STUDIES ON UNDERWATER 3D ACOUSTIC IMAGING

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by

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Certificate

This is to certify that the thesis entitled **"Studies on Underwater 3D Acoustic Imaging"** being submitted by **Ms. Nidhi Bisla** to the Centre for Applied Research in Electronics (CARE), Indian Institute of Technology Delhi, for the award of the degree of **Doctor of Philosophy** is the record of the bonafide research work carried out by her under our supervision. In our opinion, the thesis has reached the standards fulfilling the requirements of the regulations relating to the degree.

The results contained in this thesis have not been submitted either in part or in full to any other university or institute for the award of any degree or diploma.

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Abstract

Underwater acoustic imaging (UAI) has become a critical technology in various marine application domains, including oceanography, underwater navigation, environmental monitoring, and defense. The existing imaging systems have contributed significantly but continue to encounter challenges such as high hardware overhead, target ambiguity, limited angular and range resolutions, requirement of platform motion for 3D imaging, signal degradation in noisy or reverberant waters, etc.

In response to these limitations, this thesis proposes a system for underwater 3D acoustic imaging with significantly reduced transducer and electronics hardware complexity compared to planar arrays, while also mitigating target ambiguity commonly associated with Mills Cross receiver configurations. The proposed system is a novel integration of Mills Cross transceiver array architecture with good correlation waveforms, enabling single-shot transmission of all elevation beams, two-step receiver processing involving azimuth beamforming followed by cross-correlation based elevation beam decoding that achieves 3D imaging without platform motion.

To enhance reconstructed 3D image quality, we explored deconvolution techniques. Deconvolution Approach for Mapping of Acoustic Sources (DAMAS), originally developed for aeroacoustics, is the only deconvolution technique known to have been applied in UAI, with a single documented use in the literature to the best of our knowledge. However, it is identified that DAMAS always has one of the following two limitations based on the transmit waveform duration: a long-duration signal improves angular resolution but degrades range resolution, while a short duration signal preserves range resolution but leads to severe image distortion, particularly at the edges of the azimuth and elevation Field of View (FOV).

To overcome these limitations, a novel Linear Frequency Modulated (LFM) pulse based Time Domain Deconvolution (LTDD) method, is developed for planar

receiver arrays. It exploits the pulse compression property of LFM to enhance range resolution, while the long pulse duration ensures sufficient signal overlap across sensor pairs for accurate beamforming, thus improving angular resolution. In contrast, the DAMAS algorithm is not compatible with LFM waveforms due to its non-linear formulation and inherent non-negativity constraint.

The second novel time domain deconvolution technique is tailored for the proposed Mills Cross transceiver based imaging system. The system exhibits high sidelobes in azimuth due to conventional beamforming and even higher in elevation due to additional effect of spatial leakage from adjacent elevation beams. The proposed method mitigates these distortions simultaneously across azimuth, elevation and range dimensions.

In addition to enhancing image resolution, this study addresses the challenge of extending the maximum imaging range under low input Signal-to-Noise Ratio (SNR) conditions. The three deconvolution based image enhancement techniques were found to be effective only above a specific of SNR, beyond which their performance deteriorates significantly. To improve their applicability at lower input SNRs, a sensor-level SNR enhancement method is proposed. This approach is analytically supported by sonar equation analysis, which links environmental and system parameters to the achievable maximum imaging range of the UAI system.

Overall, this research aims to advance the field of 3D UAI by integrating multiple key proposals into a cohesive and unified system framework. The resulting imaging system achieves single-shot 3D imaging with significantly reduced transducer and hardware complexity and reduced target ambiguity, and simultaneous resolution enhancement in all three spatial dimensions while minimizing image distortions through an efficient two-step receiver processing strategy. All the simulation results are verified with the laboratory based tank experiments. The details of the overall work done are documented in the thesis.

सार

जल के नीचे ध्वनिक इमेजिंग (Underwater Acoustic Imaging – UAI) विभिन्न समुद्री अनुप्रयोग क्षेत्रों जैसे कि समुद्र विज्ञान, जल–नीचे नेविगेशन, पर्यावरण निगरानी, और रक्षा में एक महत्वपूर्ण तकनीक बन चुकी है। वर्तमान इमेजिंग प्रणालियों ने महत्वपूर्ण योगदान दिया है, परंतु वे अभी भी कुछ चुनौतियों का सामना कर रही हैं, जैसे उच्च हार्डवेयर आवश्यकताएँ, लक्ष्य अस्पष्टता, सीमित कोणीय तथा दूरी–रेज़ोल्यूशन, त्रिविमीय इमेजिंग के लिए प्लेटफ़ॉर्म गति की आवश्यकता, तथा शोरयुक्त या प्रतिध्वनि–प्रधान जल में सिग्नल की गुणवत्ता में गिरावट आदि।

