less important role in the surveying process (Ersilia et al. 2012).

Most recently, Remotely Piloted Aircraft Systems (RPAS), variously referred as Unmanned Aerial Systems (UAS), Unmanned Aerial Vehicles (UAV's), "Aerial Robots" or simply "drones", have enabled high-quality data to be gathered quickly and easily (Casella et al. 2014; Turner et al. 2016). RPAS platforms are typically grouped into two main categories: rotary RPAS and fixed-wing RPAS (Gomez and Green 2017). Comparing both types, rotary RPAS has more complex mechanics, which result in lower speeds and shorter flight ranges while fixed-wing RPAS have a simpler structure providing more stable platforms. Furthermore, fixed-wing RPAS enable longer flight duration and higher speeds, which are more suitable for aerial surveys over larger areas.

RPAS, integrated with modern digital camera technology, breaks the time and space constraint allowing a study site to be remotely surveyed in a significantly reduced time using the imagery acquired (Smith et al. 2009; Colomina and Molina 2014). RPAS imagery, using Structure from Motion (SfM) processing techniques, has created a new opportunity for photogrammetry to create 3D surface models from the large number of overlapping photographs (Hodgson et al. 2013). To maintain the spatial accuracy of the data, the overlapping area for each two images should be at least 60%, making sure sufficient shared points can be recognised by the software for map construction (Zelizn 2016). A multispectral camera mounted on a RPAS allows both visible and multispectral imagery to be captured that can be used for characterizing land features, vegetation health and function (Fernández-Guisuraga et al. 2018). RPAS is also a user-friendly and scalable methodology albeit with the requirement of specialized software and with restrictive image collection conditions such as high wind speed and poor light intensity (Bemis et al. 2014). For the management of RPAS, different countries have different mandatory requirements, established by their national aviation authorities. And particular operating licenses and insurances may be required before operating an RPAS (Tomasello et al. 2016).

LiDAR, TLS and RPAS technologies are capable of creating digital topographic models of coastal dune complexes. There are three different types of digital topographic model, viz. Digital Surface Model (DSM), Digital Terrain Model (DTM) and Digital Elevation Model (DEM). A DSM represents the natural and built features on the Earth's surface (Crapoulet et al. 2016). A DTM is defined as an array of orderly values that are used to describe the spatial distribution of various properties of the earth's surface, for example, topographic information, natural resource and environment information, and economic information (Liang et al. 2012).When the DTM is used only to describe and express spatial information, such as terrain relief and elevations, it is also called a DEM (Liang et al. 2012). A DTM is a bare-earth raster grid referenced to a vertical datum (Hutchinson and Gallant 1999). By filtering out non-ground points, e.g. building and vegetation cover in a DSM, a bare-earth DTM is created.

TLS and RPAS technologies create DSMs of a study site as the ground features are not filtered. LiDAR use pules of laser light to measure range. A single pulse can generate a number of returns such that the first return can be used to create a DSM and last return can be used to create a DTM.

The objective of this research was to compare three high-end methods, viz. LiDAR, TLS and RPAS technology, for topographic modelling of a coastal dune complex with particular reference to the Brittas-Buckroney dune complex (Fig. 1) in Co. Wicklow, Ireland. By comparing the efficacy of these different methods of spatial data collection, with respect to accessibility, cost, convenience and data quality, the advantages and disadvantages of these methods are considered in the context of topographic modelling of coastal dune complexes. The results can provide reference information for others involved in topographic modelling of similar environments.

Study site

The Brittas-Buckroney dune complex (Fig. 2) is located c. 10 km south of Wicklow town on the east coast of Ireland and comprises two main sand dune systems, viz. Brittas Bay and Buckroney Dunes (National Parks and Wildlife Service (NPWS) 2013). The study site for this research is Buckroney Dunes. The area of the Buckroney dune complex is c. 60 ha.

Within this site, ten habitats listed on the EU Habitats Directive are present, including two priority habitats in Ireland, viz. fixed dune and decalcified dune heath (National Parks and Wildlife Service (NPWS) 2013). This site also contains good examples of different dune types. At the northern part of Buckroney dune complex, there are some representative parabolic dunes, while embryonic dunes mostly occur at the southern part. Meanwhile, the site is notable for the presence of well-developed plant communities.

