Geographical Mosaicking of Seafloor Images Acquired by an AUV

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***Abstract*– While seafloor image mosaics are typically produced using graphical methods, this technique uses AUV navigation logs to geographically place the individual images. The resulting mosaic is free from the spatial distortion that can occur from graphical methods under the unfavorable conditions of near-seafloor survey. Large mosaics can be produced without requiring image overlap. The photomosaics discussed in this study cover 60 meter square regions with a pixel resolution of approximately 1.5 millimeters, and they are generated from over 3000 images each.**

***Keywords*—mosaicking; seafloor survey**

I. Mosaicking Methods

Seafloor image mosaics are typically generated by graphical means. Algorithms place and distort images to match control points shared by neighboring images. Oblique views of control points in addition to angular and vertical movement of the imaging platform can cause significant spatial distortion. Areas of homogeneous terrain can also lead to a loss of spatial information due to lack of control points. Consider coral communities separated by expanses of sand. When using a purely graphical mosaicking technique, relative positioning of the communities would be lost if control points could not be assigned in the homogeneous sandy images. Still, graphical techniques can produce exceptional seafloor mosaics, especially in smaller regions with sufficient image overlap and many control points.

The mosaicking technique presented in this paper emphasizes positional accuracy of each image in the mosaic at the expense of graphical artifacts caused by navigational error and oblique views of targets. This is in contrast to graphical mosaicking which resolves the artifacts at the expense of spatial consistency. Since the geographical procedure relies on navigation logs for image placement, the initial mosaic is limited to the accuracy and the precision of the vehicle's navigation. Tuning of the image placement is possible by utilizing other survey payloads (multibeam sonar, specifically) and external navigation aiding to correct positional errors, but these systems have not been used in this study. Since image pixels can represent several square millimeters, small amounts of navigational drift and jitter can have dramatic effects on the mosaic.

The intention of the method is to produce an accurate overview map of a surveyed area. The technique assumes that images are nadir or nearly so, within the limitations of the imaging platform. Over interesting subsections of the survey, a reasonable procedure would be to create graphical mosaics and georectify them onto the geographical mosaic base map.

So far, several 60 meter square surveys of over 3000 images each have been mosaicked. The earlier surveys did not use as wide a lens as the latest survey, so they lack across-track overlap between adjacent lines of the survey. During these surveys, occasional dropped images lead to gaps in the along-track direction as well. The resulting sparse surveys could not have been mosaicked using a purely graphical technique.

II. Seafloor Image Acquisition

The images used to test this technique were acquired by the AUV Mola Mola, operated by the National Institute for Undersea Science and Technology (NIUST). This vehicle is a SeaBED class AUV originating from Woods Hole Oceanographic Institution (WHOI) that is rated to a depth of 2000 meters. It operates 3 meters above the seafloor at a speed of 0.2 m/s capturing an image every 3 seconds. Images are illuminated by Deep Sea Power and Light LED arrays fore

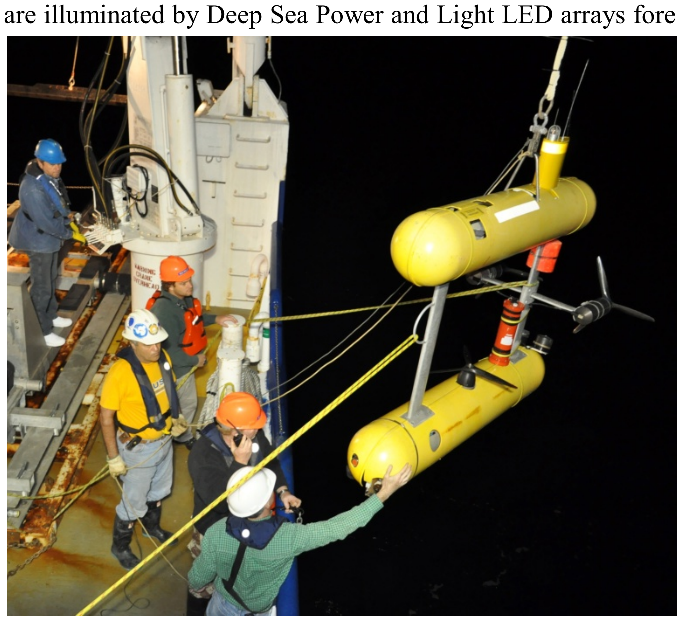

Figure 1. Mola Mola AUV during deployment operations

and aft, and the camera is centered between them within a flat-port housing from the same company.

