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Third-Generation Underwater Landscape Mosaics for Coral Reef Mapping and Monitoring

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Abstract. Underwater landscape mosaics are image-based tools for large-area (100s to 1000s of m^2) fixed-site coral reef mapping and monitoring. First–generation mosaics were created using digital video, resulting in a spatial resolution on the order of 3-5 mm / pixel. User demand for higher spatial resolution prompted development of a second-generation mosaic system that used two cameras: a high-definition video for mosaic creation and a still camera for enhanced benthic resolution. A new suite of cameras that have become available since the development of the second-generation system were tested to determine 1) if a single, still camera could be used for mosaic creation, 2) which cameras performed optimally during mosaic surveys, and 3) if mosaics could be adapted for rapid, small-area, reef surveys. In the field, still cameras with rates of image capture of one frame per second or faster provided high enough image overlap for mosaic creation. Digital SLR (DSLR) cameras provided the highest resolution and best focus; however, some low-cost (under $400 USD) still cameras produced mosaics nearly as good as the DSLR results. A new survey pattern was developed to acquire data for small-area mosaics up to 44 m^2 in less than two minutes of acquisition time. As a result of these tests, we define third-generation mosaics as those using still-camera imagery for mosaic creation. Third-generation mosaic images have up to 3x greater benthic spatial resolution than second-generation mosaics without resorting to supplemental images. In addition, the malleable survey design of third-generation mosaics creates the opportunity to combine the practicality of large-scale, rapid-reef survey needs with the high power to detect benthic change provided by permanent site monitoring.

Key words: mosaic, coral monitoring, mapping, survey design, GoPro™

Introduction

Underwater landscape mosaics are created by acquiring downward-looking images over an area of interest, aligning them through sequential and global feature matching algorithms, then blending component images into a single spatially-explicit composite (Lirman et al. 2007). Landscape mosaics utilize off-the-shelf underwater video or still camera systems to create large (from 100s to 1000s m^2) composites with the spatial resolution of individual images taken close to the seabed. Mosaics can be easily georeferenced either to absolute geographic coordinates or relative to one another to enable reef mapping and monitoring changes over time (e.g. Lirman et al. 2007; Gleason et al. 2007; Gintert et al. 2009; Lirman et al. 2010; Gleason et al. 2011). Mosaic processing is available through the University of Miami's Reef Imaging Lab or alternatively, by implementation of the published mosaic algorithms (Gracias and Santos-Victor 2000, 2001; Lirman et al. 2007; Gintert et al. 2009 and references therein).

First-generation mosaics had spatial resolution on the order of 3-5 mm / pixel, which was sufficient to discern broad benthic taxonomic categories such as stony corals, octocorals, algae, sponges, and sand (Lirman et al. 2007). Ecologists' desire to use mosaics for mapping finer taxonomic distinctions prompted development of second-generation mosaics, which employed two cameras to generate multi-layer datasets (Gintert et al. 2009). The second-generation system used high-definition video for mosaic creation and then coregistered 10 megapixel still images to the video mosaic to provide increased resolution. The second-generation video mosaics had spatial resolution on the order of 2 mm / pixel and the coregistered still images had spatial resolution of about 0.5 mm / pixel, which greatly increased capability for taxonomic identification and coral health assessments (Gintert et al. 2009).

Since the documentation of the second-generation mosaics, camera technology has continued to evolve, and new uses for the mosaics have been explored. Here we present a series of tests that evaluate 1) whether still cameras can acquire data rapidly enough to produce landscape mosaics, 2) which readily available camera systems are optimal for mosaic acquisition, and 3) if mosaic surveys can be modified for use in rapid-reef surveys.

