

SURFZONE BATHYMETRY ESTIMATION USING WAVE CHARACTERISTICS OBSERVED BY UNMANNED AERIAL SYSTEMS

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ABSTRACT

Bathymetry, or the measurement of depth in any body of water, has been an area of research since man began to venture out onto the open waters. Historically, researching the near-shore surf zone has been a time consuming and expensive process. The tools and methods used to gather data points in the surf zone are either time inefficient, expensive, or both. This is an issue considering how dynamic the surf zone environment can be. It is possible that by the time the surf zone bathymetry measurements have been completed, they are already out of date. This project utilizes unmanned aerial systems (UAS) to gather high-quality video of the near-shore surf zone waves crest. This footage is then processed using particle image velocimetry (PIV), a method for determining the velocity of particles in sequential images. This velocity is then processed using linear-wave theory shallow water approximations for calculating wave celerity from depth, but ran in reverse, to obtain the bathymetry itself. Ground-truth field measurements are used to verify the resulting velocity and depth.

Index Terms— UAS, UAV, videography, Bathymetry, Particle Image Velocimetry, Waves, Surf Zone

1. INTRODUCTION AND BACKGROUND

Bathymetry has been an important area of research used to study water depths since ancient times. The earliest form of bathymetry was lowering a rope to the bottom of the sea floor and measuring how much of the rope returned wet. It was not until the 1930's that single-beam echo sounders equipped on ships were used to gather bathymetry measurements [1]. Using these more modern methods to gather bathymetry data on the open waters is still useful and cost effective to this day, but problems arise when getting into the near-shore surf zones. Some classic methods of capturing surf zone bathymetry data, such as using small craft that can drive through the surf equipped with sonar to collect the data [2], or traditional surveying methods involving wading out into the surf, are costly and time consuming. Additionally, the surf zone's bathymetry changes frequently making such measurements outdated in as little as two days [3].

The bathymetry in the surf zone is of utmost importance for the safety of beach goers as 80% of fatalities at the beach are caused by rip currents [4]. Rip currents form as a result of specific geometry in the surf zone bathymetry. Thus, any method of mapping the surf zone bathymetry in real time could save lives by providing better rip current prediction and forecasting. Additionally, many fields are interested in this bathymetry for purposes of tracking erosion of beaches and shorelines.

The recent explosion of recreational Unmanned Aircraft Systems (UAS), or drones, equipped with digital cameras has helped to dramatically decrease the cost of collecting aerial photography or videography of the surf zone. Using UASs to gather data noticeably increases efficiency by allowing rapid and repeatable geographic data acquisition at a much more affordable cost at local scales. UASs, in particular rotary craft, are able to offer some unique advantages while collecting aerial imaging data due to the fact they can fly lower, hover, and take higher resolution images of the ground than can traditional aerial methods. For photogrammetry, overlapping image sequences can be acquired and used with Structure From Motion (SFM) algorithms in order to reconstruct three-dimensional geometry from the two-dimensional image sequences [5],[6]. However, traditional SFM methods can break down when attempting to use images collected over water for mapping of bathymetry, especially in near-shore surf zones [7]. SFM relies on the object being mapped to have little to no movement, water in general, and the surf zone in specific is notable for its extreme movement. Most challenging is water turbidity, in the surf zone the water can be too turbid for imaging, even in shallow water. SFM for bathymetry only works in very narrow situations with visible bottom topography, and even then, may require specialized image processing or flight design considerations compared to traditional SFM applications [7],[8].

In order to combat these difficulties, researchers are exploring the use of Particle Image Velocimetry (PIV) techniques to estimate the bathymetry based on videography acquired from UAS. The major advantage here is that this method can be done over turbid water, requiring only wave action for dept inversion. In order to acquire the speed of the breaking wave (wave celerity), PIV methods can be used to

determine the speed of the white-water particles generated by the breaking wave captured by aerial videography [9],[10]. This information can then be applied to approximate the depth (bathymetry) based on a relationship between the speed of a breaking wave and water depth. In this work, the team explored and tested PIV for wave celerity estimation and bathymetry inversion in a dynamic surf zone using a small UAS. The effects of various video frame rates, and data collection altitudes on the results were investigated.

2. METHODOLOGY

2.1. Project Location

The UAS video data was collected at Bob Hall Pier located along the Gulf of Mexico on North Padre Island, TX, USA. This location was chosen for two specific characteristics. First, there is a dynamic surf zone that is easily accessible and second, there is a pier structure that extends from the beach allowing for ground targets to easily be placed perpendicular to the shore for optimal video reference points.

