Measuring reef complexity and rugosity from monocular video bathymetric reconstruction

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Abstract. Structural complexity of a reef is highly correlated to coral growth rates, coral cover and overall levels of biodiversity, and is therefore integral in determining ecological processes. Modeling these processes commonly includes measures of rugosity obtained from a wide range of different survey techniques that often fail to capture rugosity at different spatial scales. Here we show that accurate estimates of rugosity can be obtained from standard video footage captured using underwater video cameras (i.e. monocular video). To demonstrate the accuracy of our method, we compared the results to exact in-situ measurements of a $2m$ x $20m$ area of fore reef from Glovers Reef atoll in Belize. Sequential pairs of images were used to compute fine scale bathymetric reconstructions of the reef substrate from which precise measurements of rugosity and reef complexity can be derived across multiple spatial scales. To achieve accurate bathymetric reconstructions from uncalibrated monocular videos, the position of the camera for each image in the video sequence and the intrinsic parameters (such as focal length) must be computed simultaneously. We show that these parameters can be often determined when the data exhibits parallax-type motion, and that rugosity and reef complexity can be accurately computed from existing video sequences taken from any type of underwater camera from any reef habitat or location. This technique provides an infinite array of possibilities for future coral reef research by providing a cost effective and automated method of determining rugosity in both new and historical video surveys of coral reefs.

Key words: Structural complexity, Monocular video, Online calibration, Reconstruction, Computer vision.

Introduction

Coral reefs are most diversity and biologically complexity ecosystems that support a variety of marine organisms, such as approximately 22% of marine fish species and more than 25% of all known marine species(Spalding et al. 2001). Structural complexity of coral reefs play an ecologically important role in observing coral growth or decline rates, coral coverage as well as levels of biodiversity, which is critical to understand the fish assemblage and abundance as well as the complex ecosystem processes(Risk 1972; McCoy and Bell 1991).

Structural complexity of coral reefs is traditionally measured *in situ* by SCUBA divers along a single, linear profile using chain-tape methods or profile gauges(McCormick 1994). Specifically, divers employ quadrats and line intercept transects sampling approaches to measure the size and distribution of coral colonies *in situ*. Accuracy of measurement is highly limited by the resolution of quadrats and the length of transects as well as the skills of divers. In addition, these human-based survey methods are labor intensive and low productivity due to high operational cost as well as human physiological limits on dive time. As a result, the surveys could only monitor a small number of individual corals and limited area of designed coral reef region. Furthermore, these surveys will be spatially and temporally sparse and difficultly repeatable. Thus these limitations would restrict our understanding of the mechanistic processes occurring at different scales. Finally these methods could potentially damage those fragile corals.

Alternative methods for surveying large reef areas are proposed based on remote sensing methods, such as aerial LIDAR and satellite-based imagery. However, these remote sensing methods can not provide fine details of underwater structures due to the limited spatial resolution(ranging between ~1-30 m^2 pixel size, QuickBird and IKONOS – LANDSAT) and the limited depth range caused by severe attenuation of laser in water.

Recently, lots of work have utilized underwater video captured by optical sensors to derive the relevant information of coral reef because it can provide high resolution images of coral colonies and cover large areas quickly. Additionally, it can also produce a permanent visual record of reef condition and prevent the potential damage due to untouched measurement. Lirman *et al.*(Lirman *et al.* 2007) applied video mosaic to construct 2D spatially accurate high resolution mosaic for underwater surveying. However, this method is not geometrically accurate due to ignorance of 3D structure of the scene. The Australian Centre for Field Robotics(ACFR) employed Autonomous Underwater Vehicles(AUVs) equipped with stereo cameras to collect reef data and calculate rugosity based on bathymetric stereo image reconstruction (Friedman *et al.* 2010). However, the operation of such vehicles and their support workstation is expensive, and their large size is not suitable for survey in shallow water. Moreover, stereo vision system requires additional design for use by AUVs or divers comparing to monocular cameras. By consider that most of historical video surveys are done by monocular cameras, the method to estimate coral reef structural complexity only by monocular video bathymetric reconstruction will provide most benefits. The drawback of monocular video reconstruction is up to the scale, however, most of the targeted experiment spots have some artificial marks which can help to resolve the scale.

The method proposed in this paper uses the uncalibrated monocular video obtained by a diver to generate dense bathymetric reconstruction of selected transect in coral reef region. Then seafloor can be detected by plane fitting approach. As the seafloor has been determined, maximum height and structural complexity of each quadrat in the transect are easily computed based on reconstructed 3D model. Finally the accuracy of computed maximum height profile and structural complexity are evaluated by the exact *in situ* measurements of the same area obtained by diver.