The first test concerns simplification of the second-generation system. If modern still cameras have sustained frame rates sufficiently high to create mosaics directly from still imagery, then a two-camera solution may not be necessary except when the highest possible spatial resolution is required. A high-frame rate is critical to our approach for making mosaics because large overlap, typically 75% or more, is necessary to find enough matches between images to generate a mosaic (Gracias and Santos-Victor 2000, 2001). Video, at 24 or 30 frames per second (fps), has nearly 100% overlap on sequential frames, therefore many can be discarded while still retaining high overlap. Although many still cameras can acquire several images per second when set to “burst mode,” these rates are only sustainable for a few seconds. The maximum sustained frame rates for still cameras, on the other hand, are currently about 1 to 2 fps. The primary question for employing still cameras in mosaic creation is whether a 1 fps acquisition rate produces sufficient overlap for previously described mosaic algorithms (see Lirman et al. 2007).

The second test concerns cost reduction of the second-generation system. High-definition video can now be acquired on pocket “point and shoot” still cameras and even smaller sport-oriented devices such as those marketed under the GoPro™ brand. These devices are typically both smaller and an order of magnitude less expensive than the hand-held camcorders used in the second-generation system and would therefore be appealing replacements if image quality is sufficient.

The third test concerns survey design. Images for the first and second-generation mosaics were acquired using a “double lawnmower” survey pattern; namely, a set of parallel transects followed by a second set of parallel transects oriented orthogonally to the first (Lirman et al. 2007). Areas of about 225 m^2 require approximately 60 min of dive time to map using this method. Users who need to visit many sites, for example to ground-truth satellite imagery or as part of a rapid reef survey, may find traditional mosaic surveys too time consuming in the field. Therefore, a rapidly deployed mosaic survey design was tested.

Material and Methods

Test 1: Still Image Mosaicing

A 10 megapixel (MP) Nikon D200 still camera with 24 mm lens and a high-definition Cannon HF S20 video camera were used to acquire images simultaneously over a test reef using standard acquisition protocols (Lirman et al. 2007). The still camera acquired images at 1 fps while the video recorded at 24 fps.

Field tests were deemed successful if a full-site still image mosaic without holes was effectively rendered using existing algorithms (Lirman et al. 2007; Gintert et al. 2009). For processing, the still image sizes were reduced by 1/2 in each direction to allow faster processing times and to remain within the memory limitations of the current version of the processing software.

Test 2: Camera comparison

Four still and six video cameras ranging in price from $299 to $5,000 (Table 1) were deployed on the same day, at the same site to assess their relative performance under realistic field conditions. Divers swam each camera in a typical “double lawnmower” pattern over a 2 m x 3 m plot approximately 1.5 m above the area of interest. Viewing angles were set to the widest setting for all video cameras. Those still cameras with adjustable lenses were set to 24 mm. Mosaics were processed using existing algorithms (Lirman et al. 2007; Gintert et al. 2009).

Benthic spatial resolution was determined for each camera by extracting the frame in which a tagged 3 cm x 3 cm coral was closest to the center of the frame.

Test	Camera	Benthic Resolution (pixels/cm)	Image Size	Estimated Cost (w/ housings)
A	Canon Power Shot D10 Video	14.0	(640 x 480) ~0.3 MP	$299
B	Sony HDV	14.9	(1440x740i) ~1.6 MP	$4,276
C	GoPro Hero2 HDV	15.5	(1920x1080p) ~2.1 MP	$378
D	GoPro Hero1 HDV	18.9	(1920x1080p) ~2.1 MP	$378
E	GoPro Hero1 Still	21.6	5 MP	$378
F	Nikon D7000 HDV	21.9	~2.1 MP	$3,417
G	Canon S20 HDV	27.6	(3264x1840p)~6.MP	$2,200
H	GoPro Hero2 Still	33.5	11 MP	$378
I	Nikon D200 Still	44.9	10.2 MP	$5,000
J	Nikon D7000 Still	56.1	16.2 MP	$3,417

Table 1: Camera information, benthic resolution, image size, and approximate cost of each camera tested. All prices are in US dollars and include the price of applicable underwater housings. All quoted prices were taken from www.bhphotovideo.com. MP= megapixel. HDV = high-definition video.

