Calibration-Free Stereo Imaging for Coastal Wave Field Reconstruction and Quantification of Wave Breaking

권영빈 (ybkwon04@snu.ac.kr, 서울대학교 건설환경공학부)

지도교수: 박용성

Introduction

Why is wave field observation important?

- South Korea is surrounded by sea on three sides, and as of 2018, **20.2% of the world's population** lives within 20 km of coastlines (Cosby *et al.*, 2024).
- Wave field observations are used to monitor beach erosion, identify rip currents, forecast waves for safety, and prepare for tsunamis.

Obtaining wave fields with stereo imaging

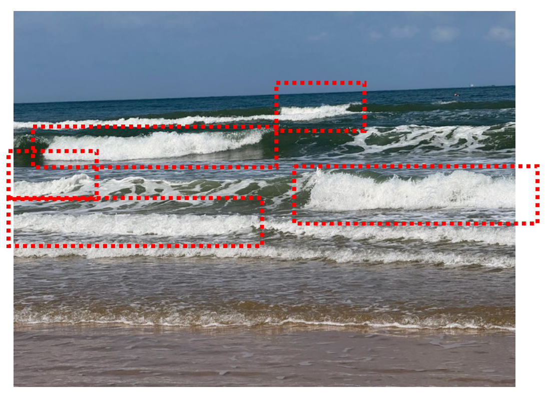
Table 1 *Comparison of wave field observation technologies*

Type	Method	Spatio-temporal resolution	Cost / practicality
Point Based	Buoys / wave gauges	Single point, very high in time	Medium–high; moorings & maintenance needed
	Radar	Wide area, moderate space & time	High; large, fixed, specialized system
Space based	LiDAR surface scanning	Local area, very high in space, moderate in time	Very high; specialized sensor & setup
	Stereo imaging	Local area, **high space & time**, dense 3D	Low; two cameras, easy to deploy

- This study employs a **stereo camera system** to reconstruct 3D wave field images.
- This model offers data in high spatiotemporal resolution at a much **lower cost** than radar or LiDAR, benefiting small communities.

Analyzing Wave breaking with Reconstructions

- Wave breaking is a phenomenon in which a wave collapses as its **nonlinearity increases** and its steepness becomes critical. (Mei *et al.*, 2005)
- The Iribarren number ξ is a widely used nondimensional parameter for classifying wave breaking types on sloping beach (Battjes, 1974).



$$\xi = \frac{\tan\alpha}{\sqrt{H_b/L_0}}$$

$\xi < 0.4$ (spilling)

$0.4 < \xi < 2.0$ (plunging)

$\xi > 2.0$ (surging or collapsing)

Figure 1 *Breaking waves in data acquisition site and wave breaking criteria*
(α: seaward slope, H_b: breaking wave height, L_0: deep-water wavelength)

- Stereo imaging enables field studies, providing high spatiotemporal resolution for the 3D reconstruction of the ocean surface, making it possible to conduct detailed wave breaking studies directly on real coastal sites.

Data Acquisition

- All data including stereo imagery and validation sensor data was obtained at Manlipo beach, Chungcheongnam-do.
- For proper set up, procedures including deploying the sensor (**Figure 2 (a)**) and surveying the area and GCP points (**(d)**) must be done during low tide.
- During high tide, the deployed sensors are underneath the free surface. Two drones were flown at this period to obtain stereo imagery.
- Aquadopp sensors are kept active throughout the acquisition period.