With land acquisition in recent years, the marginal areas of the dune system have been reclaimed as farmland. The increasing anthropogenic activities at the dune system, such as farming and recreation activities, have brought pressure to the dune ecosystems development, with hazards like soil erosion, flooding and habitat loss. Proper environmental management is required to ensure the continued survival of this coastal habitat and to maintain the diversity and stability of the ecosystem on this site and accurate topographic modelling is considered a prerequisite for such management.

Methodology

This study considered three different surveying methods to gather spatial data for the Brittas-Buckroney dune system. These were LiDAR data acquired from the NMA, and two on-site data collection technologies, viz. TLS and RPAS.

Data acquisition

LiDAR

LiDAR data of the study site were available from OSi. The Lidar scanner used by OSi was an airborne Leica ALS50

Fig. 1 Morphology of the Brittas-Buckroney dune complex

Fig. 2 Study site **(a)** General location and **(b)** Brittas-Buckroney dunes

(Ordnance Survey Ireland (OSI) 2017). This scanner emits 150,000 pulses every second creating a point cloud of millions of pixels collected in X, Y, Z (easting, northing and elevation). After capturing the raw point cloud each point is then classified into different layers, such as ground, buildings and vegetation. The final outputs are of high accuracy and provide vertical accuracies between 0.15 m to 0.25 m.

In this research, the acquisition date of the dataset was 28/04/2011. The data file contained the Easting, Northing and Elevation information for each point recorded in the Irish Transverse Mercator (ITM) coordinate system. The horizontal spatial resolution of the data was 0.5 m and the vertical accuracy was 0.5 m (Ordnance Survey Ireland (OSI) 2017).

TLS

The GLS2000 captures point cloud data with the scan rate of 120,000 pulses per second with an accuracy of 3.5 mm up to 150 m distance. The scanner has a 170° wide-angle camera and the scan range over 350 m. The field view of the scanner is 360° horizontally, and 320° vertically. A complete 3D model of an object such as sand dune typically required several scans from different locations which are subsequently registered together. These scans are captured at predetermined ground control points (GCPs) to enable precise geolocation.

The coordinate positions of GCPs used in the TLS survey of the study area were measured using a Trimble 5800 GNSS receiver recording in the ITM coordinate system. The data

Fig. 3 **a** SenseFly eBee RPAS surveyed on-site **b** GCPs set on site for RPAS surveying