Test 3: Rapid-Reef Mosaic Surveys

A fast field methodology, hereafter referred to as a “minute mosaic,” was developed and field-tested for the rapid deployment of numerous small-area mosaics at randomly selected sites. As a test, minute mosaics were acquired at 20 randomly selected sites. At each site, a rebar marker was hammered into the substrate to create a permanent reference for future monitoring of the station. Snorkelers collected a surface GPS point of the rebar pin for future re-location. Divers placed a scale and calibration grid near the permanent site marker and using a single Nikon D7000, began to

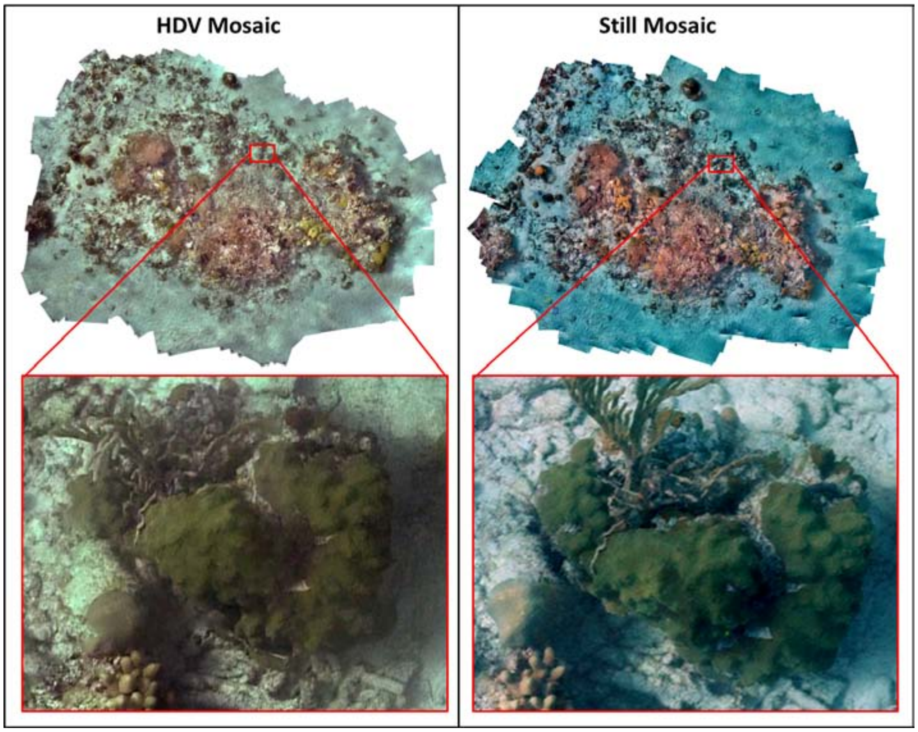

Figure 1: Comparison of a mosaic created from high-definition video frames (Left) with one created from still images (Right). The still images were processed at 1/2 resolution but still resulted in a mosaic with higher spatial resolution (15 pixels / cm) than the video mosaic (11 pixels / cm).

swim a slow and expanding circular pattern with overlapping circles around the permanent marker. After 3 revolutions around the pin, image acquisition was halted and divers swam to the next randomly selected location to repeat the survey. Image acquisition at each of the 20 test sites never took longer than 2 minutes. Each of the 20 image datasets was processed into a mosaic, analyzed for total area covered and the number of coral colonies documented within the mosaic.

Results

Test 1: Still Image Mosaicing

All acquired still frames were used in the creation of the still image mosaic whereas the high-definition video was re-sampled from 24 fps down to 1 fps for mosaic processing. A total of 1,762 high-definition video frames and 1,793 still frames were used to create the corresponding, complete mosaics (Fig. 1). Each mosaic covers an area of ~260 m^2. The spatial resolution of the test mosaics were 11 pixels/cm for the HDV mosaic and 15 pixels/cm for the still image mosaic; recall that the still images were processed at 1/2 resolution for testing purposes.

