

Second-Generation Landscape Mosaics of Coral Reefs

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Abstract. Efficient survey methodologies that provide comprehensive assessment of reef condition are fundamental to coral reef monitoring. Current state-of-the-art techniques in coral reef assessment rely on highly trained scientific divers to measure indices of reef health (e.g., substrate cover, species richness, coral size, coral mortality). First-generation video mosaics were an innovative survey technology that provided large-scale (up to 400 m²), spatially accurate, high-resolution images of the reef benthos without extensive survey times or a need for scientific divers. Despite these advances, first-generation mosaic products were insufficient for species-level identification of many benthic taxa, thereby limiting the monitoring potential of the technique. A second-generation mosaic survey technology has been developed, which integrates high-resolution still-image acquisition with high-definition video surveys of the reef benthos. These second-generation products have sub-millimeter benthic resolution allowing for species identification of coral colonies (as small as 3 cm), identification of macroalgal genera, and increased information on coral colony health and small scale competitive interactions. This combined survey technology allows users to collect imagery on both a landscape and colony level over 100's of square meters in under an hour of in-water dive time. The resulting product has excellent archive potential and is a superior tool for tracking changes over time.

Key words: Video mosaics, coral monitoring, benthic surveys.

Introduction

Worldwide decline of coral reef communities since the 1970's has prompted the development of numerous reef monitoring techniques at multiple spatial scales. Traditional monitoring methodologies rely heavily on expert scientific divers to measure indices of reef health during field surveys. These methods often result in long dive times and a lack of permanent raw data of the state-of-the-reef at the time of the survey. To address these weaknesses, many monitoring programs now incorporate underwater photography or video into their survey design so that images can be analyzed out of the water to measure metrics such as percent cover and coral colony sizes. Standard underwater video and still imagery often reduce the dive time and expense of reef monitoring, but they provide either a small image footprint or have low resolution thereby limiting their value as complete coral community monitoring tools.

An underwater video mosaic survey technology has been developed to create large (several hundred m²), spatially accurate, high-resolution video mosaics of reef communities that provide a landscape view of the seabed while minimizing dive-time (usually < 1 hr) (Lirman et al. 2007). Such "landscape mosaics" overcome many limitations of previous survey

methods while retaining most of their strengths. Mosaics can be created without trained, expert scientific divers, long dive times, or the use of extensive permanent markers that are normally required for repeated surveys of the same locations. Their high spatial accuracy allows accurate measurements of distances and colony size directly from the mosaics themselves (Lirman et al. 2007).

Over the past four years, landscape mosaics have been used to assess coral reef status (Lirman et al. 2007), hurricane impacts (Gleason et al. 2007), bleaching events, ship groundings, and the status of submerged cultural resources (unpubl. data).

The first-generation landscape mosaics were created from video taken with either a Sony TRV 900 DV camera hand-held by a diver, or a Point Grey Research Flea camera mounted on a Remotely Operated Vehicle. These two camera systems provided spatial resolution ranging from one to four mm/pixel, which was sufficient to identify taxonomic groups, such as stony corals, sponges, gorgonians, macroalgae and sand, but was not fine enough to allow species-level identification in most cases (Lirman et al. 2007). Organisms smaller than 5 cm in diameter were typically not detectable using first-generation mosaic products (Lirman et al. 2007).

The aim of this paper is to describe a second-generation imaging system with improved benthic resolution. This second-generation system was used to survey a permanent study plot at Brooke's Reef, Florida in June 2008. This mosaic was then compared to the first-generation mosaic acquired at this same site in June 2004.

Material and Methods

The use of cameras for benthic habitat mapping has been an active area of research over the last decade. (Negahdaripour and Madjidi 2003; Gracias et al. 2003; Singh et al. 2007). In the present research, the algorithm for creating large scale video mosaics is based on the approach described by Gracias et al. (2003) and Lirman et al. (2007). The first-generation of mosaic processing consisted of four steps using underwater video images. Mosaics were produced by 1) creating an initial estimation of camera motion using feature matching of textured areas between sequential image frames (Lowe 2004; Brown and Lowe 2003), 2) predicting and matching of non-sequential frames, 3) refinement of the camera motion estimation based on using bundle adjustment, and 4) blending of the individual video frames to create a seamless single image of the survey area (Gracias et al. 2006).