The camera itself is an AVT GC 1380C using first a Fujinon 9mm and later a Schneider Optics 8mm lens. Each image is 1360 by 1024 pixels. Using the 8mm lens, each image represents 2.26 by 1.70 meters at the nominal survey altitude of 3 meters. Although the vehicle tries to maintain a constant altitude, local variations in bathymetry cause the image scale to vary throughout the survey. The surveys conducted by Mola Mola have used a line spacing of 2 meters, ideally producing an overlap of 13%. This value is not uniform since the camera itself is slightly starboard of the vehicle centerline. If needed, wider line spacing can be used to sparsely cover a greater survey region.

In the along-track direction, the nominal survey speed and the image capture rate produces 65% overlap. If a single frame is dropped, this overlap drops to 29%, and if two frames are dropped, a 10 cm gap is present between adjacent images. In order to better maintain altitude, the survey speed is reduced according to the altitude error [1], resulting in additional overlap. Previously, the imaging rate was set at 4 seconds to allow recharge of the camera flash. With the conversion to LED arrays [2], this concern is no longer present, although the network infrastructure shared between navigation sensors and scientific payloads presents the current image rate bottleneck.

The vehicle is designed with a positively buoyant upper hull and a negatively buoyant lower hull to passively provide stability in terms of pitch and roll. Although the vehicle itself maintains a fairly consistent orientation, the resulting images still suffer from perspective effects that hinder mosaic generation. Most of these effects arise from the vehicle's close proximity to the bottom. Even at the altitude of 3 meters, spectral balance is affected significantly. For much higher altitudes, only grayscale imagery could be acquired efficiently. For the best case of flat bathymetry, the outer edges of the image are already angled at 21 degrees from nadir. Viewing vertical targets such as coral and geologic structures from different directions can result in drastically different appearances. This anisotropy causes control points to not correlate properly in graphical methods.

Mola Mola uses an inertial navigation system (Ixsea Phins) to derive its position and measure attitude [2]. At the surface, this system is aided by GPS, and at survey altitude the system is constrained by a downward-looking acoustic system, doppler velocity log (DVL), that measures speed in all directions relative to the seafloor. During descent through the water column, the Phins can accumulate significant error. External acoustic systems are used to correct this error [1], but application of these corrections causes a shift in position that would be detrimental during a survey. To avoid jumps in the navigation track, typically several meters, acoustic aiding is not used during a survey. The survey begins with a static offset, but one that has hopefully been minimized within the accuracy of the particular acoustic system used for the correction. The vehicle position is internally converted to a local meter-based projection used by its control system.

The Phins aided by a DVL has a manufacturer specified position accuracy of 0.1% of the distance traveled with a 50% circular error probability. That is, with reference to its survey start point, the computed position throughout the survey will drift proportionally to the distance traveled. This is a smoothly varying error that contributes to positional inconsistency between adjacent survey lines and crosslines. Additional error comes from the resolution of the vehicle navigation, currently 0.17 meters. The vehicle control software is currently being examined for ways to increase this resolution, which causes small errors between neighboring images.

III. Image Processing

All camera settings are held constant throughout the dive. The camera gain value and the exposure time are set in a mission configuration file. These settings are maintained to ensure consistency, which is intended to aid in post processing. Following the survey, the images must be processed individually and then combined to form a mosaic.

A. Image Preparation

Upon copying the images and logs from the vehicle, the images themselves are converted to color JPEG files for further processing. The images are obtained as graymaps representing the intensities observed across the imaging sensor, where each pixel represents either a red, green, or blue intensity. From this structure, color images are derived through an interpolation process called debayering. After each image is debayered, it can be color corrected. Since the spectral balance is disturbed by water column attenuation, different gains are applied to the red, green, and blue channels. Both of these steps are performed by a command line utility developed at WHOI and provided with the vehicle.

Initially, the color correction utility applied an auto-correction to each image independently. This individual treatment, however, is made at the expense of uniformity. The program was recently modified to bypass the automatic correction and instead apply constant multipliers to the red, green, and blue throughout a whole survey. Ideally, this correction would vary based on altitude and calculated attenuations. For this work, the correction was assumed to be uniform, and the values were adjusted manually in an iterative manner over a set of selected images.