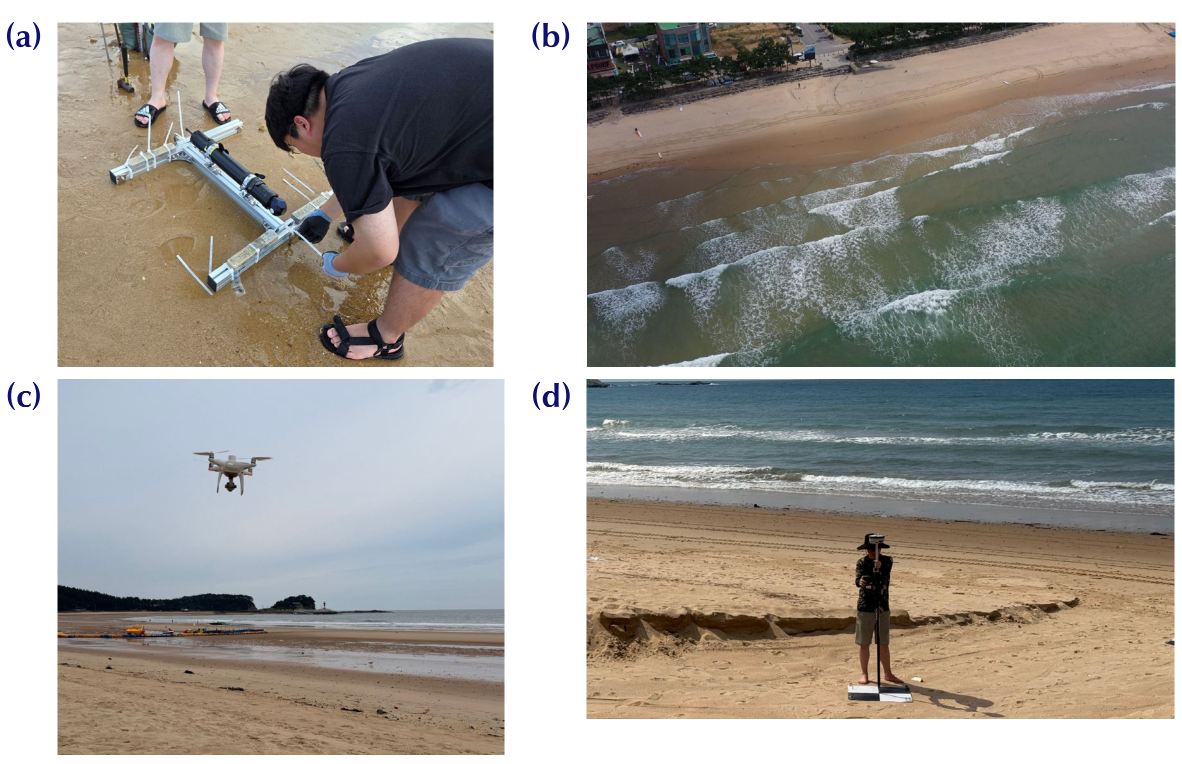
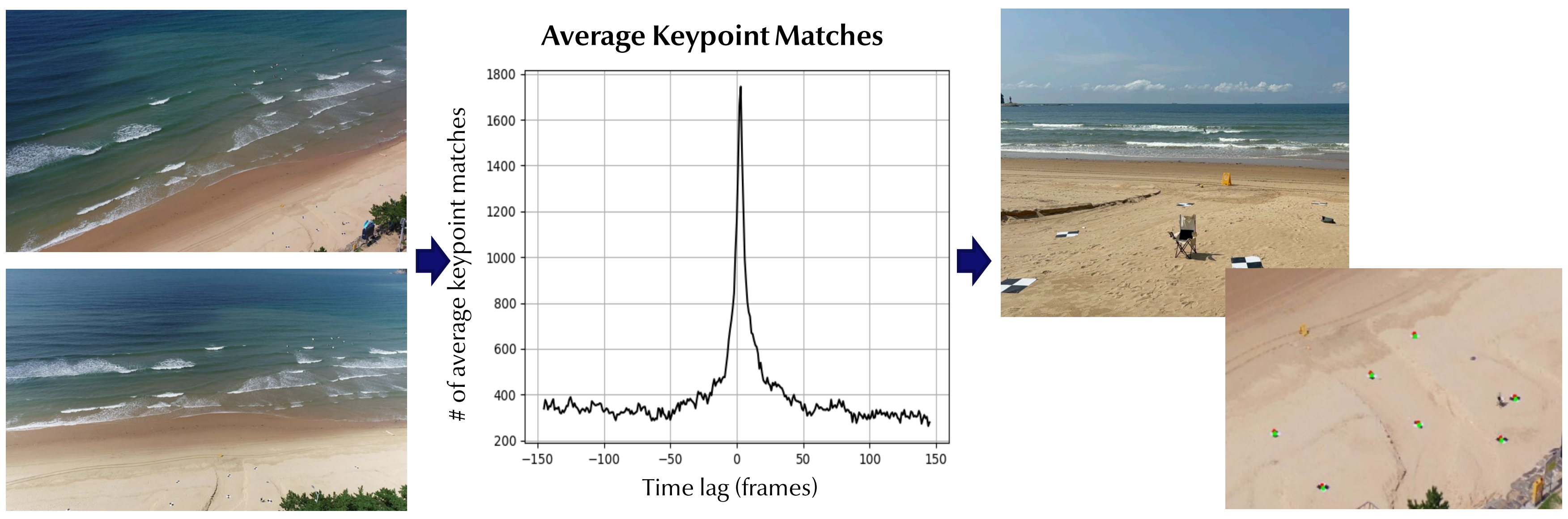