Material and Methods

Video data acquisition

The field activities for this study were conducted on Glovers Reef Atoll (87°48'W, 16°50'N), located 52 km offshore and 15 km east from the Mesoamerican Barrier Reef off Belize, Central America. Particularly, the experimental videos and measurements were collected from the Montastrea annularis dominated fore reef (depth of 10-12 m) on the eastern side of the atoll during 2009. The system has high wave energy and water flow due to its windward orientation (McClanahan 1998; Renken 2009), which has direct effect on the structural complexity of the reef.

An area of approximately 20 x 20 m was selected on the fore reef slope of the atoll, approximately 2m away from the drop off in order to avoid a steep slope or wall. The perimeter of the area was marked using a thin rope (5mm in diameter) and string was used to subdivide the area in 8 equal transects of 2*m* x 20*m*. Subsequently each transect was subdivided into 10 2*m* x 2*m* quadrats (10 per transect), flagging tape was used to mark the corners of each quadrat. Video transects following a lawnmower pattern were taken using a high definition (1280 x 720) Sanyo Xacti video camera at 30*Hz* in an Epoque housing, and then the camera was held perpendicular to the substratum at a height of approximate 1 *m*. In Fig. 1, the green dash arrows represent the video capture pattern for each transect.

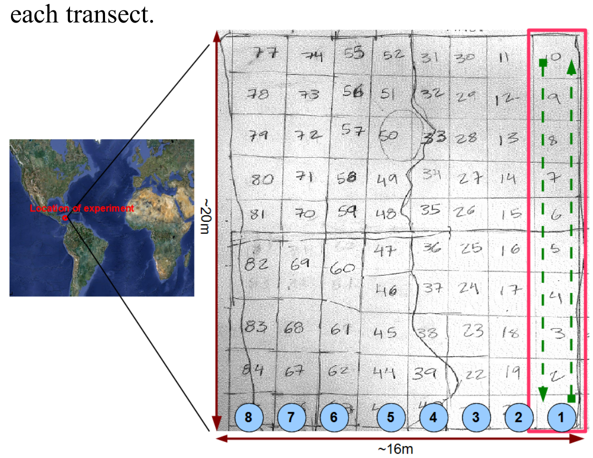


Figure 1: Area targeted for diver surveys. The surveyed spot consists of 8 transects(about 16*m* x 20*m*) indexed by blue circle with number. Each transect contains 10 quadrats or so with 2m by 2m. This study is conducted on the first transect including quadrat 1 to 10 highlighted by red rectangular on the right. The green dash line indicates the pattern how diver film the coral reef.

Ground truth from in situ measurements

A team of 4 divers mapped and characterized the benthos of the area following a modified version of the Atlantic and Gulf Rapid Reef Assessment v4 (AGRRA) methodology. This methodology was chosen because: (1)it is the most effective methodology at quantifying the condition of coral reef communities, (2) it is widely used and it has a regional database of Caribbean coral reef condition (ww.agrra.org), (3)it is the most detailed methodology available in the region and(Kramer 2003), (4)it measures rugosity and coral density (www.agrra.org).

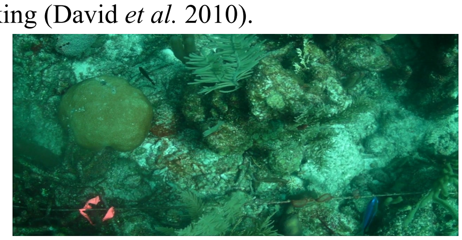
The main modification made to the AGRRA protocol was the use of quadrats instead of transects, and 100% of the benthos, not only a proportion of it, was mapped. Within each quadrat every structure larger than 10 *cm* in diameter was mapped measured and identified to species (hermatypic corals) or family (sponges, calcareous algae, etc.) level. In order to assess size three measurements were taken from each colony (dead or alive) and rigid sponge: (1)the maximum diameter a, (2)perpendicular diameter b (both perpendicular to the axis of growth) and (3)maximum height $h_{quadrat}$ (parallel to the axis of growth); these were taken to the nearest centimeter using a 1 m pvc pole marked every 5cm. The structural complexity index (0-1) for each quadrat was calculated by combining the spatial distribution and size data as following.

$$SC_{quadrat} = \frac{\pi a b h_{quadrat}}{4 l_{quadrat} w_{quadrat} h_{area}} \qquad (1)$$