As Mola Mola surveys, it logs navigational information at 10Hz and collects a raw image every three seconds. A Matlab program was written to read the image timestamps and navigation logs and then extract values for each image. These values: coordinates, altitude, attitude, and depth; are used to calculate the coefficients used in placing each image using an affine transform. Parameters of the transform are exported as a "world file" for each image.

A world file is a list of parameters that allow the transformation from image space to world space – from image pixels to geographic coordinates in meters or degrees [3]. Accounting for the vehicle heading requires a rotation operation. The vehicle's altitude above the seafloor affects the scale of the image. The image is positioned within the mosaic by a translation, which shifts the image based on the geographic position represented by its top left pixel (the image origin). The affine transform performs these operations.

Although an image scale correction based on vehicle altitude was derived, this factor produced unfavorable results. The problem is that the altitude logged by the vehicle is not the nadir altitude of the image. Instead it is an average of altitudes measured by the DVL, which looks 30 degrees off nadir in four directions around the vehicle. Additionally, this sensor is located 0.62 meters behind the camera. Modifications of the vehicle may be necessary before an altitude value can be used for scale correction.

If errors are attributed to pitch or roll of the AUV, a trapezoidal correction is proposed. So far, this additional step has not yet been required. A correction that may prove to be beneficial would be a geometric correction for optical distortion.

B. Mosaic Generation

The image files themselves contain no geographical metadata, but the world file associated with each image file lists all the information needed for a GIS package to import and transform each image. In this particular study, a directory of survey images with associated world files is loaded into a mosaic dataset in ArcGIS 10.1. This creates individual footprints to get an overall view of the geographic location of the images and their corresponding overlap. Building pyramids and statistics provides the basis for optimizing the display of the rasters, applying the mosaic method, and performing further color correction [4].

In this particular study, the mosaic method north-west was applied to the overlapped areas to determine the layering order of the images. This was chosen based on the quality of the resulting mosaicked image, as was the same with selecting the mosaic operation, maximum. The maximum operator uses the maximum pixel values in overlap areas to reconcile the images together for the resulting mosaic. This operator did not produce as many image boundary artifacts as others that were tested. Additional color correction was not applied at this time.

This method of producing a first pass georeferenced overview map is useful to quickly determine if changes should be made to the AUV mission layout and locate areas of interest that may need more investigation. Fine tuning of the transform parameters, the addition of further color correction, and continued improvement of AUV navigation (both real time and post processing) should produce a more seamless survey mosaic. Further experimentation with the mosaicking process itself may lead to a more evenly blended structure despite errors in the positioning and oblique angles in adjacent images.

