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Ground-level spectroscopy analyses and classification of coral reefs using a hyperspectral camera

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Abstract. With the general aim of classification and mapping, remote sensing of coral reefs has traditionally been more difficult to implement in comparison to terrestrial equivalents. Images used for the marine environment suffer from environmental limitation (water absorption, scattering and glint); sensor related limitations (spectral and spatial resolution); and habitat limitation (substrate spectral similarity). Presented here is a novel approach for ground level surveying of a coral reef using a hyperspectral camera (400-1200 nm) that is able to address all of these limitations. Used from the surface, the image includes a white reference plate that offers a way for correcting the water column effect. The imaging system offers millimeter size pixels and 80 relevant bands, thus empirically bridging the gap between a spectroradiometer, hyperspectral remote sensing, and digital photography. Finally, the availability of pure pixel imagery improves significantly the potential for substrate recognition in comparison to traditionally used remote sensing mixed pixels. In this study, an image of a coral reef table in the gulf of Akaba, Red sea, is classified, demonstrating the benefits of this technology for the first time. Trained classification was done using Support Vector Machine that was manually trained and tested against a digital image that provided empirical verification. For the classification of 5 core classes the best results were achieved using a combination of 450-660nm spectral range, 5nm wide bands and employing red band normalization. Overall classification accuracy was improved from 86% for the original image to 99% for normalized image. Imagery of this type can be successfully used for reef survey and monitoring using automatic classification procedures, making them an ideal tool for large scale survey.

Keywords. coral reef, spectroscopy, classification, remote sensing, hyperspectral, glint, monitoring, survey

1. Introduction

Remotely sensed spectral data analysis has the potential to become a cost-effective practice for large scale reef investigation, assessment and monitoring [1-3]. However, the integrity of remotely sensed results is often questionable as three main sources for errors contribute to the image analysis: (1) Analysis of marine habitats is confounded by the optical effect of the water and air columns above the substrate of interest [4, 5]; (2) Spatial, spectral, and noise limitations are imposed by the sensor itself; and (3) similarities between the reflectance of the desired substrate may cause errors in their identification [6, 7]. Alternatively, in situ digital photography, underwater or above, may solve the spatial resolution limitation but lacks the spectral resolution required for classification [8]. As a result, it requires lengthy manual post-processing for identifying the different substrates and is manpower intensive for large scale coral reef monitoring.

Recent developments in sensor production provide innovative remote-sensing solutions tested in this study for the first time. The use of a hyperspectral camera offers very fine resolution, providing an opportunity to deliver a potential solution for three sources of error typical for remote sensing of the marine environment: (1) water correction can be addressed by placing white reference targets within the image (atmospheric correction is unnecessary) [9]; (2) The available spectral resolution using this camera is better than most aerial or spaceborne instruments, providing up to 80 bands within the relevant range. This spectral resolution far exceeds the resolution recommended for coral reef determination [e.g.,10, 11, 12]. Spatial resolution (pixel size) is expected to be finer than that of the target substrate units (e.g., coral colony), thus delivering a pure substrate spectrum in each pixel (much like a digital image); and (3) The combination of high spectral and high spatial (pure pixels) resolution would allow superior recognition of underwater substrates, leading to accurate quantitative estimates of cover within the sampled area (the image). To date, hyperspectral imaging data of this type have never been used in the shallow marine environment. Therefore it can only be resembled to a combination of a field point spectrometer that provides hyperspectral resolution and a digital camera the produces high spatial resolution. Using the proposed technology may lead to the development of an image acquisition and processing system that enables the analysis of the reef features in a fast, accurate, and efficient way. An advanced and improved design will support a semi-automatically run system with minimal operator input over larger areas. All these reasons together formed a strong rational for testing the capabilities of the proposed technology.

The aim of this study was to give a first glance at the assessment prospects of ground-level, above-water, remote sensing of a coral reef. The objectives include acquiring a hyperspectral image, correction of environmental distortions, and classification of the underwater substrates. In line with the aim, the key objective is achieving the best (most accurate) classification for the given image, using only basic processing steps. Given the pioneering level of processing protocol, objectives included testing a variety of variables relevant to image preprocessing, including spectral resolution and spectral ranges.