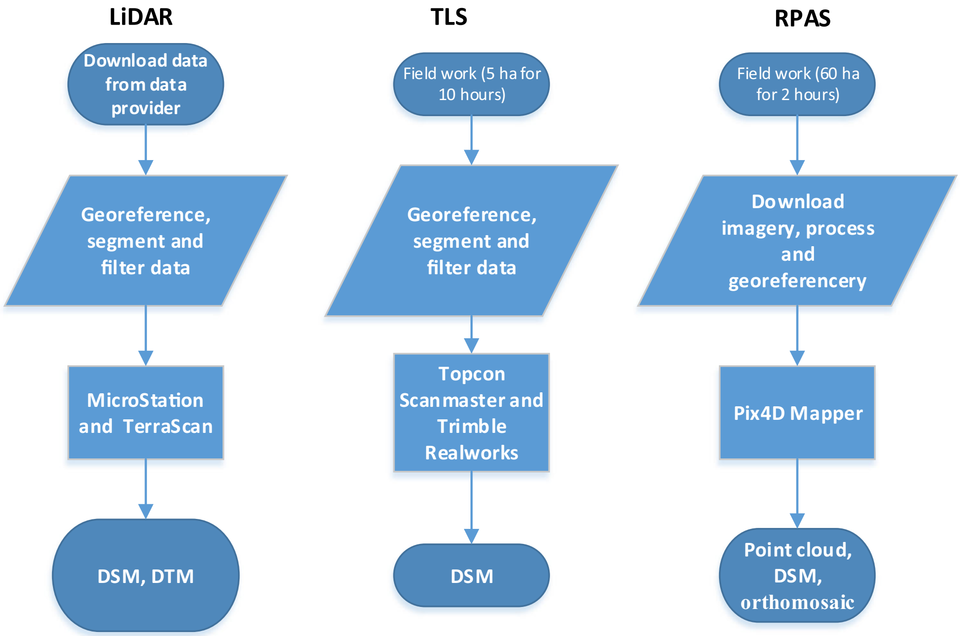


Fig. 4 The flowchart of data processing from LiDAR, TLS and RPAS technologies

from a TLS survey is in the form of a point cloud. All points within the point cloud have X, Y, and Z coordinate and laser return intensity values. The points were in an XYZIRGB format, representing X, Y, Z coordinate, return intensity, and Red, Green, Blue colour values taken from the on-board digital camera.

RPAS

A SenseFly eBee RPAS (Fig. 3 (a)) was used to capture images of the study site. The SenseFly eBee RPAS can cover up to 12 km^2 in a single automated mapping flight, while flights over smaller areas, at lower altitudes, can acquire images with a ground sampling distance of down to 1.5 cm per pixel. The resulting point cloud, with GCPs used for georeferencing, can achieve horizontal and vertical accuracy of 3 cm – 5 cm, while the resulting point cloud without GCPs has absolute horizontal and vertical accuracy of 1 m – 5 m.

Thrity-two GCPs were established around the study site to georeference the data from the RPAS. These were marked as white crosses identifiable in the images captured by the RPAS (Fig. 3 (b)). The GCPs were in the ITM coordinate system and positions were determined using a Trimble 5800 GNSS receiver connected to the Trimble VRS commercial NRTK system.

To maintain the high quality of the captured imagery, and considering the 20 min - 25 min battery life for a single flight of the RPAS, the study site was divided into three sections, North, Centre and South. Settings for each flight included 70% overlap along lines and 60% side-lap between lines, flight height of 120 m and flight times of c. 20 min optimizing the data capture time with respect to battery life. In the three sections, the number of images collected by the RPAS flight was 212, 209, and 149 respectively for the North, Centre and South sections.

Data processing

The raw datasets from LiDAR and TLS were point clouds, whereas RPAS captured numerous overlapping images. By matching different images captured by RPAS, a point cloud

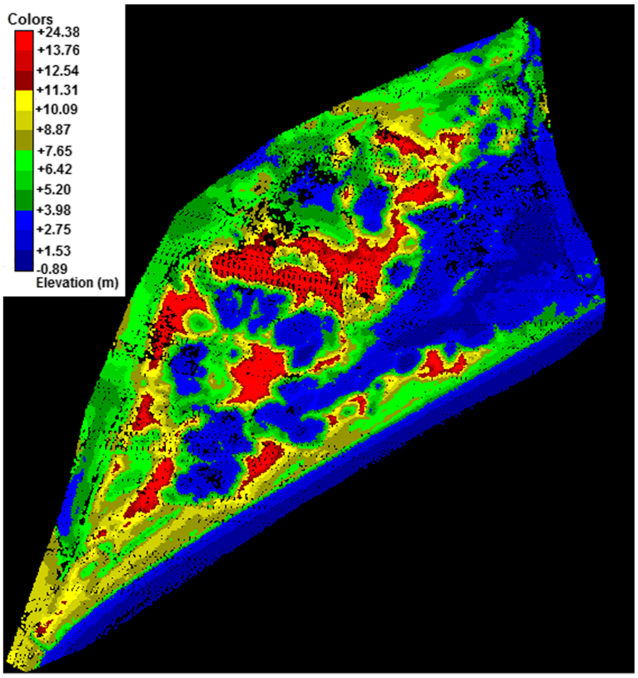


Fig. 5 Digital Surface Model (DSM) of Buckroney dune complex processed by LiDAR data