उपरोक्त सीमाओं के समाधान के रूप में, यह शोध प्रबंध एक ऐसी प्रणाली प्रस्तावित करता है जो त्रिविमीय जल–ध्वनिक इमेजिंग को साकार करती है, जिसमें प्लेनर एरेज़ की तुलना में ट्रांसड्यूसर और इलेक्ट्रॉनिक्स हार्डवेयर की जटिलता को उल्लेखनीय रूप से कम किया गया है, तथा साथ ही मिल्स क्रॉस रिसीवर कॉन्फ़िगरेशन से जुड़ी लक्ष्य अस्पष्टता को भी कम किया गया है। यह प्रणाली मिल्स क्रॉस ट्रांससीवर एरे संरचना तथा उच्च सहसंबंध वेवफॉर्म्स के नवोन्मेषी संयोजन पर आधारित है, जो सभी elevation बीम्स का एकल–संचारण (single–shot transmission) संभव बनाती है। रिसीवर प्रोसेसिंग दो चरणों में की जाती है—पहले azimuth दिशा में बीमफॉर्मिंग और फिर क्रॉस–कॉरिलेशन आधारित elevation बीम डिकोडिंग—जिससे बिना प्लेटफ़ॉर्म गति के त्रिविमीय इमेजिंग प्राप्त की जाती है।

पुनर्निर्मित त्रिविमीय छवि की गुणवत्ता को बेहतर बनाने के लिए, हमने डीकोन्वोल्यूशन तकनीकों का अध्ययन किया। ध्वनिक स्रोतों की मैपिंग के लिए डीकोन्वोल्यूशन विधि (Deconvolution Approach for Mapping of Acoustic Sources – DAMAS), जिसे मूल रूप से एयरोअकॉस्टिक्स के लिए विकसित किया गया था, जल के नीचे ध्वनिक इमेजिंग (UAI) में प्रयुक्त एकमात्र ज्ञात डीकोन्वोल्यूशन तकनीक है, जिसकी अब तक केवल एक ही प्रलेखित उपयोग की जानकारी उपलब्ध है। हालांकि, हमारे अध्ययन में यह पाया गया कि DAMAS के प्रदर्शन में प्रयुक्त प्रेषण सिग्नल की अवधि के आधार पर दो में से कोई एक प्रमुख सीमा अवश्य होती है: यदि प्रेषण सिग्नल दीर्घकालिक हो तो कोणीय रेज़ोल्यूशन बेहतर होता है पर दूरी रेज़ोल्यूशन बिगड़ जाती है; वहीं यदि सिग्नल अल्पकालिक हो तो दूरी रेज़ोल्यूशन बनी रहती है, लेकिन छवि में विशेष रूप से azimuth तथा elevation क्षेत्र (Field of View – FOV) के किनारों पर गंभीर विकृति उत्पन्न होती है।

इन सीमाओं को दूर करने के लिए, प्लानर रिसीवर एरे के लिए एक नवीन टाइम डोमेन डीकोन्वोल्यूशन विधि विकसित की गई है, जो रैखिक आवृत्ति मड्यूलेटेड (Linear Frequency Modulated – LFM) पल्स पर आधारित है, जिसे LTDD कहा गया है। यह विधि LFM सिग्नल की पल्स कंप्रेशन विशेषता का उपयोग कर दूरी रेज़ोल्यूशन में सुधार करती है, जबकि लंबी पल्स अवधि विभिन्न सेंसर युग्मों के बीच पर्याप्त सिग्नल ओवरलैप सुनिश्चित करती है, जिससे बीमफॉर्मिंग की शुद्धता बढ़ती है और कोणीय रेज़ोल्यूशन में भी सुधार होता है। इसके विपरीत, DAMAS एल्गोरिदम LFM वेवफॉर्म्स के साथ संगत नहीं है, क्योंकि इसकी संरचना गैर–रेखीय है और यह एक अंतर्निहित गैर–ऋणात्मकता (non–negativity) बाधा पर आधारित है।