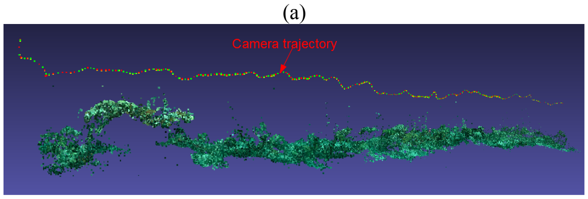
where $SC_{quadrat}$ represents the structural complexity of the quadrat, $l_{quadrat}$ and $w_{quadrat}$ denote the length and width of each quadrat which are 2m equally, and h_{area} denotes the maximum height of the survey area.

Monocular bathymetric reconstruction

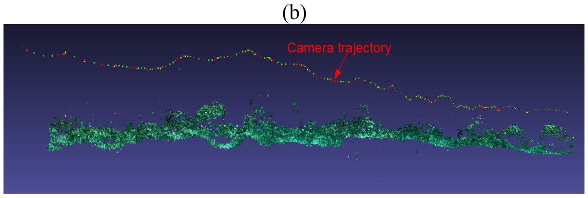
Multiple view stereo based reconstruction method (Snavely *et al.* 2006; Furukawa *et al.* 2010) in computer vision has been employed in this paper. Firstly, camera positions for each frame are obtained by structure-from-motion algorithm which consists of feature extraction and tracking, followed by camera poses estimation routines and bundle-adjustment to refine the solutions. As camera parameters (focal length, principle points, distortion etc.) is unknown, calibration results should be determined on the fly (Pollefeys *et al.* 1998). Then dense depth map for each frame will be achieved based on triangulation of matched features and precomputed camera poses. Finally, dense 3D point clouds model will be attained by projecting features with depth to 3D space and discarding the outlines through depth consistency checking (David *et al.* 2010).



(a)



(b)



(c)

Figure 2: Sample frame and dense reconstructions. (a)A sample frame from video data for the first transect, (b)dense reconstruction of quadrat 01 to 10 from the first transect, and top color line denotes the path of camera, (c)dense reconstruction of quadrat 10 to 01 from the first transect, and top color line denotes the path of camera.

As aforementioned, two video clips were taken for each transect following the lawnmower pattern. By watching the video empirically, each video clip almost covers 50% - 60% area of the transect. Due to monocular reconstruction can recover 3D scene up to scale, two half-transect monocular reconstructions might be with different scales. We reconstructed the two half-transects individually and then scale them based on the metric information from real data shown in Fig. 2. Fig. 2(a) is a sample frame of video clip, and the string line intercept at the bottom of the frame can be used to infer the scale information. Fig. 2(b) and (c) illustrate the dense reconstructions of quadrats 01 to 10 and quadrats 10 to 01 in the first transect, respectively. The red and blue dots represent estimated camera trajectory which is not necessary to be parallel to sea floor. Thus our method relax the restriction on video captures.

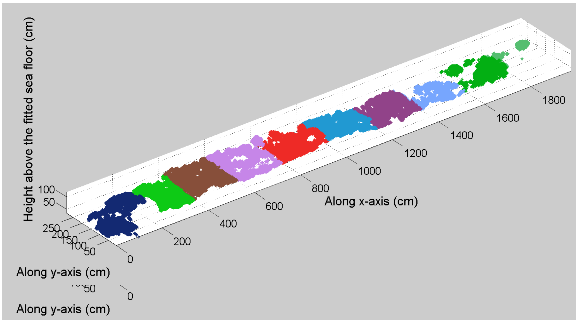
Maximum height profile and structural complexity

As the initial reconstructions of two half-transects do not lie in the same coordinates system as in situ measurements, we align the reconstructed sea floor with xy plane to make the following comparison with ground truth easily. Firstly, robust plane fitting algorithm was applied to find the normal direction of sea floor, and then transform the reconstructions to the same coordinates system in which *in situ* measurements obtained. Then both reconstructions are scaled with actual metric dimension. In Fig. 3, two reconstructed half transects are displayed in 3D space with different colors representing different quadrats. Note that there are still have some sparse regions in the reconstructions which are caused by the moving objects(sea grass, gorgonians etc.). Our reconstruction method assumes the reconstructed scene is static, otherwise the reconstructed points will be discarded.

