Lab For Ultrasonic Non-Destructive Evaluation
Summer Research Summary- Parth Patel
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Monte-Carlo Localization on Metal Plates Based on Ultrasonic Guided Waves

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Research Overview

This research, conducted by the Georgia Tech-CNRS team addresses a critical challenge in autonomous robotics: localizing defects with inspection on large metal structures like ship hulls. The study demonstrates that ultrasonic guided waves (specifically Lamb waves) can enable precise robot localization on metal plates through a particle filtering approach.

Problem Context

The marine industry faces significant operational challenges with hull inspection and maintenance. Current methods require ships to be immobilized in dry docks for up to 8 days, with human operators performing visual inspections and cleaning. This approach is time-consuming, expensive, and suboptimal. Autonomous robotic systems could revolutionize this process, but they require accurate localization capabilities to operate effectively on large metal structures.

Technical Methodology

Core Approach

The researchers developed a Monte-Carlo Localization (MCL) method using a particle filter that leverages first-order reflections of acoustic waves from metal plate edges. The system operates on several key principles:

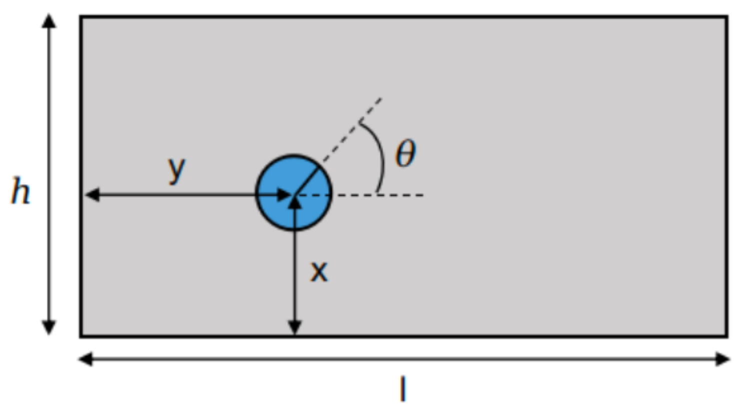

Figure 1: Illustration of an agent at position $x = [x, y, \theta]^T$ on a metal plate of dimensions $l \times h$, showing the coordinate frame and positioning system.

Sensing Configuration: Two co-localized piezoelectric transducers approximate pulse-echo sonar sensing, with one generating Lamb waves in the metal structure and the other receiving reflections from the plate boundaries.

Wave Properties: Lamb waves are ultrasonic guided waves that propagate parallel to metal surfaces, can travel long distances, and reflect perpendicularly when encountering boundaries.

Known Parameters: The method assumes knowledge of the rectangular metal plate dimensions ($l \times h$) and aims to estimate the robot state vector $x_t = [x_t, y_t, \theta_t]$ containing 2D coordinates and heading.

Echo Detection System

The team developed a probabilistic model for extracting acoustic reflections from measurements:

1. A basic wave propagation model generates signals for reflections at various distances
2. Correlation analysis between measured and modeled signals identifies echo locations
3. The Hilbert transform produces an envelope signal representing reflection likelihood
4. An exponential probabilistic model converts correlation strengths into distributions

Particle Filter Implementation

The Monte-Carlo Localization algorithm follows a standard recursive structure:

Initialization: 500 particles are uniformly distributed across ¼ of the plate (geom. symmetry)

Prediction: Each particle's state evolves according to odometry data with added noise

Update: Particle weights are calculated based on the likelihood of observing four first-order echoes (reflections from each plate edge) given each particle's hypothesized position

Resampling: Particles are resampled proportionally to their weights, causing particles with accurate position hypotheses to persist while others disappear

Experimental Setup and Results

Test Configuration

The experiment used a 60 cm × 45 cm aluminum plate (6 mm thick) with acoustic data collected at 108 positions arranged in a rectangular grid. The system employed:

- Excitation signal: Two tone-bursts at 100 kHz amplified to 100V peak-to-peak
- Sampling rate: 1.25 MHz with 500 samples per measurement
- Test trajectory: Simulated lawnmower pattern with 216 total measurement steps

