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Geometric Correction of Underwater Forward Looking Sonar-Based 3-D Reconstruction via PS-Based Slope Pattern Interpretation Using AUV

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Abstract— **Forward-looking sonar (FLS) enables long-range underwater sensing. In FLS-based 3-D reconstruction, falsely inclined surfaces arise from elevation ambiguity caused by the finite vertical beamwidth. Existing approaches mitigate these errors using multi-pass strategies, but they require repeated observations, which are often impractical in real-world underwater operations. To address this, we propose a pattern-informed geometric refinement framework that leverages structural patterns from profiling sonar (PS) to resolve ambiguity in FLS-based reconstruction. Within this framework, geometric patterns within ambiguity-dominated intervals are analyzed to distinguish between physically valid surfaces and falsely inclined surfaces, and selective geometric refinement is applied accordingly. Experimental results demonstrate effective suppression of falsely inclined surfaces and improved reconstruction accuracy without trajectory modifications. This provides a practical solution for reliable 3-D mapping and perception in underwater robotic applications.**

Sonar Imaging, Underwater Mapping, Geometric Correction, AUV.

I. INTRODUCTION

Forward-looking sonar (FLS) enables long-range underwater sensing where optical methods are limited [1]. However, an FLS image is a two-dimensional projection of a three-dimensional scene without elevation information, leading to inherent geometric ambiguity in FLS-based 3-D reconstruction. Highlight extension enables lightweight online 3-D reconstruction via beam-wise height estimation from range echoes [1]. When a sonar beam spans a finite vertical beamwidth, each return produces multiple elevation candidates. This makes it difficult to select the bottom-bin, which is assumed to represent the seafloor return, as illustrated in Fig. 1. As these errors accumulate over time, they form an ambiguity-induced inclined structure, referred to as a falsely inclined surface [2]. Previous studies mitigate falsely inclined surfaces using multi-pass approaches [2], but require repeated observations, which are often impractical under harsh underwater operational conditions.

In contrast, this work addresses falsely inclined surfaces by incorporating geometric pattern interpretation using profiling sonar (PS) into FLS-based reconstruction. We propose a pattern-informed geometric refinement framework that leverages geometric patterns from PS to resolve ambiguity in FLS measurements. The framework interprets these patterns to distinguish between physically valid surfaces and falsely inclined surfaces within ambiguity-dominated intervals, and applies selective geometric refinement accordingly, as summarized in Fig. 2.

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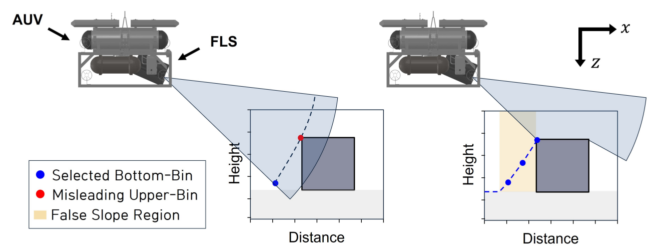


Fig. 1. Falsely inclined surface formation due to beamwidth-induced ambiguity.

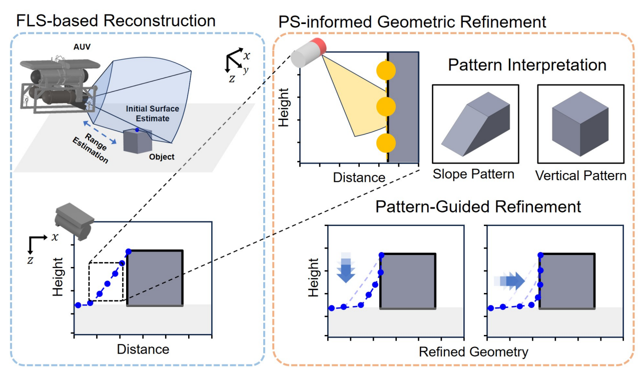


Fig. 2. Proposed framework: detection of ambiguity-dominated intervals and selective geometric correction based on slope pattern comparison.

II. PROPOSED METHOD

The proposed method interprets characteristic geometric patterns to distinguish physically valid surface structures from falsely inclined surfaces. The overall framework integrates FLS and PS to resolve geometric ambiguity in 3-D reconstruction. First, FLS measurements are used to generate an initial 3-D surface based on bottom-bin esti-

