

Marine Debris Monitoring on Uninhabited Islands Using UAV-Based 3D Modeling

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Keywords: UAV environment monitoring, Bundle adjustment, 3D reconstruction, Volume estimation, Marine debris

Abstract

Uninhabited islands in South Korea play a pivotal role in maritime activities and are increasingly vulnerable to the threat of marine debris. This paper proposes a UAV (unmanned aerial vehicle)-based 3D analysis to estimate the volume of marine debris. The proposed method consists of three main steps: bundle adjustment, 3D reconstruction, and volume calculation. Tiepoints are extracted from UAV images and used for bundle adjustment to correct the EOPs (exterior orientation parameters) and generate a sparse point cloud. The sparse point cloud is then densified through stereo matching, utilized for 3D mesh model generation. The volume of marine debris is finally calculated based on tetrahedral decomposition from the 3D mesh model. Three uninhabited islands in South Korea were selected as experimental areas. Due to the inaccessibility of the islands, a total of less than 30 images per site were acquired. Nevertheless, the coastal terrain and debris features were successfully reconstructed. The proposed method estimated the volume of a single Styrofoam buoy with a 0.0026 m³ error. Furthermore, it can estimate the volume of clustered debris without assuming a specific height. The findings demonstrated that the proposed method could overcome the limitations of 2D analysis and provide precise volume estimations. This method is expected to be effective for remote monitoring of marine debris on uninhabited islands.

1. Introduction

Islands are generally located at the boundaries of a territory and serve as hubs for maritime activities, making them important to national operations. This strategic importance is particularly pronounced in South Korea, which is surrounded by sea. A total of 3,348 islands is distributed within South Korea's territorial waters, with some located up to 102 km from the mainland (Lee et al., 2024). These islands are used as fishing bases, with intensive aquaculture and fishing activities taking place around them. There are 1,866 aquaculture farms and 50,649 fishing vessels officially registered, indicating the huge scale of fishing activity (Kim et al., 2024). However, these activities contribute to marine debris issues. South Korea generates approximately 145,000 tons of marine debris annually, with 35% attributed to fishing activities. Figure 1 shows an example of marine debris on an uninhabited island. It is estimated that over 600 tons of debris accumulate on uninhabited islands each year (Oh et al., 2022), and due to their isolated locations, efficient surveys and collection are challenging.

Marine debris is primarily investigated using remote sensing technology, which is categorized into satellite-based and UAV (unmanned aerial vehicle)-based methods. Satellite-based methods can observe multiple islands simultaneously and enable periodic monitoring (Sasaki et al., 2022). However, due to the low spatial resolution of satellite images, only larger debris can be detected. In contrast, UAV-based methods use high-resolution images capable of detecting smaller debris and usually establish multi-view geometry enabling three-dimensional analysis (Pepe et al., 2022). Related studies have mainly focused on detecting marine debris. They have applied the latest technologies such as machine learning and applied two-dimensional analysis (Zaaboub et al., 2023). Recent studies have attempted to estimate volume. Assuming that the height of marine debris is constant, they estimated volume from the detected area (Andriolo et al., 2024). They approximated debris volume using simplified two-dimensional analysis. Another study calculated the volume of marine debris using a 3D reconstruction method (Kako et al.,

2020). However, they focused on machine learning-based marine debris detection.

This study proposes UAV-based 3D modeling to calculate marine debris volume through 3D analysis. The proposed method generates point cloud using bundle adjustment and constructs 3D mesh model based 3D reconstruction. The mesh model can extract geometric information such as the area and volume of objects (Yoon and Kim, 2024; Lee and Lee, 2022). In this study, it was assumed that the coastline of the uninhabited islands was flat and that marine debris was relatively elevated. Therefore, the volume of marine debris can be calculated from the mesh model. Three uninhabited islands were used as experimental areas, and the validity of the proposed method for marine debris volume estimation was evaluated.



Figure 1. Marine debris on an uninhabited island.