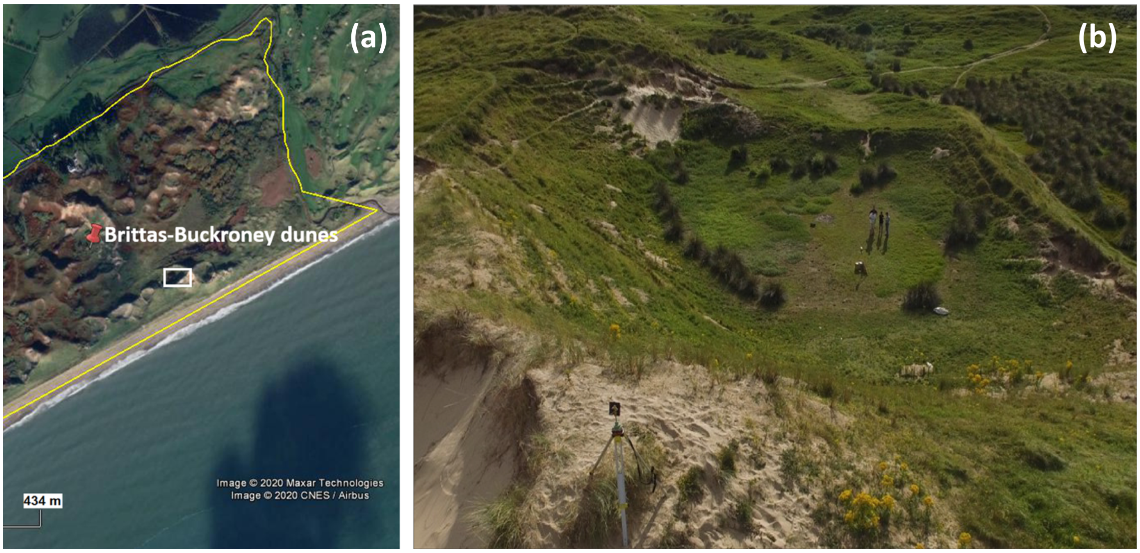


Fig. 6 Selected dune area (**a**) general location (**b**) detail imagery

of the ground surface was generated by SfM technology. Point clouds from the LiDAR, TLS and RPAS surveys then were used to generate DSMs for further study. To process the collected datasets, specific software was required in each case. Figure 4 outlines the processing steps of datasets acquired by LiDAR, TLS and RPAS.

Model comparison

DSMs were generated from the datasets collected by the three different methods, i.e. LiDAR, TLS and RPAS. Although it was not practical to create a 3D model for the whole study site by TLS technology, the model created from TLS data was used as reference data for an accuracy assessment of the models generated by both the LiDAR and the RPAS data. Single point accuracy based on TLS collection is 0.003 m (Topcon Corporation 2014). Models based on LiDAR and RPAS technology were compared with the single dune model created by TLS data via CloudCompare software. The calculated offset between the models represented the accuracy of the models created by LiDAR and RPAS.

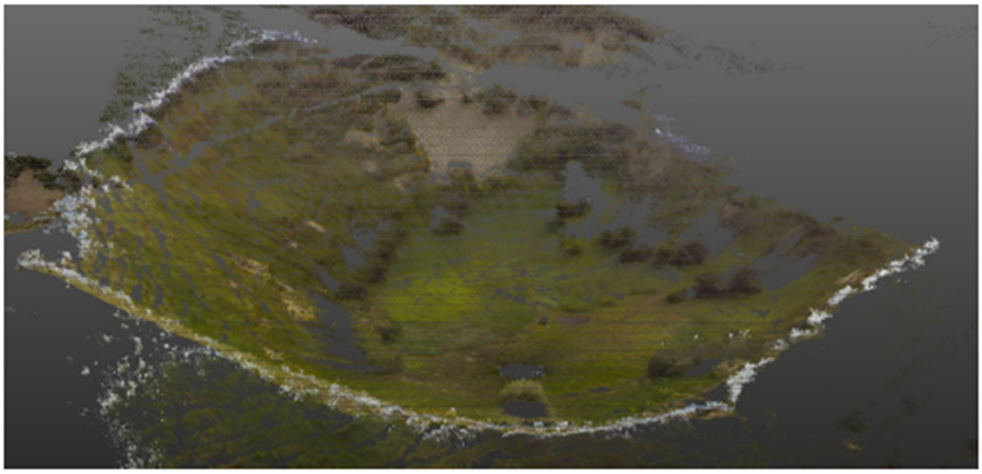
Outcomes

The results show the topographic models of the Buckroney dune system created using the three surveying technologies, viz. LiDAR, TLS and RPAS.

