Coral Reefs
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NOTE

End of the chain? Rugosity and fine-scale bathymetry from existing underwater digital imagery using structure-from-motion (SfM) technology

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Abstract The rugosity or complexity of the seafloor has been shown to be an important ecological parameter for fish, algae, and corals. Historically, rugosity has been measured either using simple and subjective manual methods such as 'chain-and-tape' or complicated and expensive geophysical methods. Here, we demonstrate the application of structure-from-motion (SfM) photogrammetry to generate high-resolution, three-dimensional bathymetric models of a fringing reef from existing underwater video collected to characterize the seafloor. SfM techniques are capable of achieving spatial resolution that can be orders of magnitude greater than large-scale lidar and sonar mapping of coral reef ecosystems. The resulting data provide finer-scale measurements of bathymetry and rugosity that are more applicable to ecological studies of coral reefs than provided by the more expensive and time-consuming geophysical methods. Utilizing SfM techniques for characterizing the benthic habitat proved to be more effective and quantitatively powerful than conventional methods and thus might portend the end of the 'chain-and-tape' method for measuring benthic complexity.

Keywords Rugosity · Bathymetry · Imagery · Structure-from-motion (SfM)

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Introduction

Rugosity is a measure of the variability or complexity of a surface and is often calculated as the ratio of the actual distance along a surface to the linear distance. Rugosity of the seafloor has been shown to be an important ecological parameter for fish, algae, and corals (Risk 1972; McCormick 1994; Fisher et al. 2007; Graham and Nash 2012). Studies have shown that bathymetric complexity in coral reef environments is generally a product of high coral cover and/or diversity. This complexity results in increased habitat heterogeneity in a given area by providing structure for refuge and more attachment points for corals, algae, and invertebrates. By utilizing previously determined relationships between corals and fish assemblage structure, measurements of benthic complexity can be used to rapidly assess coral and fish communities (Brown et al. 2004; Graham and Nash 2012). Furthermore, bathymetric complexity imparts friction on waves and currents and has been shown to be extremely important for accurately modeling waves, currents, and circulation patterns (Lowe and Falter 2015), and thus fluxes of larvae, nutrients, sediment, and contaminants over coral reefs.

Measurement of rugosity in coral reef environments has generally relied on the 'chain-and-tape' method (Risk 1972; McCormick 1994). This method compares the actual surface distance on the reef, measured by draping a chain over the substrate, to a linear distance that is measured with transect tape. Although inexpensive and simple, large numbers of samples must be taken to provide a robust measure of rugosity for an area due to often high spatial heterogeneity in coral reef environments and subjectivity in how the diver placed the chain along the transect (Leon et al. 2015).

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Over the past few decades there have been incredible advances in our ability to remotely map the complexity of the sea floor. Single-beam fathometers have given way to multibeam (Dartnell and Gardner 2004) and interferometric side-scan sonars (Storlazzi et al. 2011) in the kHz frequency range that can map morphology of the seabed at spatial and depth resolutions of meters to decimeters across swaths below the survey vessel. Airborne lidar makes it possible to map large swaths of shallow water efficiently at depth resolutions of decimeters, but generally produces data at spatial resolutions on the order of meters (Zawada et al. 2010). More recently, underwater laser-line scanners (Kocak et al. 1999), high-frequency acoustic systems in the MHz range (Siccardi et al. 1997), and underwater stereo imagery (Friedman et al. 2012) have made it possible to make fine-scale measurements of bathymetry on the order of decimeters to millimeters. Compared to the 'chain-and-tape' method, however, these methods generally demand high capital investment (tens to hundreds of thousands of US dollars) and technical expertise with both hardware and software.

Almost all benthic survey protocols (e.g., Hill and Wilkinson 2004; Brown et al. 2004) include the use of scuba diver-operated digital video and/or series of still photographs. This imagery of the substrate is used to visually assess ecosystem condition, provide optical records of survey areas, and often to statistically evaluate coral coverage and species distribution using random point-count software (Kohler and Gill 2006). Starting in the 1990s, a number of efforts worked to use sequences of two-dimensional images offset in space due to motion with unknown positional information (as would be collected using a towed underwater camera or a scuba diver swimming along a transect) and unknown intrinsic camera parameters (focal length, etc.) to develop three-dimensional structural models (e.g., Tomasi and Kanade 1992; Pollefeys et al. 1999); this technique became known as 'structure-from-motion' (SfM). SfM works similarly to how humans determine three-dimensional (3D) structure by determining correspondence between features in the images collected by both eyes, or in the case of SfM, from offset images collected sequentially along the path of a camera due to motion.

