AI-based single-beam SONAR detection module

An experimental study on material classification using a low-cost single-beam sonar

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Introduction: Single-beam sonar sensors are widely deployed in underwater systems due to their robustness, low cost, and ease of integration. Beyond conventional distance measurement, raw sonar backscatter signals may encode information about surface properties and foreign materials. This work investigates the potential of single-beam sonar data for material discrimination and anomaly detection by developing a structured experimental and data-driven framework that evaluates material-dependent acoustic responses under controlled and dynamic conditions.

Approach / Technology: A complete and reproducible processing and evaluation pipeline was developed, covering raw single-beam sonar data acquisition, synchronized video-based labeling, preprocessing, dataset curation, and model evaluation. The data processing stage compensates for distance-dependent attenuation and geometric effects through normalization of echo profiles. For dynamic measurements, a centroid-based distance estimation is applied to improve robustness against motion-induced variability and misalignment.

Three investigations were conducted. First, a feasibility study analyzed raw backscatter signals acquired in a pool, a pond, and open sea conditions using qualitative mean echo profiles and quantitative energy-based features. The results show that material-dependent characteristics are consistently observable across environments; however, overlapping backscatter responses indicate that material differences, while visible, are not always uniquely distinguishable.

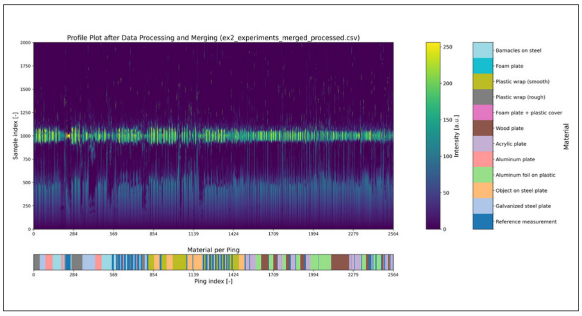
Second, stationary experiments were conducted with a significantly expanded set of test materials while systematically varying incidence angle and sonar-to-target distance. Although distinct echo patterns can be observed under these controlled conditions, the very high classification performance achieved by classical machine learning models is partly attributable to reduced variability and data leakage. At this stage, robust and generalizable material recognition cannot yet be conclusively confirmed.

Third, the experiments were extended to dynamic measurements with increased geometric and environmental variability. Under these conditions, backscatter responses become more variable and classification performance degrades substantially. Classical models achieve accuracies below 40%, while CNNs trained on raw echoes and zero-shot Visual Language Models perform even worse. This drop in accuracy is primarily attributed to ambiguous echo signatures and limited data variability rather than model complexity.

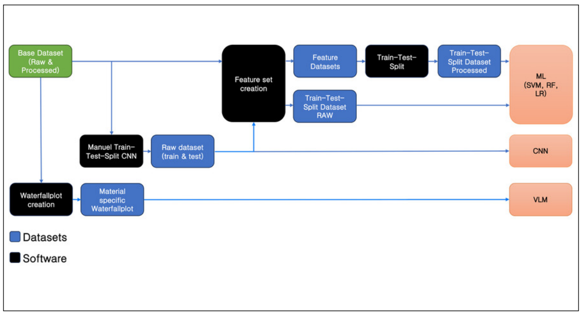
Conclusion: This work demonstrates that single-beam sonar backscatter contains material-dependent information. The results confirm the feasibility of material-aware sensing using simple sonar hardware, while also revealing limitations due to the non-unique nature of material-based backscatter under dynamic and variable conditions. The presented framework therefore serves as a proof of concept rather than a deployable solution. Future work should focus on larger and more diverse datasets, improved labeling and preprocessing strategies, systematic investigation of sonar settings, and simplified anomaly-oriented classification scenarios to improve robustness and practical applicability.

Experimental setup for the feasibility study with a stationary steel plate and opposing single-beam sonar sensor.
Own presentment

Processed base dataset from dynamic measurements, showing temporal segmentation and corresponding material labels.
Own presentment



Processing pipeline for deriving ML, CNN, and VLM datasets, using manual train–test splits to prevent data leakage.
Own presentment



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Subject Area
Data Science, Mechatronics and Automation

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