LiDAR

The LiDAR data is commonly segmented by using different filters to extract the ground surface or the above-ground features. Considering the first returns of laser light, DSM (Fig. 5) and contour models of the site from LiDAR data were produced. The spatial resolution of the models was 0.2 m. In the DSM, the colour variation from blue to red represents elevation in the range − 0.89 m – +24.39 m.

Fig. 7 DSM of selected dune produced by TLS technology



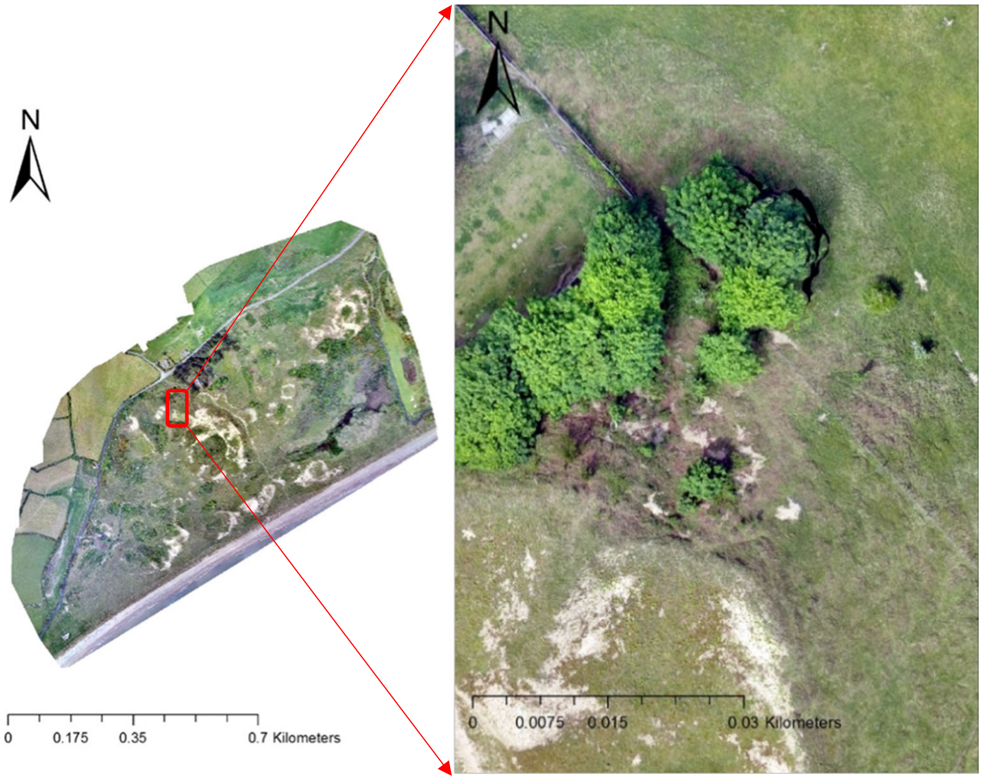


Fig. 8 Orthomosaic model of the study site with a detailed extract

Terrestrial laser scanner

From the TLS data, a higher resolution DSM of the selected dune in the white rectangle in Fig. 6 was created. The resolution of the model was 1 cm. This model was georeferenced to the ITM coordinate system by reference to three GCPs. TLS can collect multiple return signals from a target. The data presented in Fig. 7 used the first return signals to create the DSM.

RPAS

Using a dense image matching process, geo-referenced 3D point clouds, orthomosaics, DSMs, contour lines, and textured mesh models were generated for the study site from the RPAS imagery. These outcomes were referenced to the ITM grid coordinate system, with a spatial resolution of 0.034 m and a spatial accuracy of 0.035 m when checked against 10 GCPs.