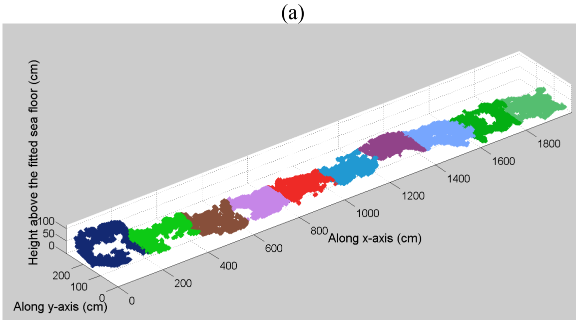
Given the reconstructions have been registered in the same coordinates, the maximum height for each quadrat in the first transect is computed as below:

$$h_{max}(i) = \begin{cases} h^1_{max}(i) & h^1_{max}(i) > h^2_{max}(i) \\ h^2_{max}(i) & h^1_{max}(i) < h^2_{max}(i) \end{cases} \qquad (2)$$

where $h_{max}(i)$ is the maximum height in the i^{th} quadrat, while $h^1_{max}(i)$ and $h^2_{max}(i)$ denote the maximum height for the i^{th} quadrat in transect with quadrat 01 to 10 and transect with quadrat 10 to 01, respectively.



(a)



(b)

Figure 3: Alignment of each quadrat in 3D space. (a)Half transect with quadrat 01 to 10, (b)half transect with quadrat 10 to 01.

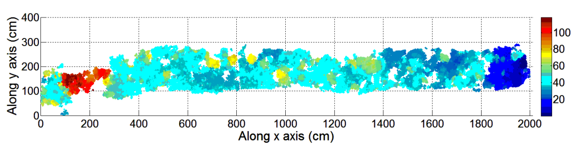
Structural complexity of the first transect are defined as the volume integral over each quadrat.

$$SC_{quadrat}(i)=\int\int h_i(x,y)\,dxdy \qquad (3)$$

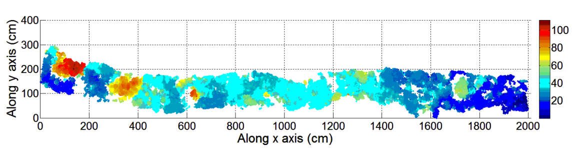
where i is the index of quadrat in the first transect, and $h(x,y)$ is the height distribution of each quadrat.

Finally, the accuracy of our method is evaluated by the absolute error (Harvey *et al.* 2000) between estimations of maximum height and structural complexity of each quadrat and *in situ* measurements (ground truth).

Results



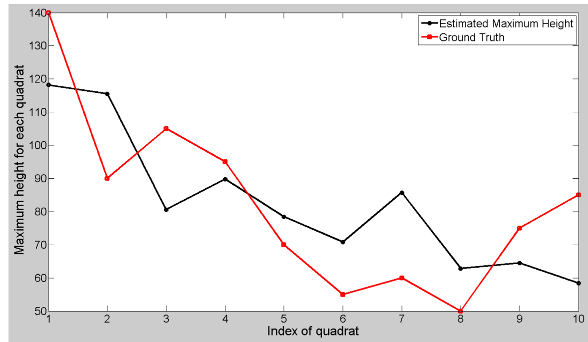
(a)



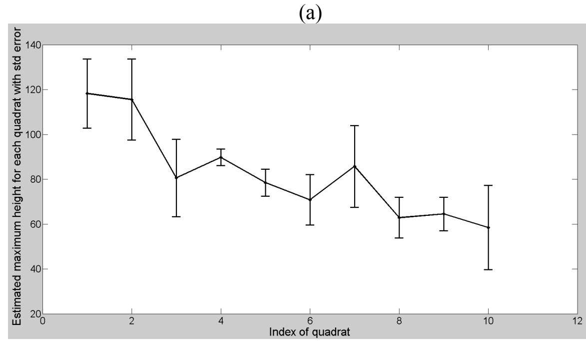
(b)

Figure 4: Height map for (a)quadrat 01 to 10 and (b)quadrat 10 to 01. Note that the dimension has been scaled with metric measurement.

Fig. 4 shows the height map for two half-transects in the first transect, *i.e.*, quadrat 01 to 10 and quadrat 10 to 01. We can find the highest coral colony lies in the first quadrat, which is qualitatively correct by comparing with diver's sketch of the same quadrat. Again, holes in the height map are caused by moving objects underwater, such as sea grass, and gorgonians. In addition, the reconstructed transect is not exact straight due to diver does not swim along a straight line.