2.2. UAS Data Collection

All footage used in this study was collected with a DJI Phantom 4 Pro. The UAS hovers with a gimbal mounted camera facing straight down over the target surf zone. The camera uses a 20MP 1" CMOS sensor and can record at various resolutions and frame rates. Two different frame rates were used, 60 fps and 30 fps both at 4096 x 2160 resolution, from 2 different altitudes above the water surface, 50m and 75m, which impacts the spatial resolution of the imagery. For each frame rate and elevation a five minute video was captured. This time was determined by the estimated flight time of the UAS (30 minutes per battery) to allow all videos to be captured on a single battery.

2.3. Field Data Collection

Apart from the UAS, several ground-based reference objects were used for image stabilization and georeferencing; see Figure 1 for layout. Four ground control targets were placed in the frame. Two were placed on the beach, and two were placed roughly perpendicular to the first two along the pier. One target from each set was placed close to the corners of the frame to make diagonal within the frame. These targets were intended for image stabilization and calculating pixels per meter (PPM) for the resulting video footage. Since pixels are discrete in nature, the distance between the reference targets for calculating PPM should be maximized to minimize bias caused by this nature. In order to do so, the targets were moved between flights at different altitudes to stay in opposite corners of the frame.

In order to collect ground-truth measurements for depth, a series of 4 cm diameter pvc and aluminum pipes of various lengths are marked alternately black and white every

10 cm and then planted upright in the surf zone (marked S1, S2, L1, L2, and L3 in figure 1.) The bottom 40 cm of these markers were driven into the sand to anchor them. A wide angle 1080p 60fps camera was mounted on a tripod on the pier to monitor these to use as depth gauges. The resulting footage was used for manually collecting ground truth data on the wave height. A distinct signal visible to both the ground camera and overhead drone was used to synchronize the time codes of both. This method gives depth measurements accurate to within 10 cm.

Each ground control target and depth gauge were surveyed in using an Altus APS-3 RTK GNSS receiver applying broadcast corrections from the Texas Department of Transportation virtual reference station service providing cm-level positional accuracies.

Additional ground truth data was collected by manually timing the waves in the video file after collection, using the pier itself for measurements. For this process the team collected detailed measurements of Bob Hall Pier including the distance between the supporting columns and the block widths. This data was used as reference data for acquiring the manual speed of the waves.



Figure 1: 50 meter UAS view with marked ground objects

2.4. Bathymetry

Wave height was determined by using the reverse bathymetry equation $c = \sqrt{gh}$ where c is wave celerity, g is gravity, and h is wave height [9]. This equation makes several assumptions as wave properties in the near-shore can be highly non-linear and therefore provides a first order approximation. Wave height in this case is defined as the distance from the ground to the crest of the wave rather than the distance from the crest to the trough.

2.4.1 PIV

In order to calculate the wave celerity, a python script was used to analyze footage of the surf zone shot from a UAS directly above the place of interest. First openCV was used to convert each frame of the video to gray scale. Each pair of frames were then sent to openPIV [11]. OpenPIV split the frame pairs into 32x32 pixel windows. The particles in each window was compared against the particles in the equivalent window from the other frame in the pair. The difference in

position of each particle was then averaged to create a velocity for the entire window. Additionally, openPIV was used to create a signal to noise mask of each window to help filter out noise from real particles (Figure 2).

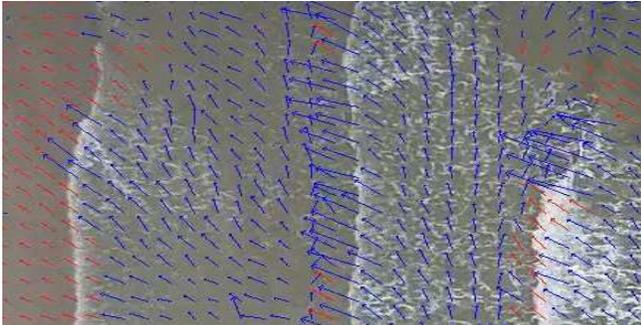


Figure 2: Visualization of PIV velocity output. Red arrows have a low signal to noise ratio.

2.4.2 Bathymetry Calculation

After the PIV process the resulting velocities were averaged across the length of the video to acquire a single average velocity for each window. Velocity outliers were removed to attempt to isolate the velocity of the wave and to remove any errors in PIV tracking. These average velocities were then converted to wave celerity. The PPM of the video was then calculated using the pixel distance between the corner reference targets and the real distance between the targets when surveyed. The PPM was used to convert the wave celerity from pixels per second to meters per second. From there the wave height was calculated from celerity using the equation $h=c^2/g$. These heights were combined with the center position of each PIV window to create a three dimensional point cloud.

2.5 Manual Calculation

In addition to the PIV process, the wave celerity at each depth gauge was manually measured for each video by timing how long it took a wave crests to travel a specific distance as determined by the measurements of the pier. The celerity of each wave crest was averaged at each gauge and the depth of each gauge was manually calculated from that average. The footage from the tripod camera of the gauges were used to calculate average depth. Depth at each gauge was sampled every 6 seconds and the final depth was acquired by averaging all samples.