With decreasing price of computer processing power and high-resolution digital imagery and advances in software capable of creating three-dimensional structural models from uncalibrated monocular imagery, there has been a large increase in the application of SfM technology to help address earth science issues (e.g., Westoby et al. 2012; Javernick et al. 2014). He et al. (2012) first proposed the application of SfM technology to develop a high-resolution bathymetric model of the seafloor and derived structural complexity from uncalibrated monocular video collected by a scuba diver that demonstrated good agreement with in situ height measurements. More recently, Burns et al. (2015), Figueria et al. (2015), and Leon et al. (2015) performed similar analyses using commercially available SfM software and measured multiple metrics of 3D habitat complexity, provided accuracy measurements, and computed rugosities. These efforts demonstrated the applicability of SfM for mapping coral reefs from standard uncalibrated video to accurately quantify bathymetric complexity. Here we use previously collected, uncalibrated underwater monocular video to develop a high-resolution (~cm) 3D bathymetric model of a fore reef using off-the-shelf SfM and geographic information system (GIS) software. We compare SfM-derived surface models to both airborne lidar-derived and KHz-scale interferometric side-scan sonar-derived models and then show the applicability of a SfM-derived bathymetric model to computing rugosity or complexity of the seafloor.

Methods

Underwater digital imagery

Georeferenced underwater digital video imagery (http://cmgvideo.usgsportals.net/) was collected in an area of spur-and-groove structure on the fore reef off Lahaina, west-central Maui, Hawaii, using a Sony FCB-H11 block camera that transmits full-resolution high-definition video (1920 × 1080i), enclosed in a custom-made titanium and acrylic housing. The camera was fastened to the side of the boat at a depth of 1 m and oriented vertically toward the seabed. Due to the sufficient ambient light, no additional light sources were used. A Red Hen Systems, LLC, VMS-300 video mapping system was used to geotag the video with GPS data from a hand-held Garmin-76cs. The GPS data integration was necessary to compare the data from the underwater video to co-located lidar and side-scan sonar data discussed below.

Microbathymetry and rugosity from structure-from-motion

The video was converted to individual high-definition (1920 × 1080) still frames using software developed by the Center for Coastal and Ocean Mapping at the University of New Hampshire; this can similarly be done with freely available commercial software such as FFmpeg (www.ffmpeg.org). Every fifth frame was loaded into the Agisoft PhotoScan software (Agisoft, St Petersburg, Russia), a SfM package that is simpler than freely available software and thus more suitable for those not well versed in photogrammetric methods. The frame spacing was