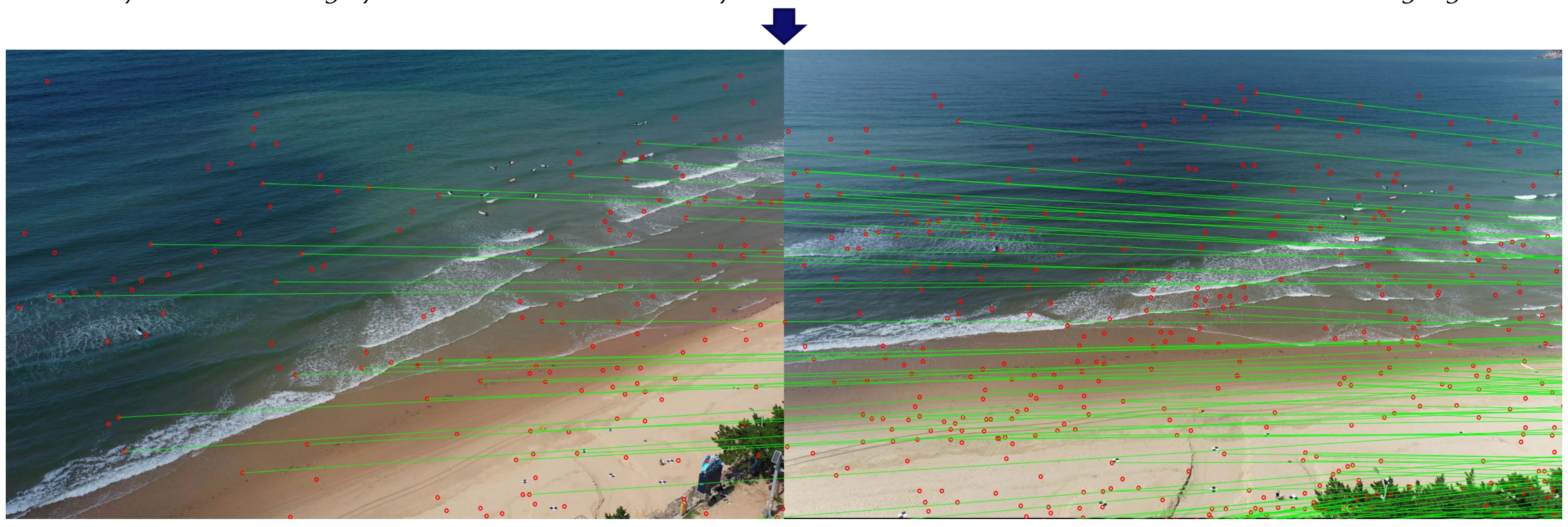
Figure 2 **(a)** *Setting up Aquadopp sensor* **(b)** *Drone Image Manlipo beach overview* **(c)** *Drone flight* **(d)** *Surveying GCP points using RTK GPS*