Pix4D software was used for the processing and a 3D point cloud of the study site was generated from the overlapping images. The orthomosaic (Fig. 8) is a mosaic image adjusted for topographic relief, lens distortion, and camera tilt so it can be used to scale true distances. This high resolution orthomosaic is a useful product suitable for land feature classification and volumetrics analysis. The DSM (Fig. 9) when combined with the position of land features, can provide the basic morphological data for environmental modelling. Environmental models can then contribute to the exploration and identification of important processes at coastal dune complexes, for example, dunes formation, structure changes to dunes and vegetation, aeolian and other environmental influences on morphology.

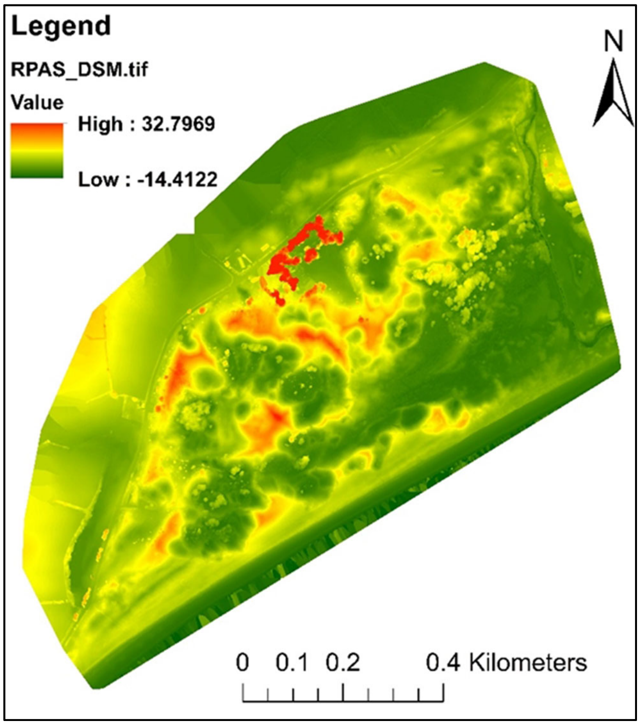


Fig. 9 DSM of study site produced from the RPAS survey

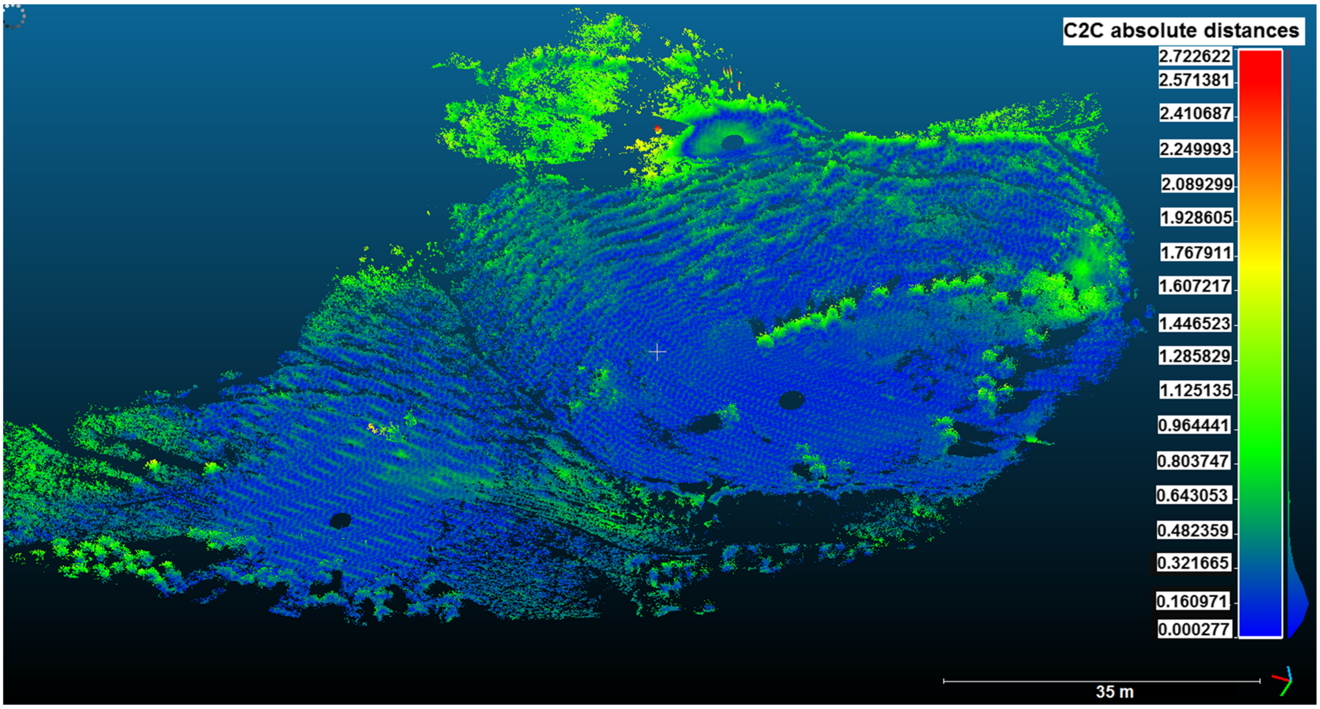


Fig. 10 Offset between the TLS model and the LiDAR model

Analysis

Based on the accuracy for a single point measurement of 0.003 m, and allowing for a typical error budget, the estimated accuracy for the TLS model is ±0.010 m. Thus, the TLS model (Fig. 7) was used as the reference model for a comparison with the LiDAR model (Fig. 5) and the RPAS model (Fig. 9). A spatial accuracy assessment was carried out using package cloud-to-cloud separation estimation in the CloudCompare software package. The offset between TLS model and LiDAR model was 0.27 m and standard deviation was 0.18 m (Fig. 10). The offset between TLS based model and