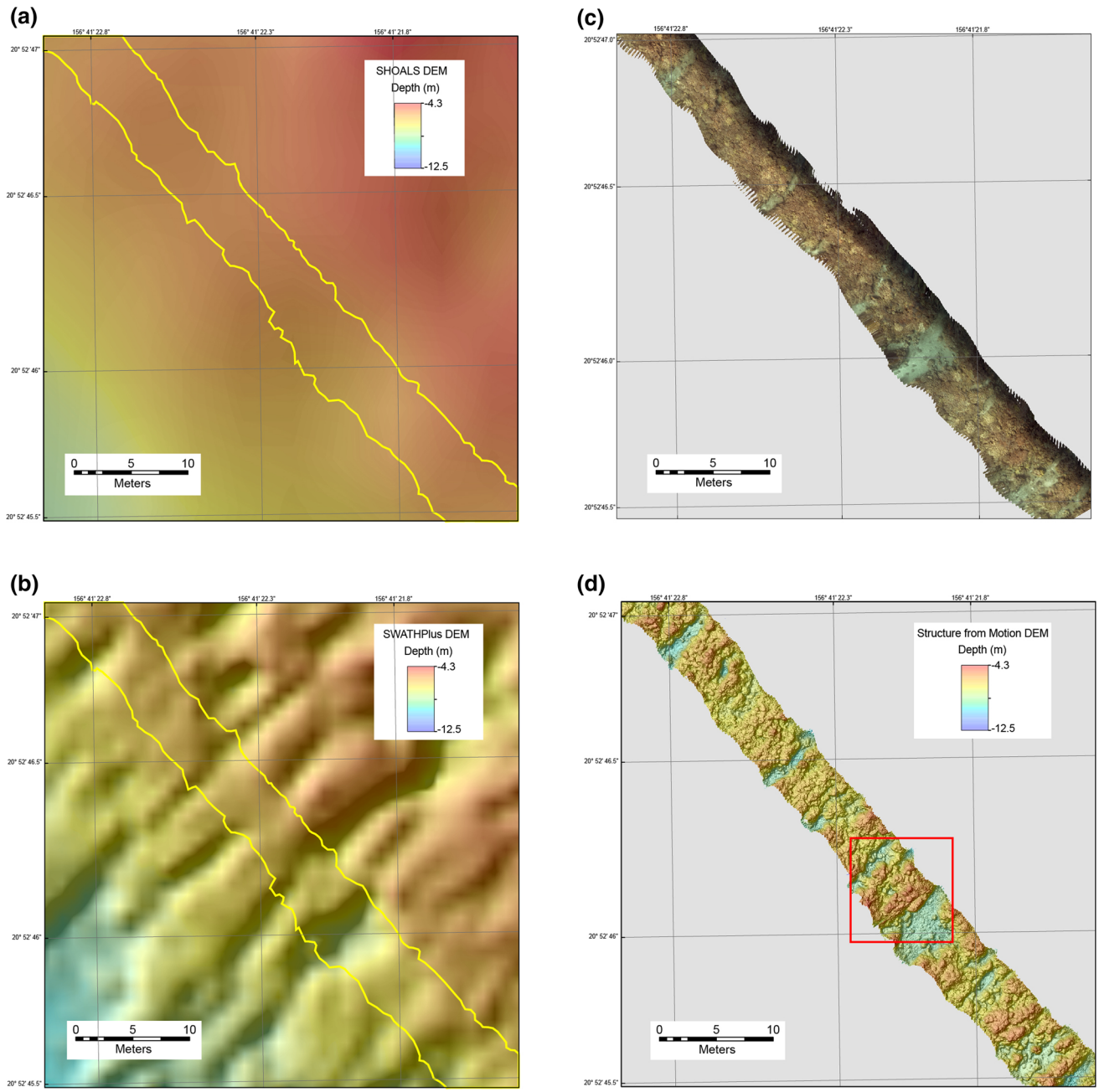

Fig. 1 Map views showing the different scales of data generated from the different systems. **a** Bathymetry from airborne lidar. **b** Bathymetry from shipborne swath sonar. **c** Digital imagery from underwater video. **d** Bathymetry generated from digital underwater video shown in (**c**) using structure-from-motion technology. The *yellow outline* in (**a**) and (**b**) shows the location of the underwater video displayed in (**c**) and (**d**). The *red box* in (**d**) denotes the region discussed in Fig. 2

determined by at least 75% overlap between frames, making sure specific seafloor features were observed in 4–5 frames. A 3D bathymetric model was created in PhotoScan from the video frames using the following steps [for more detail, see www.agisoft.com and Burns et al. (2015)]. The software searches for common points (at pixel scale) in overlapping video frames, matches them, and determines the position of the camera for each video frame. The next step builds a dense point cloud based on the estimated camera positions and pictures. The third step builds a 3D polygonal mesh representing the object surface based on the point cloud. Finally, the point cloud is exported as an XYZ ASCII file in relative coordinates.

The XYZ file was converted to a bathymetric surface using Fledermaus software (QPS, Zeist, The Netherlands), then exported as an ASCII Raster file and imported into an