Methods

Calibration-Free Stereo Imaging SWASSZ Pipeline



(a) *Unsynced Stereo Imagery* **(b)** *Video time synchronization* **(c)** *GCP annotation and tracking algorithm*

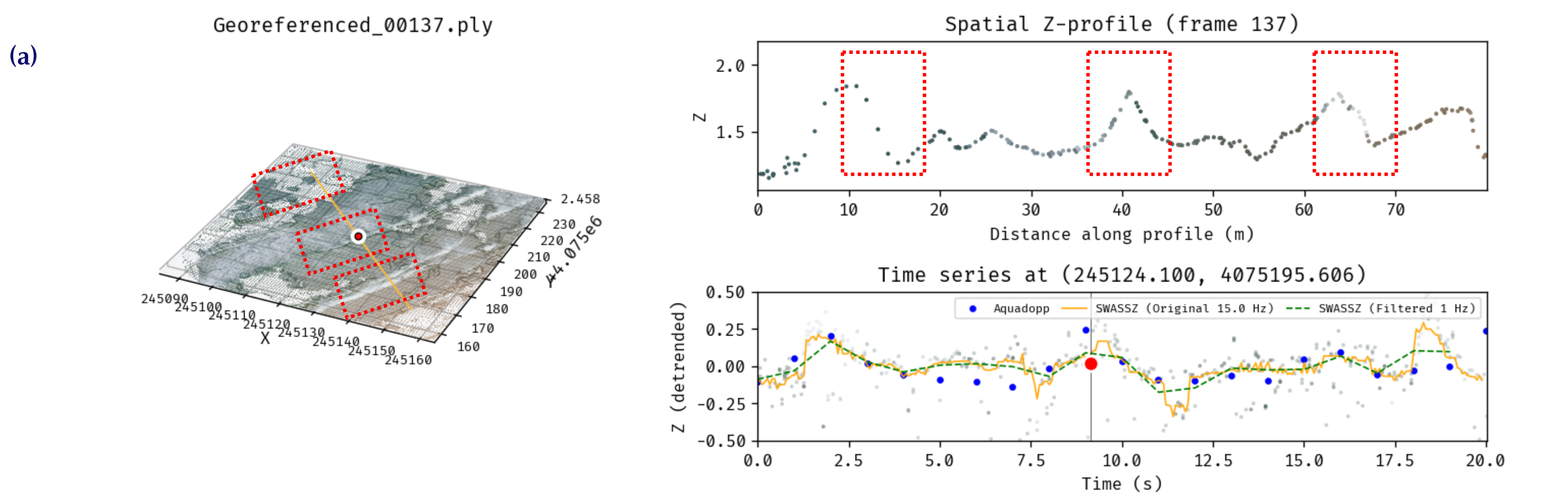


(d) *Water surface point cloud reconstruction (SfM-MVS), example of keypoint matches (COLMAP)*

Figure 3 *Overview of the SWASSZ Framework*

- SWASSZ is a new framework for stereo wave analysis in the surf-swash zone (Noh *et al.*, 2025).
- Videos (**Figure 3 (a)**)are time-synchronized by scanning frame lags and choosing the offset yielding the maximum number of averaged matched keypoints (**(b)**).
- Ground control points (GCPs) are tracked in synchronized frames, later used to transform the point clouds into real-world coordinates.
- The SWASSZ reconstruction workflow uses the *structure-from-motion* and *multi-view stereo* (SfM-MVS) framework, specifically COLMAP.