2. Methods

The Coral Reef Marine Park (CRMP, 29°33′N 34°57′E) is located 8 km south of the city of Eilat. The hyperspectral image was obtained from the jetty (bridge) over the reef. Timed to provide the best results, the image was acquired during the late morning -- when the sun was at an angle that avoided glint effect. Other conditions included low wind (approximately 5 knots), and the water was close to low tide so the average depth was 30 cm (ranging from 20 to 50 cm). The camera/instrument used was a pushbroom line scanner Spectral Camera HS by Specim Systems. It was fixed on a boom, overhanging the reef as close as possible to the nadir position. The camera’s 28° lens, opening at 2.5 m above target, captured approximately 2X3 m of the reef table, and the acquisition time was near 32 seconds. The camera provides 1600 x 1400 pixels; therefore, divided by 2 m of image width, it gives, on average, 1.25 mm of reef substrate area per pixel. Spectrally, 849 bands are captured in the spectral range of 400-1000 nm with a 0.67-0.74 nm band width. For demonstrating the technique, a subset of 500X500 pixels was selected from the entire image in order to minimize pixel stretching due to camera angle. The image included a plastic quadrate frame and two white reference plates -- one at the reef table depth and another at the water surface (not shown).

The first step of image preparation included removing saturated pixels and dark object subtraction (the camera’s dedicated noise reduction algorithm by Specim Systems). Following this, the image was converted from the original DN to reflectance using the white reference plate. This step also accounted for the water scattering and absorption. Next, the image treatment included spectral resampling to 5 nm bands, reducing the original number of bands between 400-800 nm to 80.

The final step of the pre-processing focused on addressing the severe variability in spectral albedo, including the glinting effects caused by surface ripples. Those glinted pixels were different from their surrounding pixels, both by their reflectance magnitude and their spectral features in the NIR spectral range. Instead of filtering out high albedo pixels and imposing a uniform correction approach on the darker pixels as well as the light ones, a normalization procedure was employed. This processing adopted the deglinting method described by Hochberg [13] and Hedley et al. [14]. This correction is based on using the water opacity in the NIR wavelengths (thus reflectance values are independent of water absorption) as a baseline for normalization. In this respect, it is similar to more familiar normalization techniques based on the mean or mode of all bands. For this study four bands were used for normalizations – two in the NIR spectral range (765 nm and 775 nm) and two in the red spectral range (665 nm and 675 nm).

In order to find the best image specification for classification, 24 variations were made from the original image. These included two spectral ranges (450-700 nm and 450-650 nm), three spectral resolutions (5 nm bands, 10 nm bands and 20 nm bands) and four normalization techniques (red-band and NIR-band). Image classification was applied using Support Vector Machine (SVM), a standard supervised classification procedure in ENVI software. SVM is based on modeling the training classes in hyperspace and minimizing each pixel's distance to its most similar target. The SVM enables one to seek those distances in a non-linear way (Cortes and Vapnik 1995) and is particularly effective with spectral data. Image classification focused on five classes: massive hard coral, branching hard coral, deeper turf rock, shallow turf rock, and shade. For every identified class, 10 adjacent pairs of areas of interest (AOIs) were selected; each AOI contained in excess of 250 pixels (therefore, each class average was based on more than 2000 pixels). Adjacent AOIs were expected to contain pixels of the same class, so one of every pair was allocated for classification training while the second AOI was later used for verification. Two measurements for accuracy were calculated – total accuracy, representing the number of correct classifications as a fraction of the total, and the Kappa Coefficient, representing accuracy that takes into account classification occurring by chance.

3. Results and discussion

Overall, the most accurate classification was achieved using the combination of 5 nm bands, a 450-660 nm range and red-band normalization (total accuracy was 0.99 and Kappa coefficient was 0.99). Throughout, despite the normalization, severely glinted spectra and very dark spectra were more likely to be misclassified or unclassified. Normalization improved the micro-scale – within colony – classification for both high albedo (glint) and low albedo (shade) pixels (fig 1). In all cases, class perimeter is better defined after normalization that improves the identification of turf areas significantly.

