Laboratory tool for spatio-temporal measurements of waves and slopes based on polarimetric sensing and Machine Learning

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We present a noval accurate and cost-effective measurement methodology for obtaining spatio-temporal distribution of water surface elevation (water waves) and directionality (slopes) in laboratory conditions. To this end, numerous measurement techniques have been developed over the years. None of these techniques, however, provide near-real-time spatio-temporal data of waves and slopes. Here we utilize Deep Learning (Artificial Neural Nnetworks - ANNs), approach, and latest advances in polarimetric imaging technology, to develope a remote sensing methodology for laboratory implementation. Inferring surface elevation, slope maps and waves' directional spectra with high accuracy, from polarimetric data of artificial light source reflections from the water surface.

The methodology, based on our proof of concept[1], was further developed to constitite applicable laboratory measuremnt tool by improving supervised data collection of larger variety of monochromatic wave trains serving as the treaining sets, achieving higher Signal to Noise Ratio (SNR) in larger spatial sampling area obtained by in house developed artificial light source. In addition, we utilized Bayesian optimization algorithm for hyperparameters tuning for the deep learning on the collected data. We demonstrate the ability of the on deep learning network, trained on the collected simple monochromatic wave trains data, to produce high-resolution and accuracy reconstructions of the 2D water surface slopes of irregular waves fields propagating at arbitrary angle relative to the polarimetric camera optical axis. To obtain the spatio-temporal water surface elevation from slopes map we apply the surface-from-slopes post processing utilizing state of the art computer vision algorithm of surface reconstruction from gradient fields algorithm[2], aided by the data acquired by a single resistancet type wave gauge. Furthermore, we present capability to reconstruct the surface waves celeritiesy's directly, without assuming simplified dispersion relation. The method's performance is demonstrated to provide dense estimate of the water surface, efficiently and accurately reconstructing wave field parameters across the full range of wave lengths. We also discuss in detail the techniques for selection of optimal ANNs hyperparameters and the use of spatial filters to improve the signal-to-noise ratio while maintaining adequate spatio-temporal resolution.

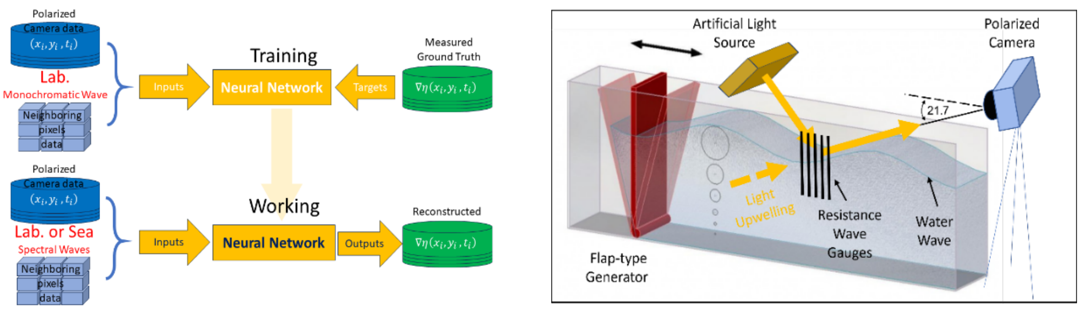

Figure 1: Left – Tarining and implementation of ANNs; Right – Expereimntal setup

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[1] Ginio et al., *Measurement Science and Technology*, **34** (2023)

[2] Harker et al. *Journal of Mathematical Imaging and Vision*, **51** (2015).