This mosaic algorithm requires a high degree of overlap between sequential images to accurately estimate camera motion. In the field, high overlap between images is achieved by using a video camera with a high rate of frame capture (i.e. 30 frames per second, fps). Video cameras, however, have relatively low image resolution (< 1 Megapixel, MP). Therefore high benthic resolution images can only be acquired with these cameras if a very small field of view is maintained during the survey. This is accomplished by maintaining a small distance from the camera to the seabed (typically 40 cm or less). Although in use for some monitoring programs (e.g. Somerfield et al. 2008), this approach does not allow for the 1.5 to 2 m disparity between the benthos and camera normally needed for accurate landscape mosaic processing (Lirman et al. 2007). Current camera technology does not provide a single reasonably priced camera system that can simultaneously capture frames at a high rate with the image resolution necessary for species level identification from 2 m above the bottom.

To overcome the resolution limits of the first-generation mosaic survey technology while maintaining the high frame rate and altitude requirements of the mosaic processing algorithms, a two-camera system was adopted. This second-generation mosaic imaging system combines information from (1) a high-definition video (HDV)

camera capable of full video frame rate (30 fps) and (2) a digital still camera capable of acquiring very high-resolution images (10 MP) at low capture rates (1 fps).

The second-generation mosaic imaging system was created using commercially available components, including a Nikon D200 10 MP Digital SLR camera and Ikelite underwater housing, Sony HVR-A1U HDV video camera and Amphibico housing, and a 3.5" LCD color external monitor. All components of the enhanced mosaicing system were mounted in an aluminum/stainless steel frame (Fig. 1). The enhanced acquisition hardware allows for simultaneous collection of video and photographic stills using two independent cameras mounted on the same frame.



Figure 1. Second-generation mosaic imaging system with Sony HVR-A1U camera and underwater housing (left), Nikon 10 MP still and housing (right) and 3.5" LCD color video monitor (top).

In the field, the second-generation imaging system is deployed with both cameras in a down-looking position. Cameras are swum by a single diver 2 m above the reef area-of-interest in a double lawnmower pattern as described previously (Lirman et al. 2007).

Data processing of the second-generation mosaic data is divided into two parts. First, a landscape mosaic is created using the same four steps as the previous generation of mosaic images with HDV images substituted for regular DV imagery (Lirman et al. 2007).

The second part of data processing represents a new step designed to register high resolution still images to the landscape mosaic. Automated feature matching algorithms (Lowe 2004; Brown and Lowe 2003) are used to map the still images to their geographic locations within the video mosaic. This mapping is obtained by matching individual still images to individual video frames used to create the landscape mosaic of the survey area.