2. Proposed Method

As shown in Figure 2, the proposed method performs three processes: bundle adjustment, 3D reconstruction, and volume calculation. Firstly, bundle adjustment extracts tiepoints from UAV images and uses them to correct the EOPs (exterior orientation parameters) of the images. Then, a sparse point cloud is generated based on the corrected EOP. Secondly, 3D reconstruction refines the point cloud through stereo matching. Next, a triangulation mesh is formed through Delaunay triangulation, and a 3D mesh model is completed through texturing. Thirdly, volume calculation extracts the volume of marine debris based on tetrahedral decomposition. The area of marine debris was extracted through visual analysis. Pix4Dmapper and CloudCompare software were used in this study.

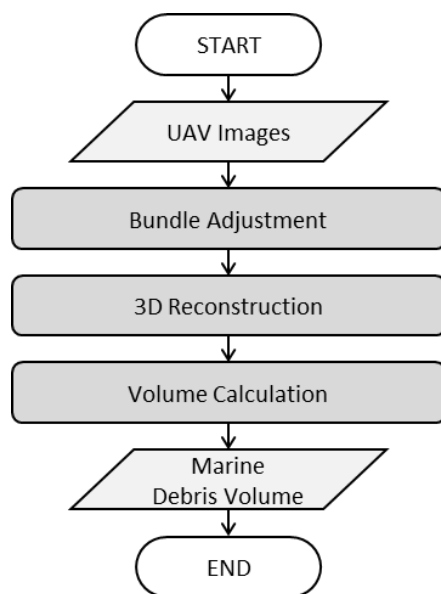


Figure 2. Flowchart of proposed method.

2.1 Bundle Adjustment for Geometric Correction

Bundle adjustment corrects EOP by analysing the geometric relationships between images. These geometric relationships are constructed based on photogrammetric models such as collinearity and coplanarity, utilizing tiepoints. The tiepoints are determined from UAV image pairs and automatically extracted using image matching techniques such as SIFT (scale invariant feature transform) and SURF (speeded-up robust features). Hence, outliers of tiepoints are eliminated through filtering such as RANSAC (random sample consensus) for stable bundle adjustment. The corrected EOPs and 3D model points of tiepoints are estimated through the least square method based on a photogrammetric model. This study used Pix4Dmapper and confirmed the number of tiepoints, the number of estimated model points, and the reprojection error of bundle adjustment for quality evaluation.

2.2 3D Reconstruction for 3D Mesh Modeling

The tiepoints with 3D model point through bundle adjustment were defined as sparse point clouds in this paper. The sparse point clouds can reproduce terrain features with the accuracy level of bundle adjustment, but their distribution is usually uneven. Therefore, for 3D mesh modeling, the sparse point clouds must be refined through stereo matching. UAV images are firstly epipolar resampled using the sparse point cloud. Then, depth maps are determined from the resampled images, and model points for all pixels are extracted.

Figure 3 shows the 3D triangle mesh constructed from densified point cloud and the mesh model with added textures. The 3D triangular mesh is formed based on either Delaunay triangulation or Poisson reconstruction. Then, the 3D mesh model is completed by mapping textures from the UAV image onto the 3D triangular facet.



Figure 3. 3D mesh model with texture.

2.3 Volume Calculation

The volume of marine debris is calculated based on the 3D mesh model. By defining the surrounding area of marine debris as a reference plane, the facets of the debris model are integrated into a closed surface, and its volume is calculated based on tetrahedral decomposition. In this study, the accuracy of volume calculation was analysed using Styrofoam buoys with known actual volumes. Furthermore, the possibility of calculating the volume of clustered debris was evaluated.

3. Experiment Results and Discussion

In this study, three uninhabited islands in South Korea were selected as experiment sites, as shown in Figures 4 to 6. These islands are known for their high quantity of marine debris and are surveyed annually by government agencies. We used DJI Phantom 4 Pro. Since the uninhabited islands are difficult to be accessed, the UAV must be operated from a ship. Considering the limited working environment, we acquired fewer than 30 images with 75% overlap, as shown in Table 1. To ensure detectability of small debris, a low flight altitude was maintained, resulting in a GSD (ground sample distance) below 3 cm.