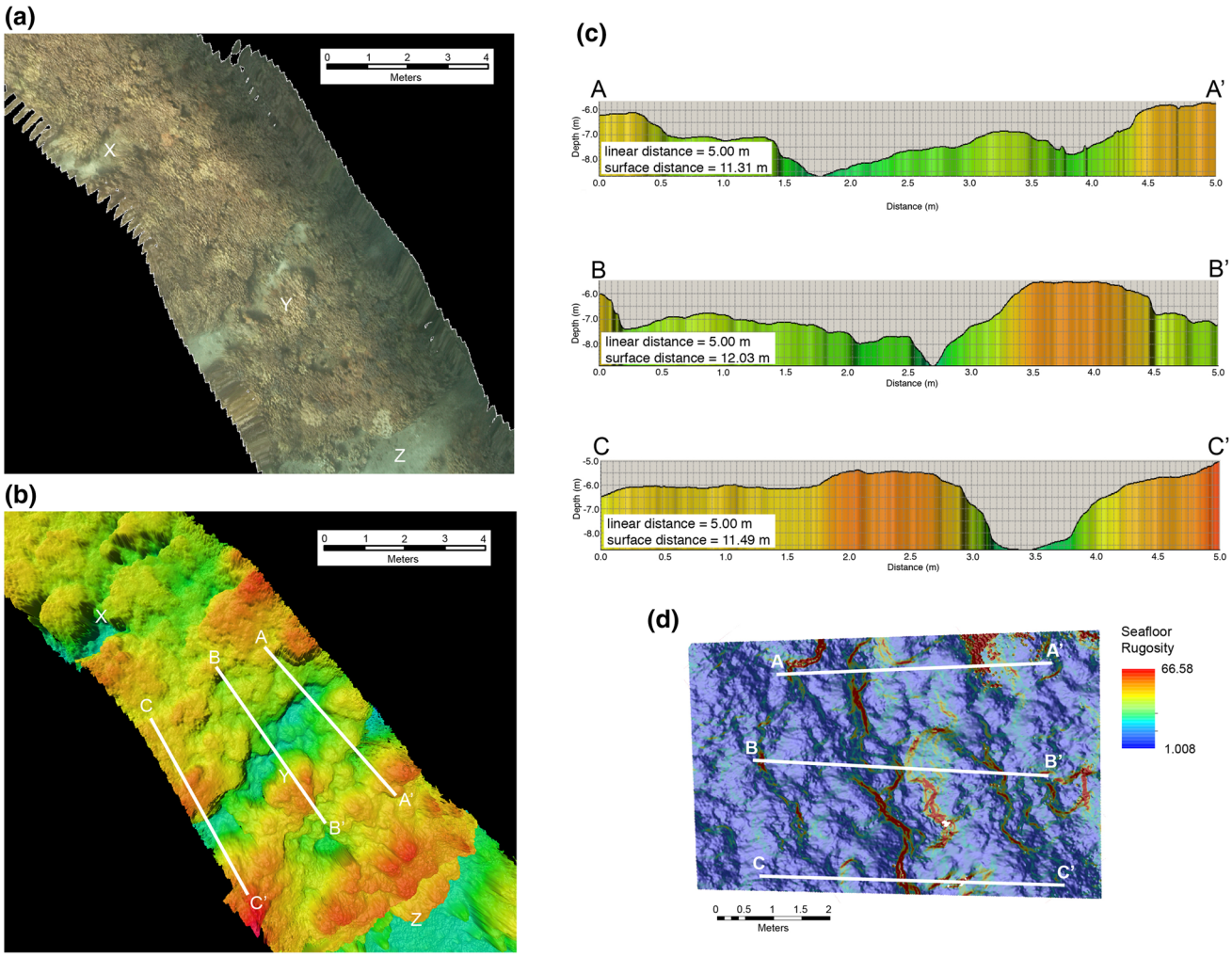

Fig. 2 Comparison of 'chain-and-tape' two-dimensional method to determine rugosity to the three-dimensional methodology using structure-from-motion technology. **a** Map view of seafloor imagery for a section of the study area. **b** Map view of the bathymetry from structure-from-motion technology for the same portion of the study area presented in (**a**). **c** Cross sections showing theoretical 'chain-and-tape' profiles *A–A′*, *B–B′*, and *C–C′*, respectively, draped over the bathymetry from (**b**); these are shaded using the same color range of the bathymetry in (**b**). **d** Map of the spatial variability in rugosity from structure-from-motion technology for the same area shown in (**b**)

ArcMap version 10.1 GIS and converted to a grid in relative coordinates. The grid was rectified using the georeferencing tool in ArcMap using navigational coordinates recorded at the time of the video survey. Once the bathymetric surface was georeferenced, it had a spatial resolution of 0.01 m. Finally, seafloor rugosity was calculated using the surface area to planar area roughness tool available in ArcMap's benthic terrain modeler extension (Wright et al. 2012).

Other bathymetric data sources

For comparison of scale, SHOALS bathymetric lidar data collected in 1999, which are freely available at http://shoals.sam.usace.army.mil/Hawaii/pages/Maui.htm, were used (LaRocque et al. 2004). These lidar data have vertical and horizontal resolutions of ±0.15 and ±3 m, respectively.

Concurrently during the acquisition of the high-resolution underwater video, swath-sonar bathymetric data were collected using a 234 kHz Submetix SWATHplus-M interferometric bathymetric sonar system (SEA Group, Frome, UK). Geodetic stability for the survey was established using a motion reference unit and a shore-based GPS base station that was post-processed to achieve centimeter-scale accuracy. The resulting vertical and horizontal accuracies were ±0.2 and ±0.5 m, respectively.