Hyperspectral imagery is probably the only means for addressing features separation necessary for positive identification of different substrates. The spectral resolution of the camera used for this study provides adequate spectral resolution to successfully separate common substrates within the study site. Furthermore, sub-classification to branching hard coral (Acropora spp.) and massive hard coral (Platygyra spp.) was also possible, a novel applicability not possible until now. The combination of pure pixels and spectral resolution gives an exciting chance to investigate and address within-class variability like shading and 3D complexity. For monitoring and conservation, the potential applications include automated quantitative image analysis and accurate substrate identification. In turn, this facilitates larger scale campaigns with much less manpower investments compared to knowledge based digital photography analysis.

The potentiality of reducing spatial and spectral resolution is currently being tested. Up-scaling experiments may provide resolution limits for this type of remote sensing analysis of coral reefs. Further work planned for this source of imagery focuses on these key options including classification automation and more complex classification techniques such as decision tree and object recognition. Additional avenues for exploration include micro-scale (single colony) spectral variation and spatial upscaling of similar images.

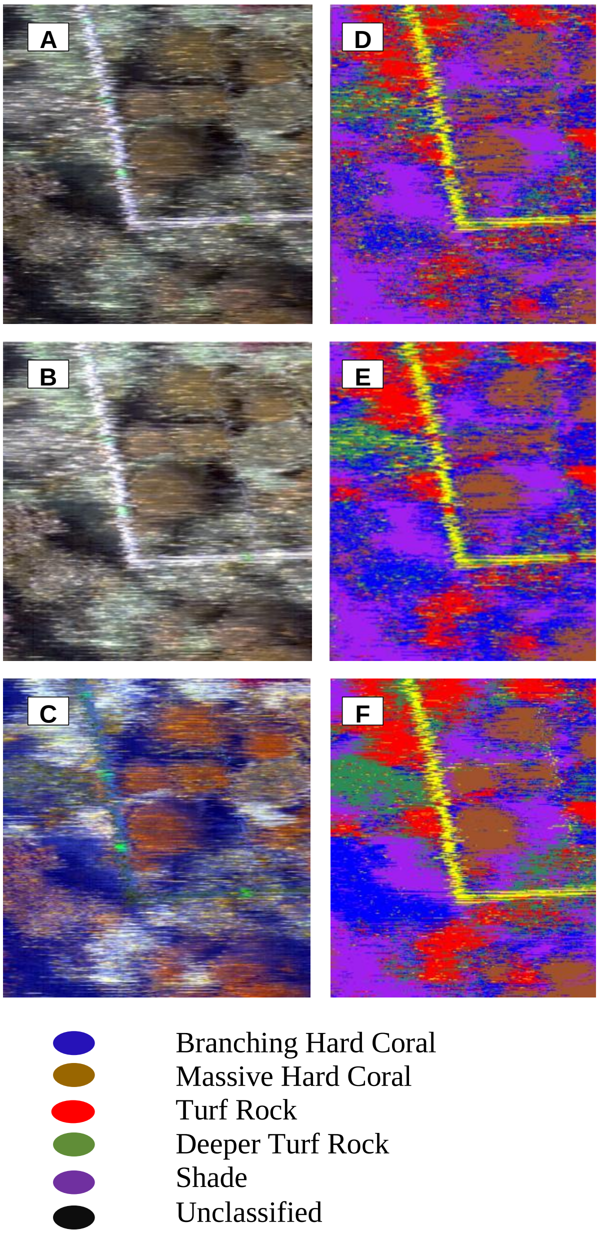

Figure 1. Deglinting and classification results. (A), (B), and (C) are the images before normalization, after NIR-band normalization, and after red-band normalization, respectively. The marked areas of interest (AOI) in the image represent the training and verification AOIs used for the classification process. Color legend follows previous colors (Fig. 3). (C), (D), and (E) are the classified images. (C) is the non deglinted image; (D) is the classified deglinted image; and (E) is the normalized. Accuracy in classification is visually noticed.

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