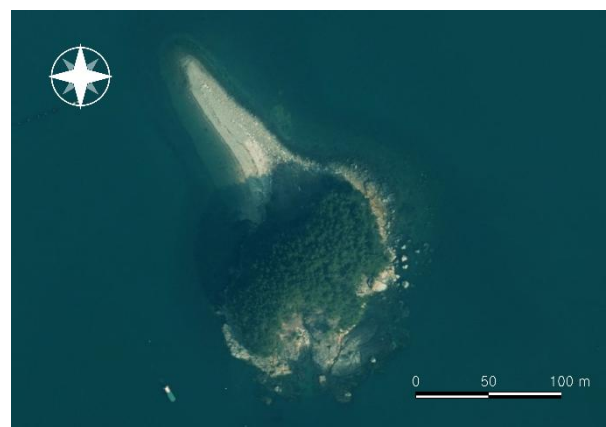


Figure 4. Island #1 seen in satellite basemap.



Figure 5. Island #2 seen in satellite basemap.



Figure 6. Island #3 seen in satellite basemap.

Dataset	Island #1	Island #2	Island #3
UAV	DJI Phantom4 Pro		
Overlap	Sidelap: 75%, Endlap: 75%		
Flight strips	2		
Flight height	105.6m	103.6m	98.5m
Number of images	27	10	13
Ground sample distance	2.90cm	2.84cm	2.70cm

Table 1. Descriptions of the dataset information

Table 2 shows the results of bundle adjustment and 3D reconstruction. For the Island #1, which has a relatively wide beach, the most tiepoints and point clouds were determined. Furthermore, the reprojection error was 0.14 pixels, indicating that the point cloud was highly accurate. The accuracy for the Islands #2 and #3 also were less than 0.20 pixels. However, since the number of point clouds was relatively small, it was expected that missing areas were observed in the 3D mesh model.

Dataset	Island #1	Island #2	Island #3
Number of tiepoints	189,289	22,051	49,601
Number of initial point clouds	73,384	10,141	22,105
Number of densified points	70,253,502	23,040,280	16,699,997
Reprojection error	0.14pixels	0.20pixels	0.18pixels

Table 2. Results of bundle adjustment and 3D reconstruction

Figures 7 to 9 are DSMs (digital surface models) generated using the densified point cloud by the 3D reconstruction. These DSMs show the terrain patterns of the uninhabited island and let us indirectly infer the distribution and accuracy of the point cloud. The DSM of Island #1 could distinguish even the coastal rocks. In the forested area at the center of the uninhabited island, the resolution decreases, which may be caused by using fewer images. Similar results were observed in Islands #2 and #3, and errors also occurred in the sea areas. Nevertheless, relatively high quality was maintained in the coastal regions.

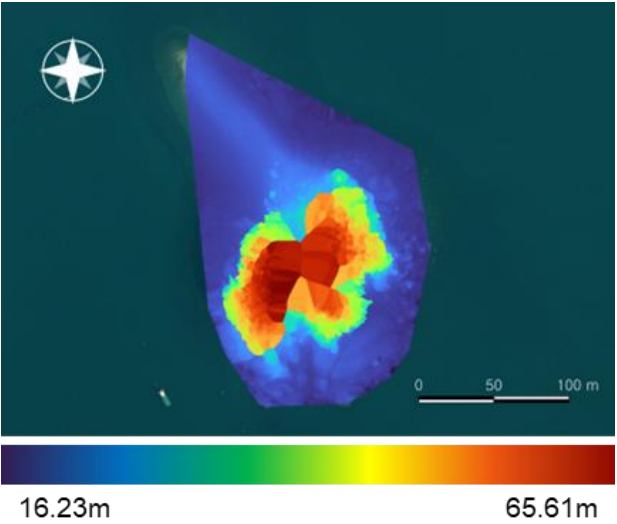


Figure 7. Digital surface model of Island #1 generated.