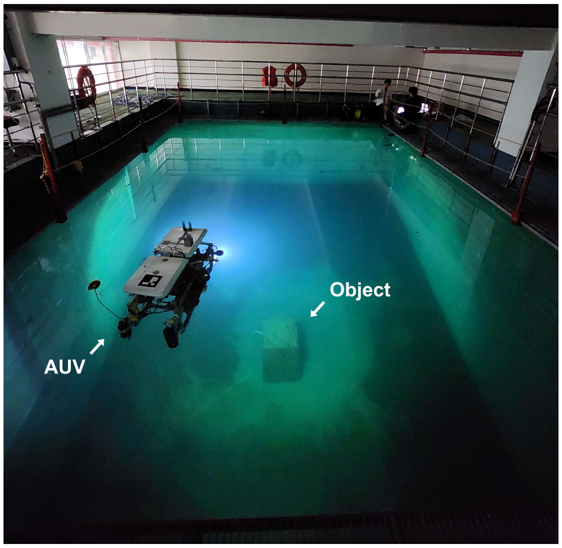
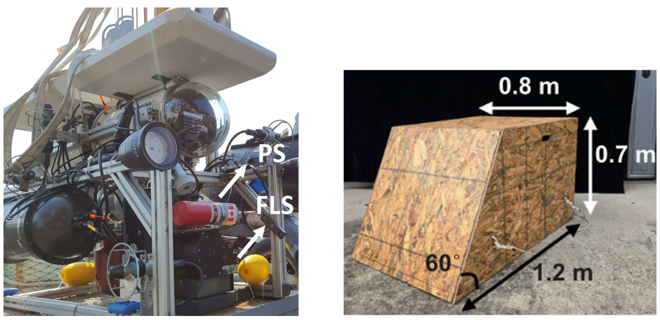


Fig. 3. Water-tank environment



(a) AUV platform (b) Sloped object

Fig. 4. Experimental components including the AUV platform with sonar sensor and test object used for validation.

mation, providing a lightweight reconstruction of the scene. Subsequently, the temporal trajectory of the bottom-bin, assumed to correspond to the seafloor return, is analyzed to identify ambiguity-dominated intervals. Next, geometric patterns extracted from PS measurements are compared with reference patterns corresponding to surfaces with varying slopes, ranging from gently inclined planes to near-vertical structures. Finally, the reconstructed surface is selectively refined, where ambiguity-dominated regions are corrected while geometrically consistent regions are preserved.

To construct the initial geometry, the range $r_j(t)$ along each beam N_j is estimated from the bottom-bin index $b_j(t)$ as

$$r_j(t) = r_{max} - (r_{max} - r_{min})\frac{b_j(t)}{M}, \tag{1}$$

where M is the number of range bins. While this formulation enables efficient 3-D reconstruction, it inherently suffers from elevation ambiguity, which is subsequently resolved by the PS-based pattern interpretation described above.

III. EXPERIMENTS

Water-tank experiments were conducted using an AUV platform to validate the proposed framework, as shown in Fig. 3 and Fig. 4. The experimental setup consists of a controlled water tank environment, an AUV equipped with FLS and PS sensors, and a sloped test object. The AUV collects synchronized FLS and PS measurements, which are used to evaluate the performance of the proposed method.

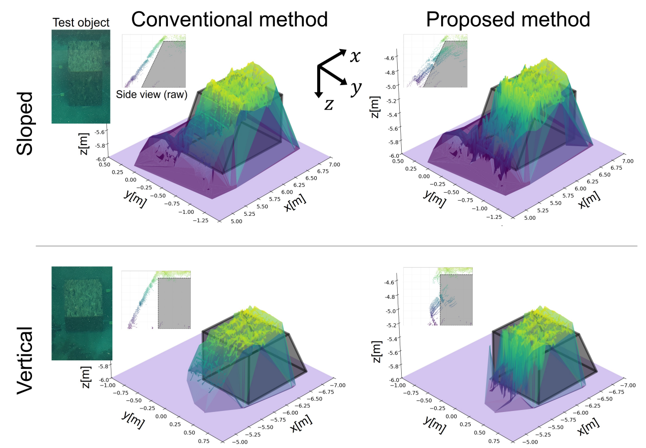


Fig. 5. 3-D reconstruction comparison between conventional and proposed methods for sloped and vertical objects.

TABLE I
COMPARISON OF RECONSTRUCTION ERRORS.

Surface Type	Method	Mean (m)	Median (m)
Sloped	Conventional	0.127	0.108
Sloped	Proposed	0.104	0.086
Vertical	Conventional	0.231	0.136
Vertical	Proposed	0.110	0.092

IV. RESULTS

The experimental results show that the proposed method effectively suppresses falsely inclined surfaces compared to the conventional approach, as illustrated in Fig. 5. The proposed framework preserves the geometric structure of both sloped and vertical surfaces, while the conventional method suffers from significant distortions. Table I further shows error reductions of 18–20% on sloped surfaces and 32–52% on vertical surfaces.

V. CONCLUSION

We proposed a framework that suppresses falsely inclined surfaces by interpreting patterns from profiling sonar and refining FLS-based 3-D reconstruction. This approach preserves valid measurements without requiring trajectory modifications.

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