Results



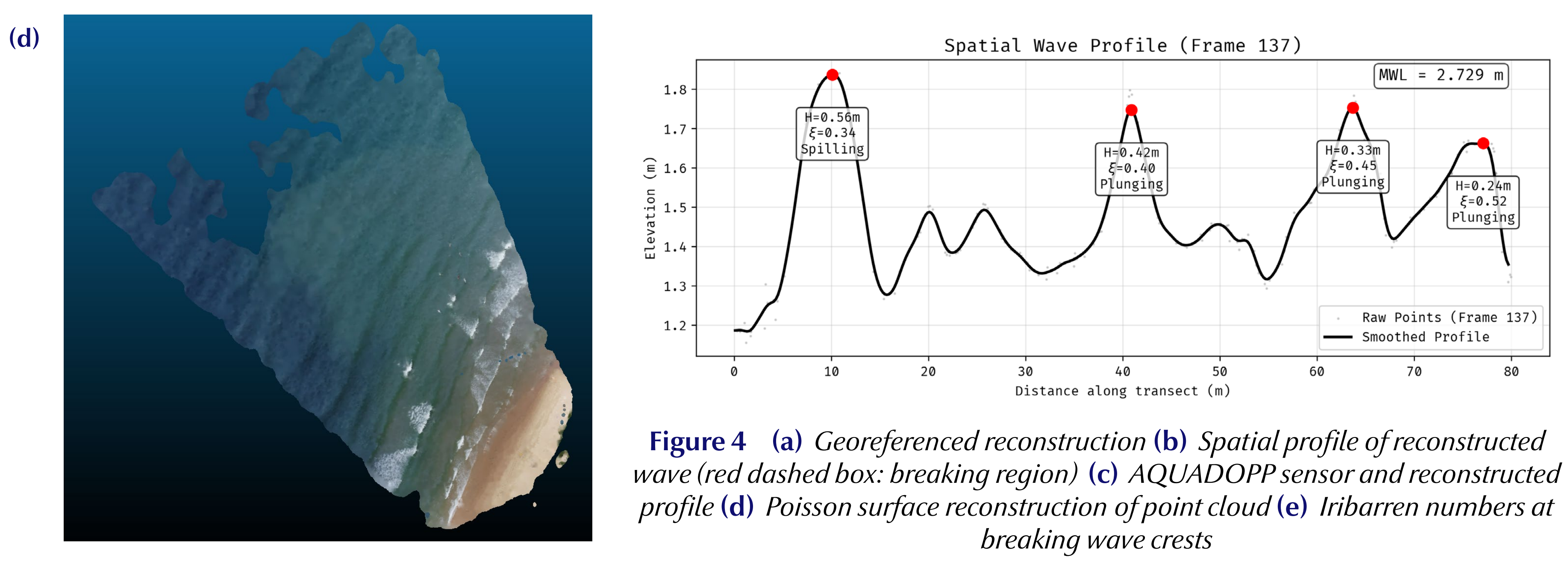


Figure 4 **(a)** *Georeferenced reconstruction* **(b)** *Spatial profile of reconstructed wave (red dashed box: breaking region)* **(c)** *AQUADOPP sensor and reconstructed profile* **(d)** *Poisson surface reconstruction of point cloud* **(e)** *Iribarren numbers at breaking wave crests*

Conclusion

- We have successfully reconstructed the wave field of a real coast environment with **a temporal resolution of 15 Hz**.
- The reconstructed wave field data also includes the **color** of the stereo image, which is not obtainable from conventional methods.
- Regions of wave breaking from spatial z-profile plots.
- The reconstruction has been validated against Aquadopp sensors, showing generally good agreement in wave components.
- Remaining discrepancies are likely due to the smoothing nature of Aquadopp sensors as discussed in (Noh *et al.*, 2025).
- Established wave-breaking criteria were found to be consistent with our reconstructed wave field.

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