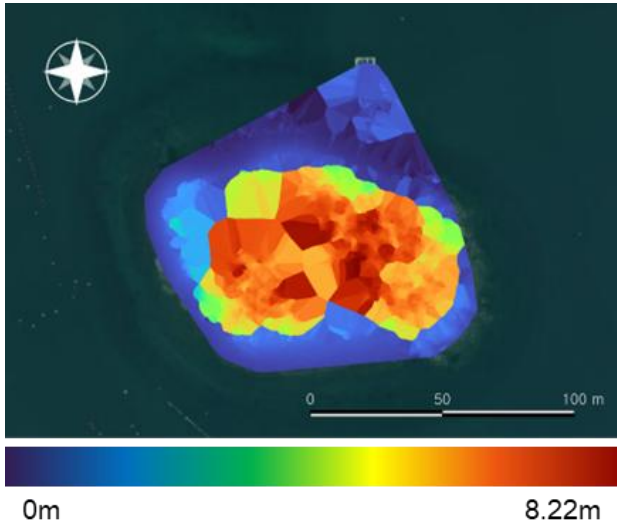


Figure 8. Digital surface model of Island #2 generated.

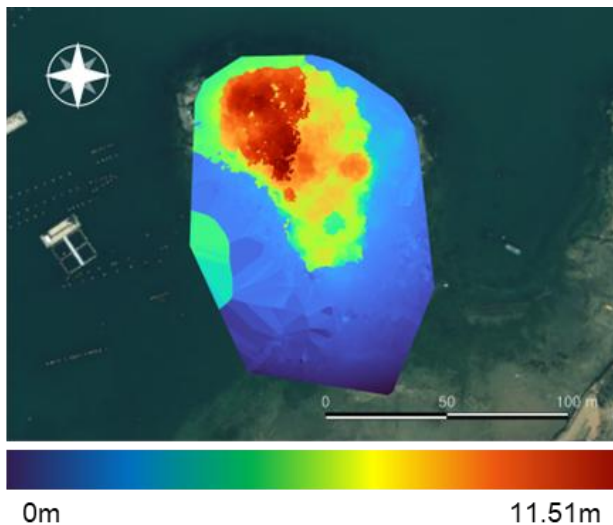


Figure 9. Digital surface model of Island #3 generated.

The results of the 3D mesh model generation are shown in Figure 10. In the 3D mesh model of Island #1, no missing areas were observed, and the shapes of rocks and cliffs were detailed as shown in Figure 11. The coastal terrains of Islands #2 and #3 were also represented with high resolution. However, some missing areas occurred as shown in (b) and (c) of Figure 10. These results indicated that more images need to be acquired.

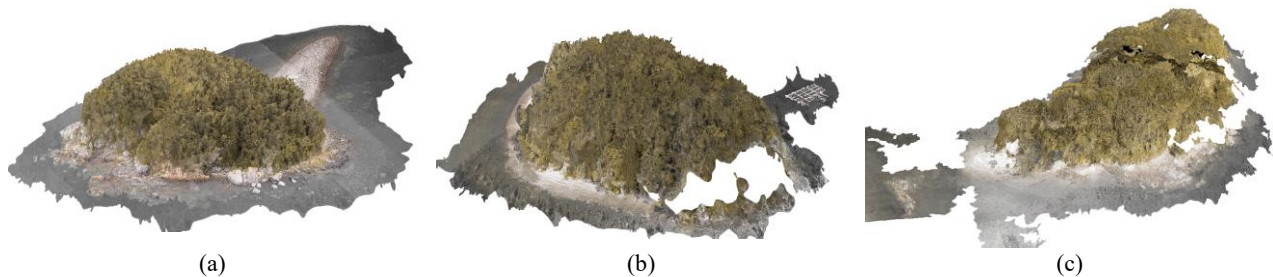


Figure 10. 3D mesh model of (a) Island #1, (b) Island #2 and (c) Island #3.