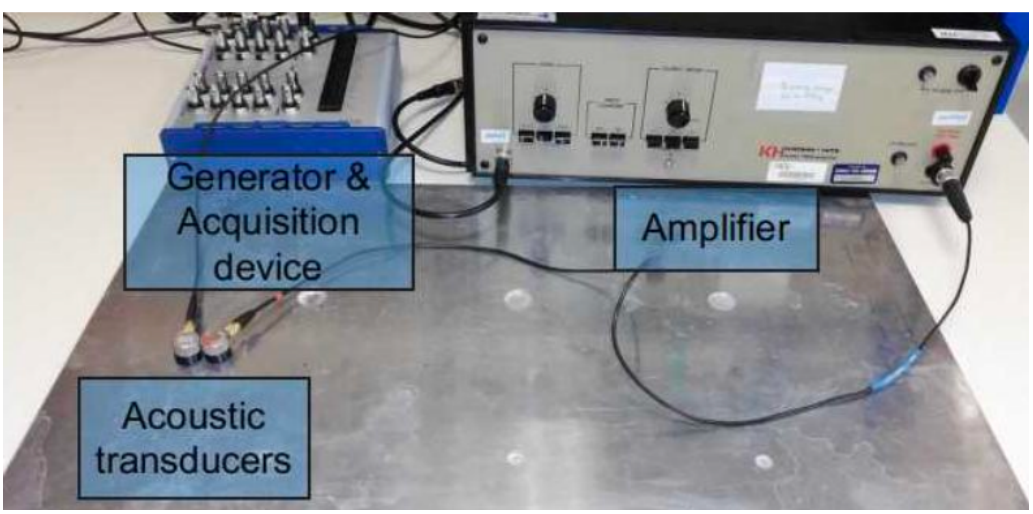

Figure 2: Picture of the experimental setup showing two acoustic transducers co-localized to approximate pulse-echo sensing on the aluminum plate.