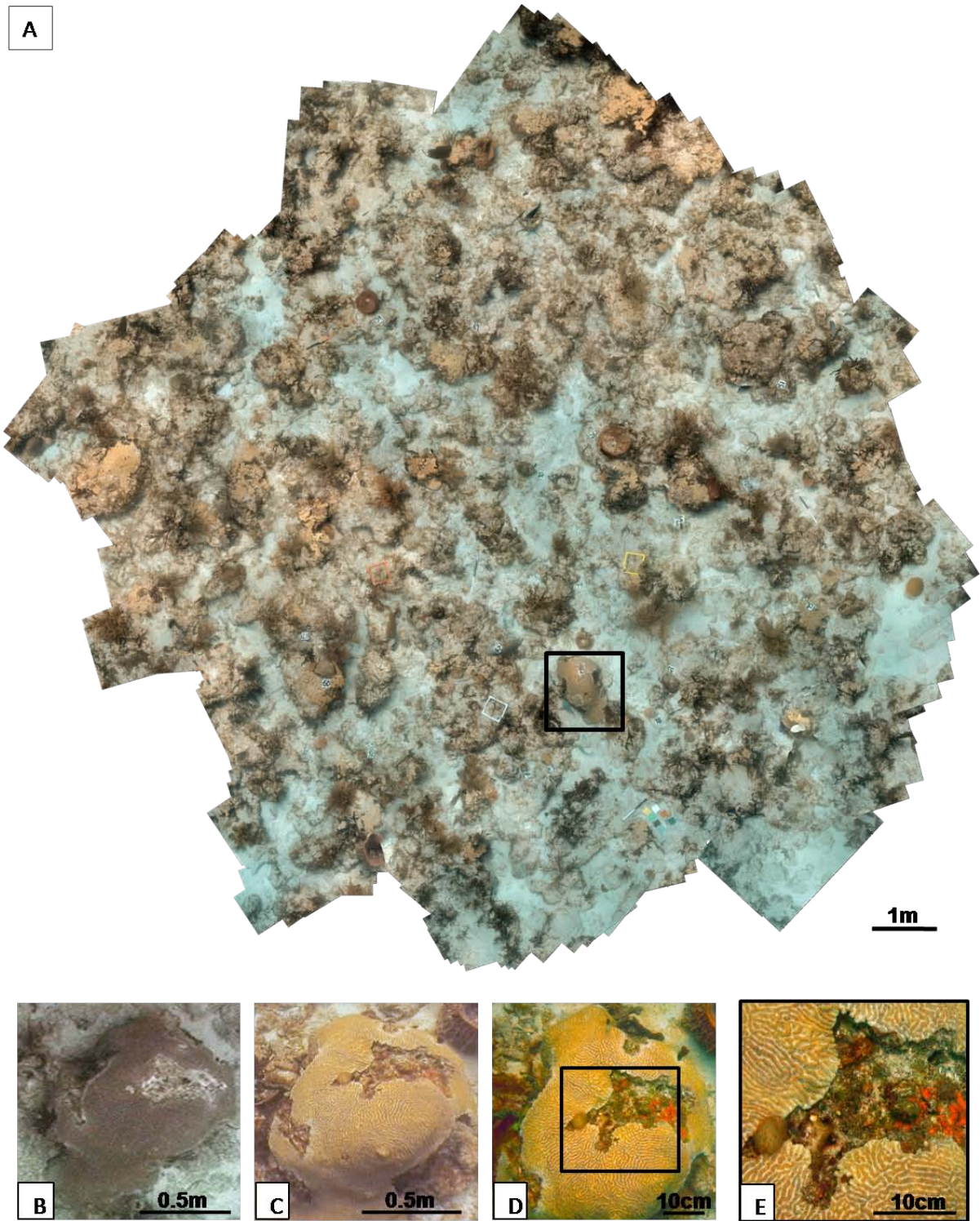


Figure 2. (A) A second-generation video mosaic from Brooke's Reef, FL taken in June 2008. Images of a *Meandrina meandrites* colony (shown in A) selected from mosaic surveys created using: (B) a Sony DV camcorder in June 2004, (C) high definition Sony camcorder from June 2008, and (D-E) 10 MP Nikon D200 still camera. All images were acquired at a distance of 2 m from the benthos. The combination of high resolution still images with video acquisition provides increased reef health information such as (D) tissue partial mortality and (E) cyanobacterial, macroalgal, and sponge interactions.

As a result of this process, each video frame used in the mosaic creation process is linked to a corresponding still image.

Display software was developed that allows users to select any point within the landscape mosaic produced by the second-generation imaging technology and retrieve the corresponding 10 MP still image and corresponding video frame of the area surrounding that point.

Results

In June 2008, a portion of Brooke's Reef, FL (25° 40.508'N, 80° 5.908'W) was mapped with the second-generation system. The landscape mosaic generated from the high-definition video of the second-generation system covered 156 m² (Fig. 2A). The first-generation landscape mosaic of Brooke's Reef taken in June 2004 has a spatial resolution of 3 mm/pixel (Fig. 2B), whereas the second generation version has a spatial resolution of 2 mm/pixel (Fig. 2C). The second-generation still camera images were acquired at a frame rate of 1 fps, resulting in approximately 1,800 10 MP images of the reef benthos. The 1,800 still images were then matched to key video frames. The average spatial resolution of the still images from the second-generation system was 0.4 mm/pixel, almost an order of magnitude improvement over the video of the first generation system (Fig. 2D, E).

The 2 mm/pixel spatial resolution of the second-generation landscape mosaic, produced from the high-definition video, enabled improved analysis of the mosaic. Boundaries between sponges, corals and gorgonians were clearer and large colony identification (> 25 cm) was possible for most Caribbean species (Fig. 2C).

Analysis of the 10 MP still images from the second-generation system provided the greatest taxonomic resolution. The sub-millimeter resolution of the still images allowed for species-level identification of colonies as small as 3 cm in diameter. In addition macroalgal groups were identifiable to genus with species level identification possible for macroalgae with obvious defining characteristics such as *Halimeda tuna* and *H. opuntia*. Coral colony health information such as partial mortality boundaries and evidence of bleaching and disease were all recognizable using the still images. Small-scale indicators of reef health such as cyanobacteria, macroalgal, and sponge competition were also visible using high-resolution still data (Fig 2D, E).

Discussion

The first-generation video mosaics demonstrated that mosaic-based monitoring could be accomplished without trained, expert scientific divers, long dive

times, or extensive tagging of coral colonies. This technique also allowed users to assess basic reef health indices and monitor coral colonies using a large-scale image-based approach that limited the need for extensive dive-time and provided long lasting visual information on the state-of the reef at the time of the survey (Lirman et al. 2007).