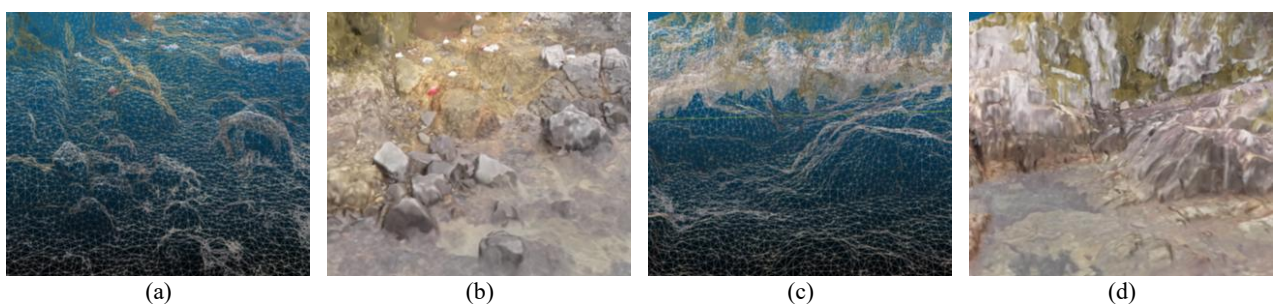


Figure 11. Appearance of rocks ((a) without texture, (b) with texture) and cliffs ((a) without texture, (b) with texture) on the 3D mesh model of Island #1.

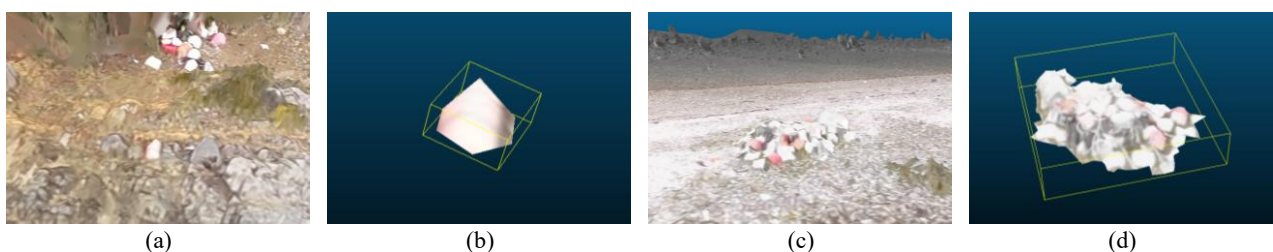


Figure 12. Marine debris on the 3D mesh model (a, c) of Island #1 and the results of its extraction (b, d).

Figure 12 shows marine debris on Island #1 to be used for volume calculation evaluation. The (a) and (b) in this figure show a single Styrofoam buoy, and the volume of the buoy was 0.2649 m^3 . The volume calculated by the proposed method was 0.2623 m^3 . The volume difference of 0.0026 m^3 from the actual measurement indicated that volume calculation based on a 3D mesh model could be used as an alternative to on-site observations. The (c) and (d) of Figure 12 show clustered Styrofoam buoys, which were estimated to be between 20 and 30 buoys as seen visually. Figure 13 shows the DSM of this cluster of debris, and its volume was calculated to be 6.8250 m^3 . This showed that the proposed method can calculate the volume of marine debris without height simplification.

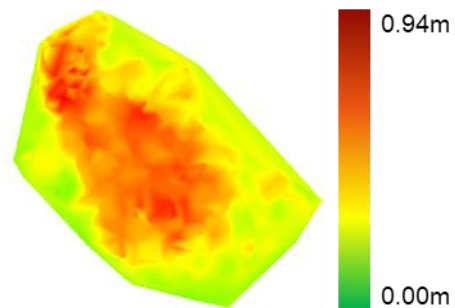


Figure 13. Digital surface model for the debris of Figure 12(d).

Figures 14 and 15 show large clusters of marine debris found on islands #2 and #3. For such large clusters of marine debris, it was expected that assuming a specific height is more difficult, and the accuracy of volume estimation would also be reduced. In contrast, the proposed method was able to calculate volumes of 1,879.0832 m³ and 288.5776 m³ based on a 3D mesh model. This could be interpreted as being more effective for the unique phenomena observed on uninhabited islands.