Acoustic Signal Analysis

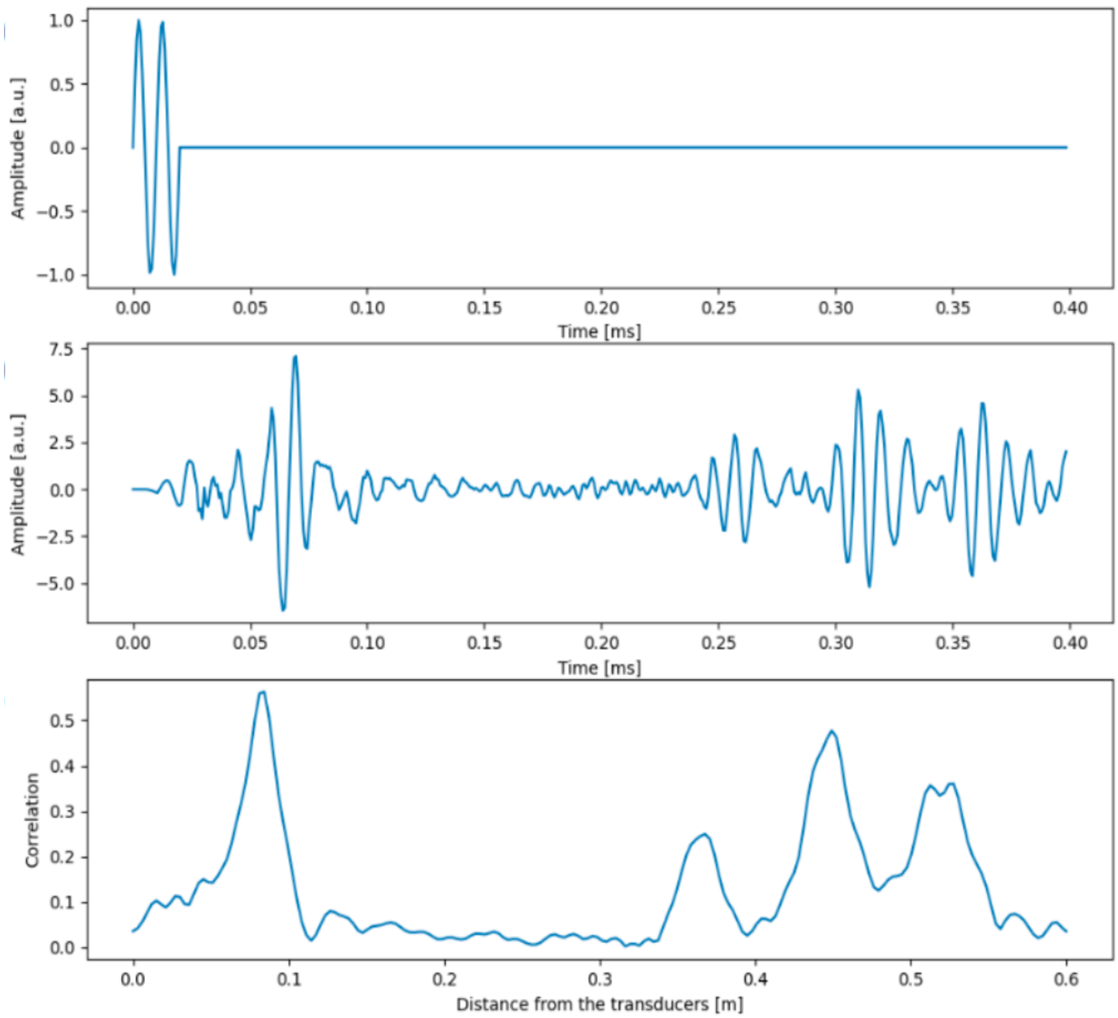

Figure 3: (a) Excitation signal used to generate Lamb waves. (b) Acoustic measurement obtained at position [x, y] = [0.08, 0.08]. (c) Correlation envelope signal showing clear peaks for the 4 first-order echoes at expected ranges [x, y, l-x, h-y] = [0.08, 0.08, 0.52, 0.37].

Performance Outcomes

The results demonstrated impressive localization accuracy:

Convergence Speed: After only 12 measurement steps, the particle filter achieved accurate position estimation from an initially uncertain state

Precision: The y-coordinate achieved sub-centimeter accuracy (< 1 cm error) within a few steps and maintained this throughout the trajectory. The x-coordinate required slightly more steps to converge but ultimately reached comparable precision levels.

Stability: Position estimation remained accurate across the entire 216-step trajectory, with particles consistently clustering around the true position

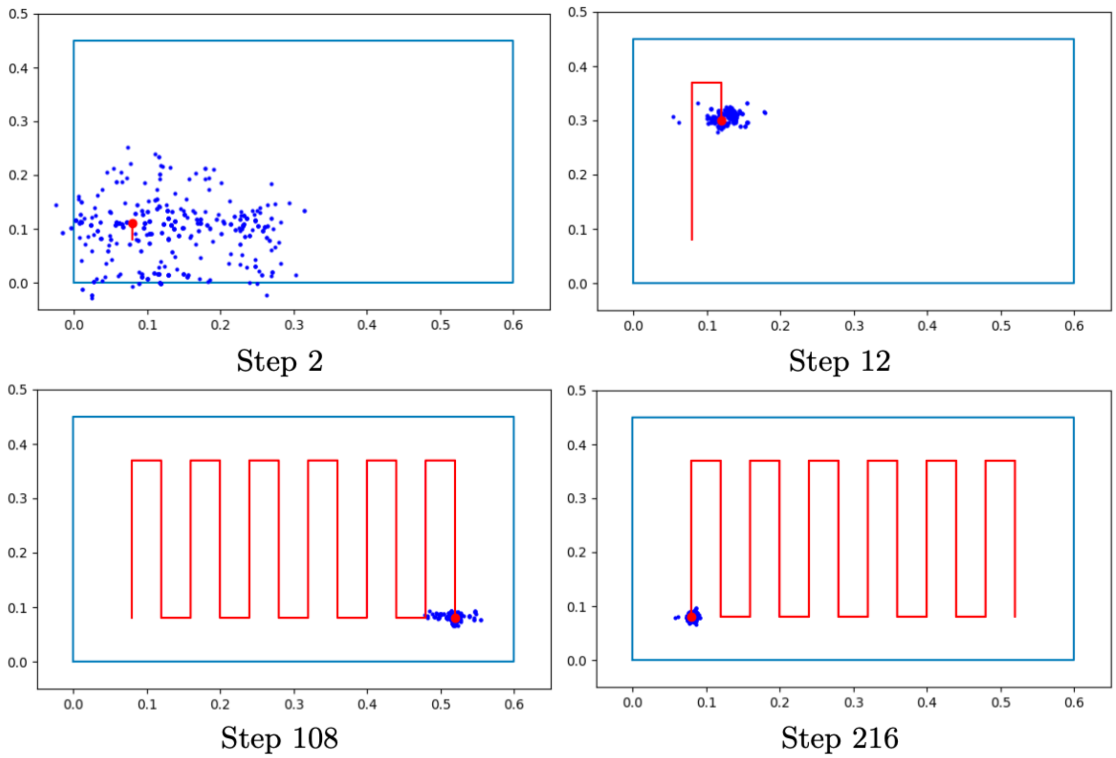

Figure 4: Position estimated by all particles (blue dots) during Steps 2, 12, 108, and 216 for a lawnmower path on the plate. The blue rectangle shows the true plate outline and the red dot indicates the true sensor position.