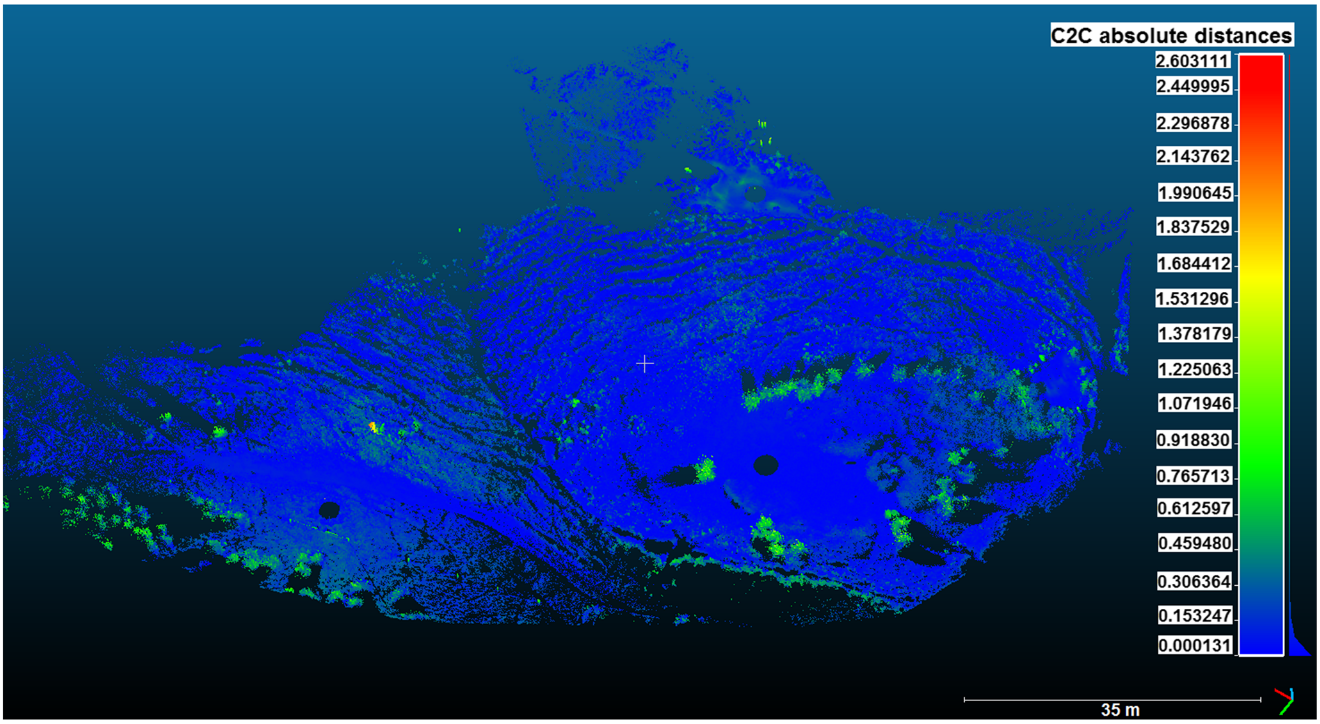


Fig. 11 Offset between the TLS model and the RPAS model

Table 1 Comparison of LiDAR, TLS and RPAS for DSM generation of study site

		LiDAR	TLS	RPAS
Data acquisition	Area coverage	High	Low	Medium
	Cost	€250 per square kilometre	About €21,000	About €10,000
	Expertise level required	Competent	Proficient	Competent
	Data collection time om-site	No field work	7 h field work for a single dune including mobilisation and establishment of GCPs	8 h field work for 60 ha site including mobilisation and establishment of GCPs
	Weather dependencies	Not influenced by weather change	Limited by precipitation	Limited by precipitation and wind
	Flexibility	No flexibility	Flexibility	High flexibility
	Collected dataset	Point cloud	Point Cloud	Georeferenced imagery
Data processing	Software	MicroStation and TerraScan	Topcon Scanmaster and Trimble Realworks	Pix4D Mapper
Outcomes	Outcome packages	DSM, DTM	DSM	3D point cloud, DSM, orthomosaic image
	Resolution	0.2 m	0.003 m	0.034 m
	Accuracy	0.3 m	0.010 m	0.1 m

RPAS model was 0.11 m and standard deviation was 0.18 m (Fig. 11).

LiDAR, TLS and RPAS are all options for generating DSMs of a small coastal dune complex. However, the resolution, coverage and labour investment of these three methods vary. Based on this study, Table 1 compares the three methods considered for topographic models.

Based on these accuracy assessment figures (Figs. 10 and 11) and further comparison between the models (Table 1), RPAS was considered as the better choice for the topographic modelling of this 60 ha coastal dune complex for this particular study.

Conclusion