Results and discussion

The trade-off between spatial coverage and resolution between the different remote sensing techniques is evident in Fig. 1. Although the lidar (Fig. 1a) and sonar data

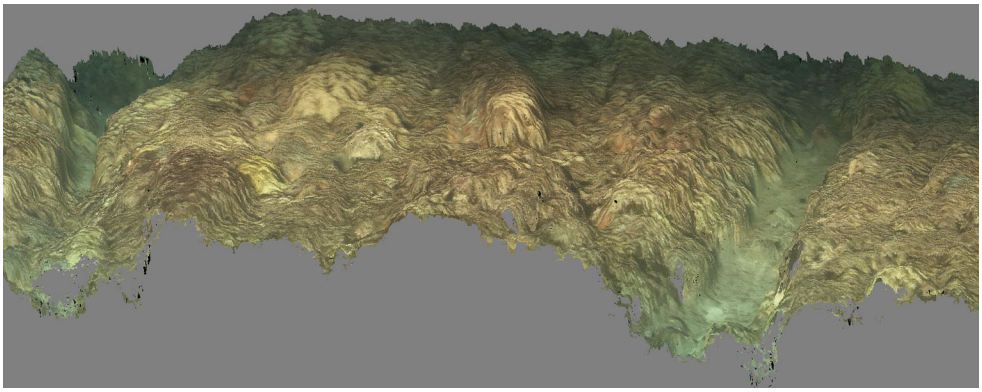

Fig. 3 Three-dimensional perspective view of the digital underwater imagery draped over the bathymetry generated using structure-from-motion technology. The field of view is approximately 4 m wide by 12 m long, with a maximum vertical relief of 6 m

(Fig. 1b) have greater spatial coverage than the optical SfM data (Fig. 1c, d), the resolution of the SfM data is two orders of magnitude greater than that of the lidar data and one order of magnitude greater than that of the sonar data. A total of 201 individual frames were extracted from the underwater video, and all were used via 1.12 million projections and 0.42 million tie points to generate a photomosaic with a 0.51-pixel matching error (Fig. 1c). The resulting bathymetric model that was developed with scale provided by the sonar data has a 1-cm resolution, with a point density of 312 points m^{-2}; the footprint of the data is approximately 4.5–7.0 m wide by 60 m long and ranged in depth from 4.3 to 12.5 m (Fig. 1d).

Rugosity values computed for the co-located lidar, sonar, and optical SfM data are 1.003, 1.046, and 2.322, respectively, demonstrating that as resolution increases for a given complex surface, rugosity increases as more of the complexity can actually be measured (Zawada et al. 2010); further work is needed to test this in different habitat types of varying complexity. The increased robustness of the optical SfM data method compared to the 'chain-and-tape' method is demonstrated in Fig. 2, which includes both coral and sand patches (Fig. 2a). Theoretical 'chain-and-tape' transects A–A′, B–B′, and C–C′ (Fig. 2b) have rugosity values of 2.262, 2.406, and 2.298, respectively (Fig. 2c). The variability between these profiles, separated by just 1 m, highlights how the high spatial heterogeneity in coral reef environments and subjectivity of placement of the chain along the transect can result in different numbers, whereas the composite rugosity for the entire region (Fig. 2d) has much greater robustness, with values ranging from 1.000 to 66.588, with a mean $\pm$ 1 standard deviation of 3.071 $\pm$ 3.194.

Because uncalibrated underwater monocular video is often collected for habitat characterization, the use of such imagery to produce high-resolution bathymetric models and rugosity of the seafloor using SfM technology comes at no additional field cost and lower hardware, software, and salary time than traditional remote sensing methods. The high-resolution bathymetric models developed from such imagery can provide finer-scale and more robust measurements of bathymetric complexity such as rugosity than provided by more expensive and time-consuming remote sensing or simpler and less expensive yet less robust 'chain-and-tape' methods. The ability to produce high-resolution, co-located benthic cover and benthic structure information (e.g., Fisher et al. 2007) from new or previously collected underwater imagery (Fig. 3) makes it easier to more rapidly quantify benthic habitats and improves our ability to address how changes in benthic structure may affect other organismal populations, such as fish and invertebrates. Utilizing SfM techniques for characterizing the benthic habitat proved to be substantially more effective and quantitatively powerful than conventional methods, and thus might portend the end of the 'chain-and-tape' method for measuring benthic complexity.

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