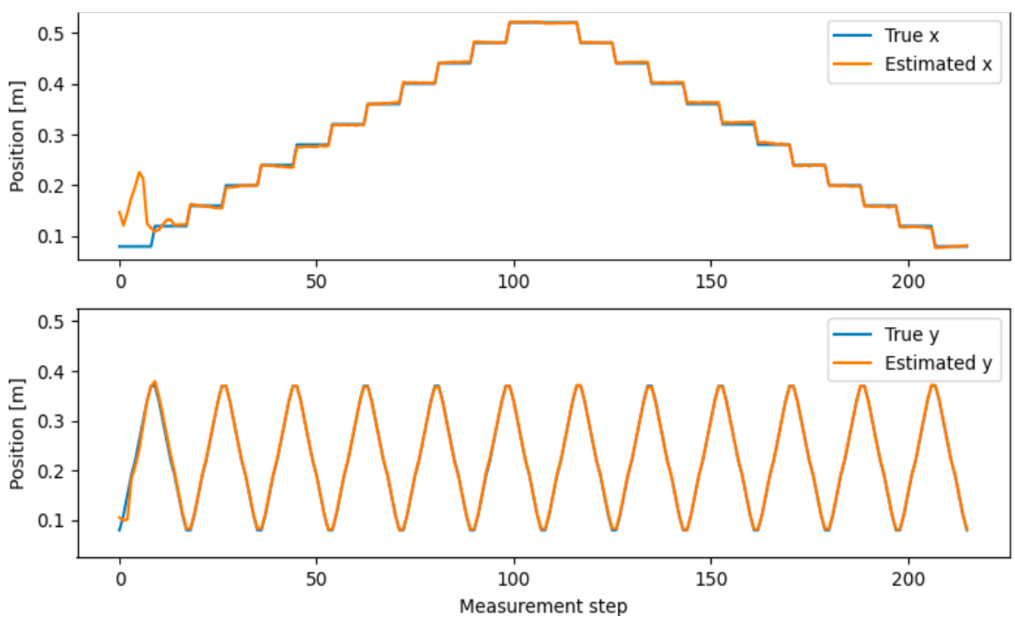

Figure 5: Quantitative results showing the median of the belief on position versus ground truth throughout the trajectory. The graphs demonstrate sub-centimeter accuracy for both x and y coordinates after initial convergence.

The correlation analysis successfully identified first-order reflections in the acoustic measurements, with peaks corresponding to expected ranges based on distances to plate edges.

Limitations and Future Directions

Current Constraints

The research team identified several limitations requiring further investigation:

Transducer Configuration: Using two separate transducers introduces approximation errors compared to true pulse-echo operation. Future work will employ single-transducer setups for improved accuracy.

Environmental Factors: Laboratory conditions provided high signal-to-noise ratios that may not reflect real-world ship hull environments with surface irregularities, larger plate sizes, and outdoor conditions.

Algorithm Robustness: Insufficient particle density could cause filter failure, and the current approach only uses first-order reflections while ignoring potentially useful higher-order echoes.

Planned Developments

1. **Robot Integration**: Implementing the system on actual robotic platforms with real-time acoustic acquisition and odometry
2. **SLAM Capabilities**: Extending to simultaneous localization and mapping for unknown plate geometries
3. **Enhanced Signal Processing**: Incorporating higher-order reflections and improved noise handling
4. **Field Testing**: Validation on actual ship hulls under realistic operational conditions

Significance

This research represents a significant advancement toward autonomous robotic inspection of marine vessels. By demonstrating millimeter-level localization accuracy using acoustic guided waves, the work provides a foundation for combining this approach with conventional systems (laser theodolites, UWB beacons) to create robust localization solutions for industrial robots operating on metal structures. The success of the particle filtering approach, despite the complex nature of guided wave propagation and geometric symmetries, suggests promising potential for practical deployment in the marine industry.