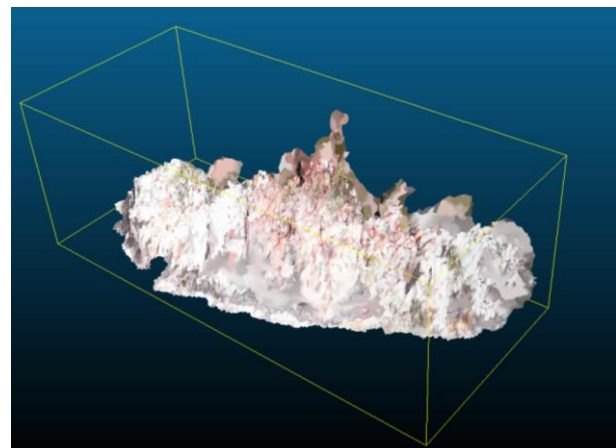
4. Conclusion

This study proposes a volume estimation method for marine debris on uninhabited islands using UAV-based 3D modeling techniques. This method consists of three steps: bundle adjustment, 3D reconstruction, and volume calculation. It was implemented using Pix4Dmapper and CloudCompare software. Three uninhabited islands in South Korea where marine debris is frequently observed were selected as the experiment sites, and 3D mesh models were created based on UAV images taken at the sites. The results showed that the 3D mesh models created from a small number of images had missing areas on Islands #2 and #3, but the coastal areas were highly detailed. Hence, a highly accurate and complete mesh model was obtained for Island #1.

The volume calculated by the proposed method showed a difference of 0.0026 m³ from the actual measurement, demonstrating its potential to replace on-site volume measurements. It also meant that the 3D analysis-based method can calculate the debris volume without height assumptions for both small and large clusters of debris. These results suggested that it is possible to overcome the limitations of 2D analysis in marine debris surveys and perform more detailed volume analysis. Future studies will perform accuracy assessments for various types of cluster debris. Through this, we expect that the proposed method can be effectively utilized for monitoring of marine debris on uninhabited islands.

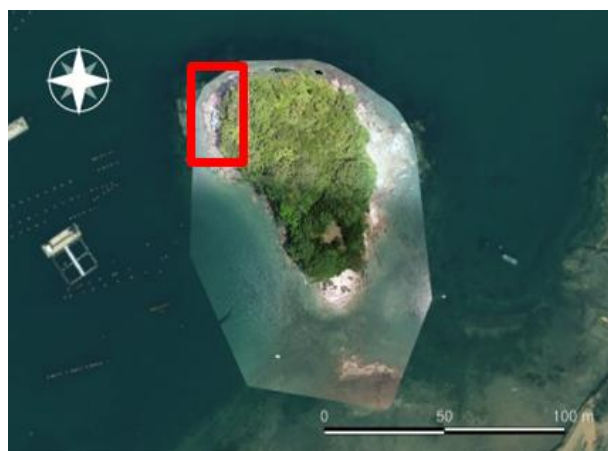


(a)

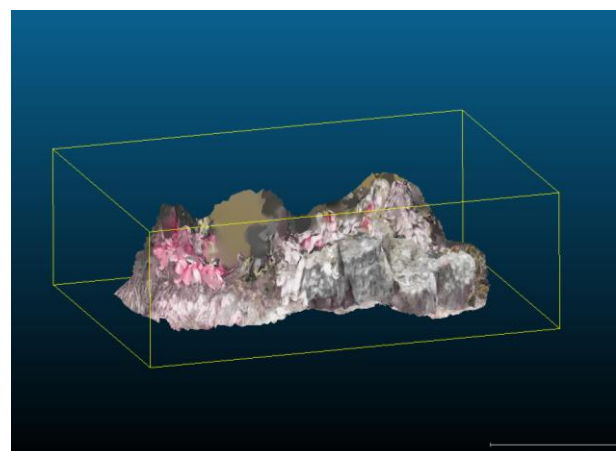


(b)

Figure 14. (a) Location and (b) 3D mesh model of marine debris clustered on island #2.



(a)



(b)

Figure 15. (a) Location and (b) 3D mesh model of marine debris clustered on island #3.

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