Second-generation mosaics retain these monitoring strengths while providing increased benthic resolution over the entire survey area, enabling species level information for most coral colonies. This allows greater taxonomic information with respect to percent cover and diversity indices than was available from first-generation mosaics. In addition, change detection

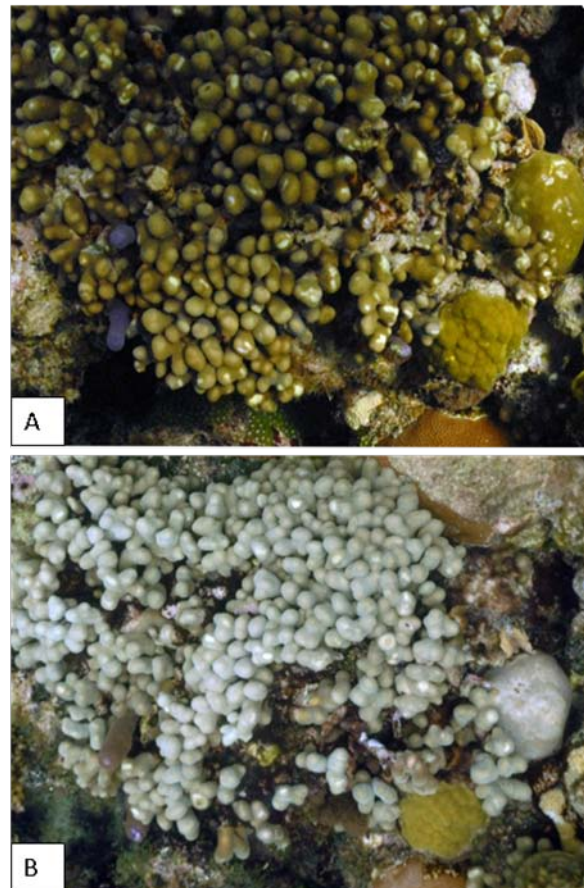


Figure 3. Example of change detection potential using second-generation imagery. High resolution still images were acquired from approximately 2 m water depth during video mosaic surveys. Images were automatically matched to their geographic locations within the survey area for change detection analyses. Between February, 2008 (A) and September, 2008 (B) the *Porites porites* (center) and *Stephanocoenia intersepta* (right) colonies shown above have undergone considerable paling. Evidence of partial mortality and an increase of cyanobacteria within the *P. porites* colony are also identifiable by comparing the survey images. Small indicators of coral health such as fish bite predation are also clearly present on both the *P. porites* and the *S. intersepta* in February 2008 and can be followed through time to monitor long-term impacts (A).

analysis using second-generation mosaic products provides information on conspicuous indices of reef health (such as bleaching and tissue loss) while also allowing users to monitor fine scale stressors such as macroalgal and cyanobacterial interactions and predation events (Fig. 3). This represents a significant monitoring improvement over first-generation products that could only discern dramatic indicators of colony health such as bleaching, and significant tissue loss (Gleason et al. 2007).

Although many monitoring programs take pictures of the reef for analysis and documentation purposes, the extensive cataloging and database management required in the laboratory often limits the amount of photographic data acquired during a survey. The automated matching of high resolution still images to their geographic location within a second-generation mosaic removes the need for user-intensive laboratory cataloging and allows the archiving of several thousand high resolution images of a reef area with minimal user input.

Image-based techniques for reef monitoring have an excellent archive potential that is vastly superior to written notes by divers. The second-generation mosaic survey technology described here provides both landscape level and colony level (as small as 3 cm) permanent records of the state-of-the-reef at the time of the survey without increasing the dive-time of first-generation mosaic products. The simultaneous capture of both of these scales of information allows users to monitor large-scale changes in reef communities such as hurricane or ship grounding damage, as well as small scale interactions such as sponge and macroalgal competition using the same survey design and the same raw data set.

Conclusions

The incorporation of high-resolution still imagery into the second-generation imaging equipment and mosaic processing resolved the species identification limitations of the first-generation system.

The ability to capture high resolution images over 100's of square meters and georeference these images within video mosaics without user input is a major advantage of the landscape mosaic technology. The combination of large-scale image maps and high-resolution benthic information provides a unique tool that maintains the strengths of most traditional monitoring methods, such as the ability to extract indices of reef health (percent cover, coral colony sizes, and diversity indices), while also providing a rapid method to document and assess changes at both large and small scales in coral communities without extensive tagging. This combined with the extensive archive potential inherent to this technology provides

a significant advancement in coral reef community monitoring technology.

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