In this study, three surveying methods for data collection were explored for topographic modelling of the 60 ha Buckroney coastal dune complex in Ireland, viz. LiDAR data, TLS and RPAS. Using both existing LiDAR data and RPAS technology, it was possible to complete the high resolution topographic modelling of the site within one day. In this timescale, TLS was only capable of generating a topographic model of a single dune within the study site. However, this model was of high resolution (0.01 m) and high accuracy (0.010 m) and was used as the reference model for an accuracy assessment of the models created by LiDAR and RPAS. The results show the model based on RPAS data has higher resolution (0.034 m) and higher accuracy (0.11 m) than the model generated from the LiDAR dataset. The RPAS solution also provided more up-to-date and flexible data for modelling. Data collection using RPAS was completed in one day for a 60 ha study site which demonstrated the efficiency of the RPAS survey method in dune complex areas. As the RPAS surveyed remotely, it eased the difficulties of access through dunes areas with deep slopes and difficult vegetation.

However, notwithstanding the many benefits and advantages of RPAS technology in modelling, it still has some challenges with dune complexes surveying. RPAS is unable to create DTMs of coastal dune complexes as it lacks bare-earth data in areas of dense vegetation. RPAS is also sensitive to certain environmental conditions, such as wind, precipitation, low light. Although the use of RPAS can save significant time at the on-site data collecting stage, more time is required for data processing. Preliminary items need to be take into consideration as well, such as arranging permits to fly and training under RPAS regulations from the relevant aviation authority.

Acknowledgements This work was funded by the Fiosraigh scholarship programme of the Technological University Dublin. The authors wish to acknowledge SLR Global Environmental Solution Company for providing the fixed wing drone eBee for data collection and Ronan Hogan and Ray Tighe for assistance in data collection.

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