3. RESULTS

After the data was collected, it was compared to our ground truth data and other runs. By visually comparing resulting point clouds (figure 3), it was determined that in general, the 30 fps footage was less noisy than the 60 fps footage. And the 75 meter footage was less accurate but covered a larger area than the 50 meter footage. Additionally, a large portion

of the 75 meter footage was in an area with no breaking waves and was poorly mapped as a result.

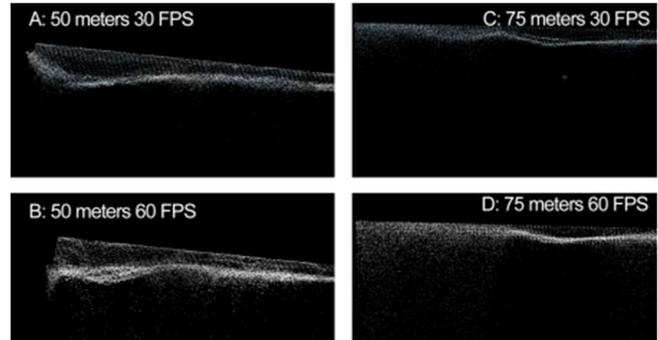


Figure 3: Point cloud profiles for each height and frame rate.

3.1 PIV Results

When PIV velocities were compared to the manually calculated velocities it was found that the method of averaging all velocities yielded a velocity up to 3x slower than the manually calculated velocity. Further investigation revealed that velocity on the crests of waves were much closer to the manually calculated velocity. For the 50 meter footage at 30 fps, the PIV velocities were within 3% of the manual velocities. For the 60 fps the velocities were within 4%. The 75 meter 30 fps velocities had an error of 10%. Because of the high amount of noise observed in 75 meter 60 fps footage (Figure 3.D vs Figure 3.C), the exact velocity error for it was not calculated.

3.2 Bathymetry Results

The bathymetry formula expects velocities from the wave crests. As the current automated process yields velocities almost 3x slower from the wave crest, the depths in the automated bathymetry calculation were off by as much as 8x. However, the process does yield accurate sandbar shapes and it would be accurate for general sandbar geometry inspection. Additionally, the results are off by a non-uniform linear constant that can be calculated from limited reference depths. This constant is likely related to the period of the waves, however more research is required.

In a related test, it was discovered that a minimum of 90 seconds of video was required for the bathymetry process to give approximate geometry, but that the more time available the better the results represent the sandbars. This time and constant are likely dependent on the period of the waves, more research into this is required.

The bathymetry formula was applied manually to the manually calculated velocities and the PIV velocities found on wave crests. The result from this manual calculation was then compared to the depth gauges. For the 50 meter footage at both resolutions the all manually calculated depths were within the $\pm 5\text{cm}$ margin of the depth gauges. For the 75 meter footage, the depths were outside the

±5 cm margin but within 30% of the control depth.

3.3 Preprocessing

Image stabilization and lens correction were intended, but not used due to technical issues during processing. For Image stabilization Adobe After Effects CS6's (AE) two-point image stabilization effect was attempted. The two points used were the corner targets. Preview of the effect appeared good, however during rendering AE encountered an error with the video codex used during filming and would only produce blank video files. It is likely that this could be corrected using the latest version of AE, however it was not available to the research team.

For lens correction all attempts yielded more distorted results than not using lens correction. As the observable lens distortion found in the UAS images was minimal, it was decided to forgo lens correction.

Three pre-processing filters found in OpenCV, erosion, opening, and closing, were also tested. All methods reduced particles too much for PIV, however erosion shows promise as a wave crest detector.

4. CONCLUSIONS AND FUTURE WORK

During the course of this research, several tangential items were discovered that may prove useful for future research in this area. It is recommend using professional video editing software such as Adobe After Effects for stabilizing drone footage. 2-point camera stabilization is a common problem in the film industry and the tools are easy to use and highly effective. So long as the program recognizes the provided footage. Results from this study also suggest that using a 30 fps or lower camera rate when recording videography from the UAS. The resulting footage is more reliable for PIV processing and the decreased required bandwidth will allow for less compression and resulting artifacts. Videos should be a minimum of 90 seconds, 5 minutes is recommended. For field validation, the striped pvc pipes provided a simple yet effective method to help validate results. However, one must ensure that the ground camera utilized can record in high enough quality to make out the marking bands. Also, ensure that a minimum of 1/3rd of the depth gauge's length is planted in the sand or it will likely not be stable enough. Gauges should be checked and the sand at their base replaced between flights.

Plans for future work in this area include determining the effects of video stabilization and lens correction on the existing process, potential use of openCV's erosion filter as a crest detector and examining potential edge tracking algorithms as a replacement for PIV.

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