Test 2: Camera comparison

All cameras used in the test had the capability of capturing images at regular intervals of 1 fps or higher. Of the cameras tested, benthic spatial resolution ranged from 14 pixels / cm for the video function on the Cannon Powershot D10 to 56.1 pixels / cm for the Nikon D7000 digital SLR (Fig 2; Table 1).

Test 3: Rapid-Reef Mosaic Surveys

All 20 of the minute mosaics were processed successfully (Fig 3 presents an example). The area covered per mosaic ranged from 19 to 44 m^2 with a mean value of 33 m^2. The number of coral colonies imaged in each minute mosaic ranged from 10 to 98 with a mean value of 55 colonies.

Discussion

First and second-generation mosaics provided a method to create large images of the reef benthos for use in various coral reef monitoring and mapping applications. The benthic spatial resolution of first and second-generation mosaics was tied to the resolution of video cameras, which at the time were the only consumer-grade equipment that could provide the ~75% overlap needed for previously developed mosaic processing algorithms (Lirman et al. 2007).

Recent improvements in still camera technology enable a third-generation of mosaicing in which still cameras with sustained image capture rates of 1 fps or faster can be used to create landscape mosaics (Fig. 1).

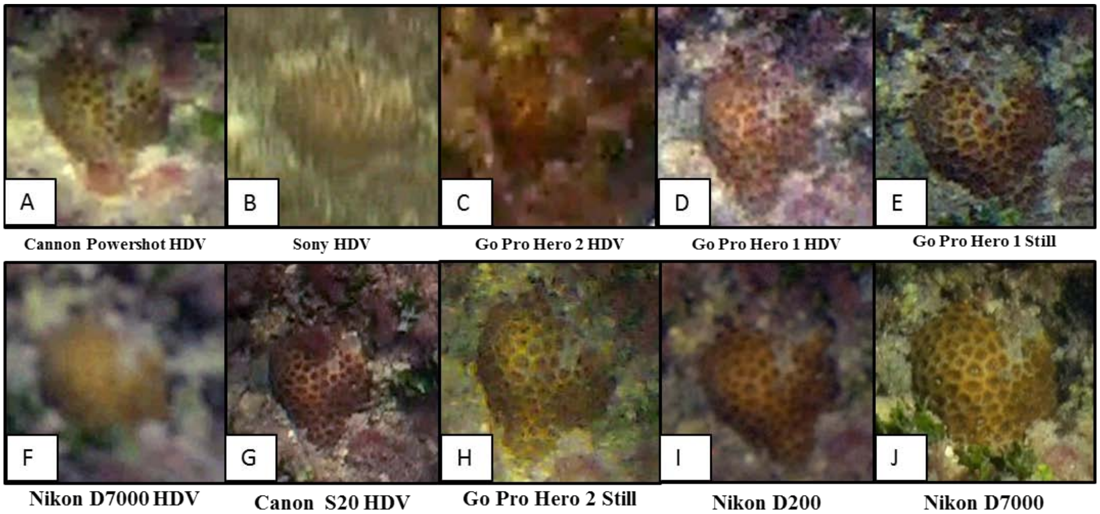

Figure 2: Visual results of the camera comparison test. The letter of an image corresponds with the camera information available in Table 1. Each image is a close-up of the same 3cm x 3cm *Siderastrea siderea* colony located in the center of the test plot. Images are placed in order of ascending benthic resolution with A being the lowest and J being the highest.

Third-generation mosaic images (Fig. 2J) have 3x better benthic resolution than second-generation images (Fig. 2B), and can therefore improve a user's ability to identify benthic organisms directly from mosaic images without the need, or additional cost, of obtaining supplemental images.