(a)

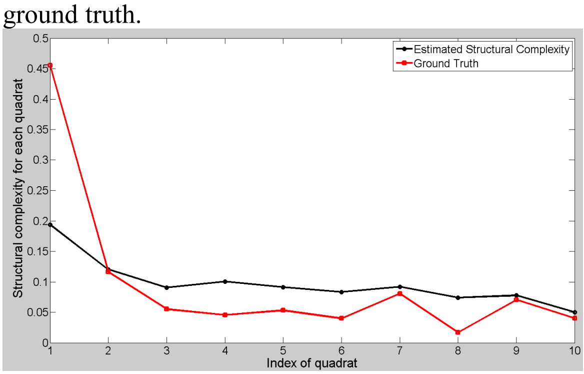


(b)

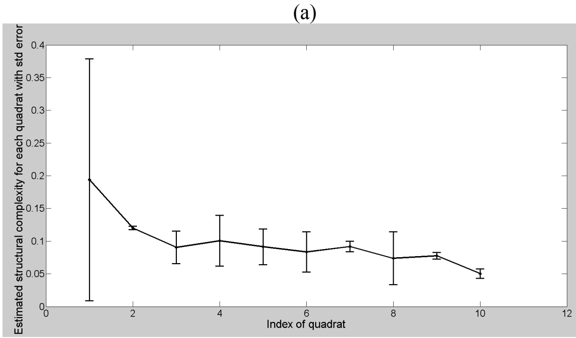
Figure 5: Comparison between estimated maximum height of each quadrat in the first transect with ground truth. (a) shows maximum heights plot of each quadrat for estimation(black) and ground truth (red), (b) indicates the estimated maximum height for each quadrat with error *w.r.t* ground truth.

Fig. 5 illustrates the quantitative comparison between the maximum height of each quadrat in the first transect and ground truth. In Fig. 5(a), the trend of maximum heights are quite similar to *in situ* measurements except quadrat 3, 9 and 10. Regarding quadrat 3, there are too much moving sea grass in that quadrat which occludes the coral colonies in the same quadrat partially. Thus some coral information can not be reconstructed. While error for quadrat 9 and 10 is introduced by drift of the proposed algorithm. As video data is captured by a uncalibrated camera, estimated camera poses would drift along the path. Fig. 5(b) demonstrates error level for maximum height estimation for each quadrat in the first transect. We find that the quadrats with less moving sea grass often have small error *w.r.t* ground truth. Even for the quadrat with largest error, it is still under 30*cm*.

In Fig. 6, it shows the quantitative comparison between the structural complexity of each quadrat in the first transect and ground truth. Fig. 6(a) indicates estimated structural complexity of each quadrat matches with *in situ* measurements correctly except in the first quadrat. According to Fig. 4, the largest size coral colony appears in the first quadrat. Generally, it is not easy to measure the cross section area and height accurately for large coral colony by divers. Moreover, divers take the video quite close to sea floor, thus large size coral colonies might not be covered completely due to limited field of view. Despite there are large error in quadrat 9 and 10 for maximum height estimation (Fig. 5), structural complexity of these two quadrats can be recovered reasonably. Because structural complexity is computed via integration over the whole quadrat, which would spread the error uniformly to the whole quadrat region. Fig. 6(b) provides the quantitative accuracy of estimated structural complexity *w.r.t* ground truth.



(a)



(b)

Figure 6: Comparison between estimated structural complexity of each quadrat in the first transect with ground truth. (a) shows structural complexity plot of each quadrat for estimation(black) and ground truth (red), (b) indicates the estimated structural complexity for each quadrat with error *w.r.t* ground truth.

Discussion

As the use of digital imagery and video surveys in benthic monitoring has increased dramatically, accurate and efficiently image based method become more and more important in coral reef research. In this paper, the proposed monocular bathymetric reconstruction method can obtain height profile and structural complexity of the surveying region automatically and quickly. Moreover, it can provide the type of ecological information related to coral reef condition commonly measured by divers *in situ*.

Regarding on the comparison between estimated coral reef characteristics and ground truth, several research questions could be explored further as following: (1)Currently, cross section of coral colony is assumed to be elliptic shape, and volume of coral colony is computed by the area of approximate ellipse multiplied by maximum height of that coral colony. It might introduce large error if coral colony has different cross section shape and steep contour. (2) Improved online calibration might prevent camera poses drift. Better reconstruction could be achieved by using color correction on current video data.

In conclusion, the proposed method is promising to provide ecological information of coral reef powerfully and efficiently. It can be used for old videos conducting temporal comparison for the same region which is critical for bioerosion. Furthermore, it might be incorporated into existing monitoring protocols.

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