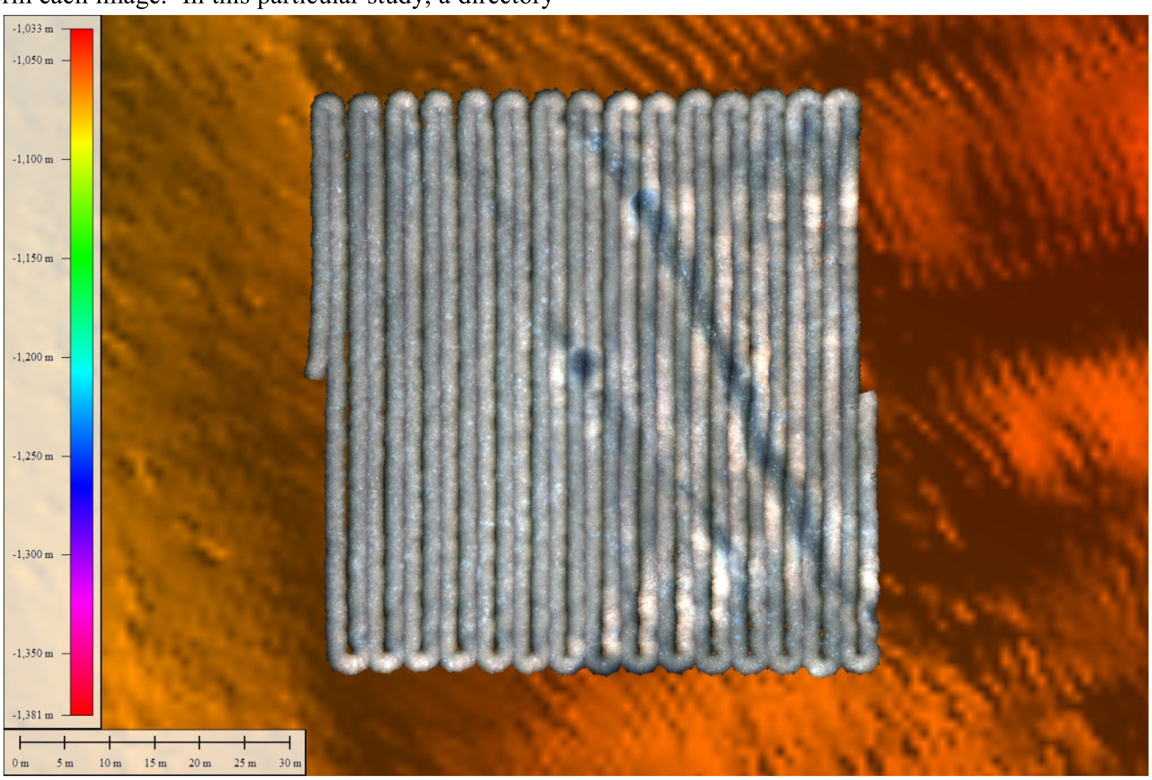

Figure 2. Mosaic at AT357 over AUV-derived bathymetry (GoMRI data identifier for bathymetric base map: R1.x132.137:0029).

IV. Mosaicking of Field Data

The Mola Mola AUV was acquired by NIUST in 2009, but it was heavily modified to prepare it for photographic seafloor mapping missions [2]. Its first successful complete surveys were completed in October of 2012 during a cruise supported by the ECOGIG program and by NIUST's NOAA funding. ECOGIG is a Gulf of Mexico Research Initiative (GoMRI) funded project studying the environmental effects of oil and gas inputs to sites in the Gulf of Mexico. A further ECOGIG survey was conducted in June of 2013. Results of one particular survey (GoMRI data identifier R1.x132.137:0032) are shown in this paper to outline technical aspects of the mosaicking methods, while a related paper discusses scientific implications of the data set [5].

A survey was conducted within Atwater Valley block 357 (AT357) in the northern Gulf of Mexico. This survey represents a 60 meter square area around 1100 meters depth. The original mosaic represented by the following sample graphics is composed of 2.65 billion pixels and occupies 7.41 gigabytes. Each pixel of the full mosaic represents 1.3 millimeters, which is roughly equivalent to the resolution of the individual images. It is stored in TIFF format with 24 bit color depth. Fig. 2 shows the resulting photomosaic overlaying 1 meter resolution bathymetry gathered by the NIUST Eagle Ray AUV.

Georeferencing at the current stage has involved using the vehicle's local coordinate system during the time of survey and converting it to a real-world geographic location after the mosaic has been created. By using the local coordinate system, the images are plotted using their relative locations to one another. An origin latitude and longitude stored in the vehicles configuration file serves as the basis for the local coordinate system. The mosaic was shifted to its proper location in UTM coordinates by using the origin coordinate as an offset value. In future processing, this additional step could be integrated into a previous task to streamline the mosaic generation process. Either UTM coordinates can be logged by the vehicle software and integrated directly into the world files, or the world files can be transformed from the local coordinates in meters to the already available latitude and longitude.

In Fig. 3, a subset of the AT357 mosaic is shown. At the scale of this subset, the mosaic provides information about the seafloor structure, bottom type, and biological diversity. At further zoom levels, multiple appearances of targets caused by navigation jitter becomes obvious, visible on the left side of Fig. 4. If the effect of navigation jitter is not acceptable in an enlarged image, a graphical technique may be required.

In order to compare the georeferenced mosaic to a graphically produced mosaic, the Hugin open source software was explored. Hugin is used to stitch together individual images for producing a larger panoramic image. Ideally this involves having two or more overlapping images so that control points can be automatically selected. The images are then aligned by control points and stitched together. Hugin has the capability to stitch multiple rows of images together as long as enough control points can be defined. It also corrects exposure differences between images in a blending process to produce a more seamless looking image.