Even though test 1 revealed still cameras at 1 fps were capable of acquiring data sufficient for mosaicing, a two-camera solution would still be valuable for situations in which the highest spatial resolution is required. One camera (still or video) would be set at a wide angle, to capture data for the mosaic, and the second camera, a still, would use a higher zoom setting to increase spatial resolution.

All of the cameras used in the camera comparison test (Test 2) were theoretically serviceable for mosaic processing. This is a testament to the flexibility of the mosaicing algorithms and is a promising feature for monitoring programs that already own underwater camera equipment. However, only those still cameras that have a time lapse or interval timer setting of 1 fps or better are realistic options for diver-swum surveys of large areas.

The high-definition video features of the Nikon D7000 and Canon Powershot D10 still cameras (Figs. 2A, 2F) did not maintain focus well during moving surveys and are not recommended.

In contrast to the D7000 and D20, which are general-use still cameras that have video functions, the GoPro Hero versions 1 and 2.1 are cameras with both still and video options that are specifically designed for high-motion applications. The 11 MP still image function of the GoPro Hero 2.1 (Fig. 2H) had the third-highest benthic spatial resolution in our tests, but cost a tenth of the total price of the Nikon D7000, the best performing camera in this dataset ($378 vs. $3,417, Table 1).

The Nikon D7000 was the most expensive camera tested but when used in still-image mode, it had both the highest benthic spatial resolution (Table 1) and sharpest images (Fig. 2J). The D7000 also has a built-in interval timer mode and excellent battery life that make it ideal for capturing still images at the highest possible resolution for ecological assessment.

Malleable survey designs have increased the ecological relevance of underwater mosaic technology. Recently, surface-based ground control points were used to combine 19 traditional image mosaic surveys of 200-300 m^2 to create a single image map covering nearly 5,000 m^2 over a ship-grounding site in Puerto Rico (Gleason et al. 2011). On the opposite end of the spectrum, the minute-mosaic surveys presented in test 3 provide a solution that can be quickly deployed in surveys that aim to rapidly sample numerous sites.

Minute-mosaic surveys covered significant areas (up to 44 m^2) and captured photographic health information on as many as 98 corals / minute-mosaic. Unlike linear transects, circular mosaics are less prone to positional drift and thus, over time, are more likely to re-sample the same areas/colonies in repeat surveys. This capability of acquiring high-resolution photographic monitoring data on an average of 55 coral colonies per site in less than two minutes is a valuable new tool for monitoring applications.

As with landscape mosaics collected with other survey designs, minute-mosaics can be used to extract common indices of reef health such as coral colony size, condition, and percent cover (Lirman et al. 2007) while at the same time providing a permanent record

Figure 3: Left: A minute mosaic covering approximately 30 m^2. Right: A full-resolution zoom of a portion of the mosaic.

of the reef-state at the time of the survey. A permanent photographic record is useful because it can be re-analyzed to answer questions of demographic change and measure coral recovery. Minute-mosaics combine the practicality of quickly gathering benthic information at hundreds of reef sites and the high power to detect change of demographic surveys that follow coral communities through time.

Since the documentation of the second-generation mosaicing system (Gintert et al. 2009), improvements in computing power and consumer electronics have provided a means to increase benthic resolution of mosaics by incorporating still images into mosaic creation without supplemental cameras. The flexibility of mosaic processing algorithms increases the applicability of the mosaicing technique for coral reef monitoring programs with various underwater cameras and budgetary constraints. Cameras capable of taking high quality images at regular intervals are readily available and can cost less than $400 USD.

Finally, the adaptability of mosaic surveys has increased the scientific potential of reef mosaic technology by delivering a novel survey design that combines the practicality and large-scale needs of rapid-reef surveys with the high power to assess change of permanent monitoring sites. Thus, third-generation mosaicing technology provides improved benthic resolution and greater hardware and survey flexibility than both first and second-generation systems.

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