Figure 3. Subset (approximately 38 by 24 meters) of photomosaic at AT357.

When control points cannot be determined automatically, Hugin requires manual matching of points. When provided the images in the vicinity of a coral community, Hugin produced three unconnected strips, which correlated to the three adjacent survey lines. A second mosaicking step required manual control point selection because the survey lacked sufficient overlap between rows for the software to be able to select control points automatically. An additional issue affecting automated control point selection was that the color balance between survey lines was inconsistent. For some image pairs, expanses of featureless sediment did not provide clear control points.

Ultimately, creation of the mosaic in Hugin, shown at right in Fig. 4, was a time consuming and tedious effort due to the manual assignment of control points. Although the resulting mosaic is not constrained spatially, it appears to create a better representation of the coral community itself. In an additional procedure, this mosaic could potentially be georectified using the original mosaic as a reference. Thus patches of interesting bottom features could be mosaicked graphically and layered upon the geographical mosaic base map.

V. Summary

Both the techniques of graphical and geographical mosaicking have been shown to have numerous advantages and disadvantages with respect to each other. As indicated in the discussion, mosaicking operations may even benefit from combining the two techniques to some degree. Low-altitude AUV surveys pose significant challenges to mosaic generation including several types of navigation errors and oblique views of targets from different directions. The geographical mosaicking technique presented in this paper has been demonstrated to successfully handle these obstacles to produce a mosaic base map accurate to the resolution of the AUV navigation, which is constantly being improved.

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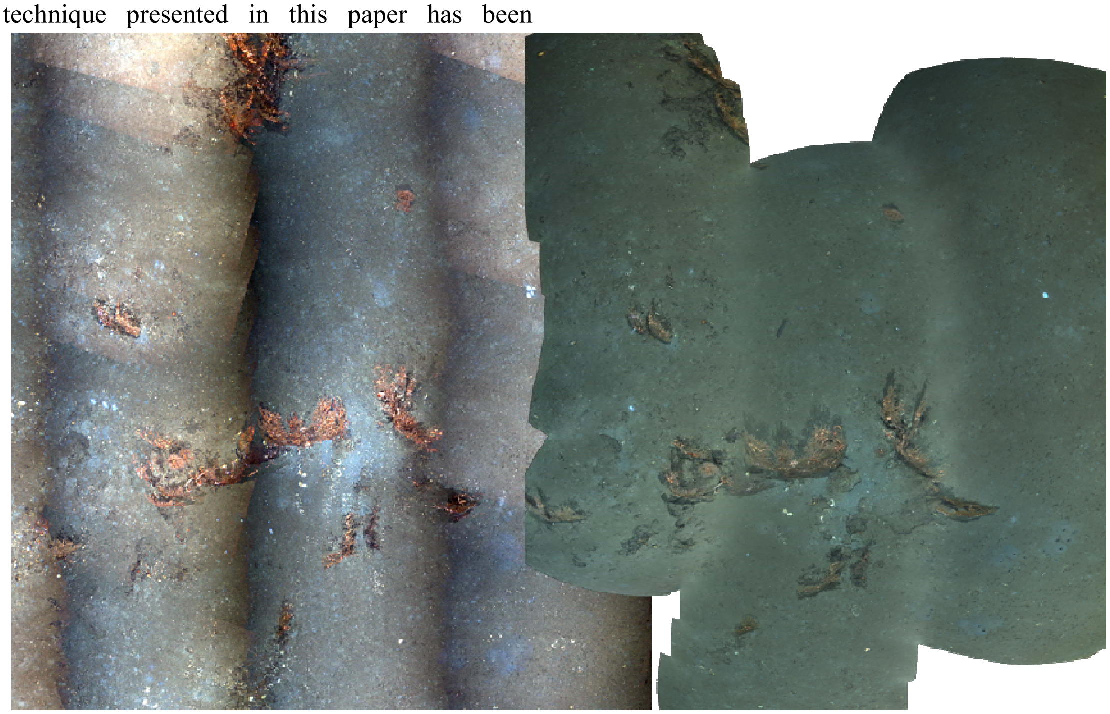

Figure 4. Graphical (right) and geographical (left) mosaic comparison.