दूसरी नवीन टाइम डोमेन डीकोन्वोल्यूशन तकनीक को प्रस्तावित मिल्स क्रॉस ट्रांससीवर आधारित इमेजिंग प्रणाली के लिए विशेष रूप से डिजाइन किया गया है। यह प्रणाली पारंपरिक बीमफॉर्मिंग के कारण azimuth दिशा में उच्च साइडलोब्स दर्शाती है, तथा elevation दिशा में और भी अधिक साइडलोब्स उत्पन्न होते हैं, जिसका मुख्य कारण समीपवर्ती elevation बीम्स से उत्पन्न स्थानिक रिसाव (spatial

leakage) है। प्रस्तावित विधि इन विकृतियों को azimuth, elevation और range — तीनों स्थानिक आयामों में एक साथ प्रभावी रूप से न्यूनतम करती है।

इमेज रेज़ोल्यूशन को बेहतर बनाने के साथ–साथ, यह अध्ययन निम्न इनपुट सिग्नल–टू–नॉइज़ रेशियो (SNR) स्थितियों में अधिकतम इमेजिंग रेंज को बढ़ाने की चुनौती को भी संबोधित करता है। छवि संवर्द्धन के लिए प्रस्तावित तीनों डीकोन्वोल्यूशन–आधारित तकनीकें केवल एक निर्दिष्ट SNR स्तर से ऊपर ही प्रभावी पाई गईं, जिसके नीचे इनकी कार्यक्षमता में तीव्र गिरावट देखी गई। इन तकनीकों को निम्न SNR स्थितियों में भी प्रभावी बनाने के लिए एक सेंसर–स्तरीय SNR संवर्द्धन विधि प्रस्तावित की गई है। यह दृष्टिकोण सोनार समीकरण (sonar equation) विश्लेषण द्वारा सैद्धांतिक रूप से समर्थित है, जो पर्यावरणीय एवं सिस्टम पैरामीटर्स को UAI प्रणाली की प्राप्त करने योग्य अधिकतम इमेजिंग रेंज से जोड़ता है।

समग्र रूप से, यह शोध कार्य त्रिविमीय जल–ध्वनिक इमेजिंग (3D UAI) के क्षेत्र में प्रगति लाने का प्रयास करता है, जिसमें कई प्रमुख प्रस्तावों को एकीकृत कर एक संगठित और एकीकृत प्रणाली ढाँचे के रूप में प्रस्तुत किया गया है। विकसित इमेजिंग प्रणाली एकल–संचारण (single–shot) द्वारा त्रिविमीय इमेजिंग प्राप्त करती है, जिसमें ट्रांसड्यूसर और हार्डवेयर की जटिलता में उल्लेखनीय कमी के साथ–साथ लक्ष्य अस्पष्टता में भी सुधार होता है। यह प्रणाली तीनों स्थानिक आयामों (azimuth, elevation और range) में एक साथ रेज़ोल्यूशन सुधार प्रदान करती है, और दो–चरणीय कुशल रिसीवर प्रोसेसिंग रणनीति के माध्यम से इमेज विकृतियों को न्यूनतम करती है। सभी सिमुलेशन परिणामों का सत्यापन टैंक प्रयोगों के माध्यम से किया गया है। इस शोध कार्य से संबंधित सभी विवरण इस शोध प्रबंध में प्रस्तुत किए गए हैं।

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Abbreviations

2D	Two-dimensional
3D	Three-dimensional
ACF	Auto Correlation Function
AI	Artificial Intelligence
CCF	Cross Correlation Function
CW	Continuous Wave
DAMAS	Deconvolution Approach for Mapping of Acoustic Sources
DAS	Delay and Sum
DFT	Discrete Fourier Transform
DOA	Direction of Arrival
FLS	Forward Looking Sonar
FOV	Field of View
LFM	Linear Frequency Modulation
LTDD	LFM based Time Domain Deconvolution
MBES	Multi Beam Echo Sounder
ML	Machine Learning
MSE	Mean Squared Error
MUSIC	MUltiple SIgnal Classification
MVDR	Minimum Variance Distortionless Response
NL	Noise Level
PSF	Point Spread Function
RL	Reverberation Level
SL	Source Level
SNR	Signal-to-Noise Ratio
SRR	Signal-to-Reverberation Ratio

SSIM	Structural Similarity Index Measure
TL	Transmission Loss
TS	Target Strength
UAI	Underwater Acoustic Imaging
ULA	Uniform Linear Array

Notations

Notation	Description
$a^{l_r}, a^{l_{r'}}$	range dependent attenuation for a voxel at range l_r from the transmitter, and range $l_{r'}$ from the receiver respectively
$a^{l_{\phi'}}$	attenuation coefficients due to elevation ($l_{\phi'}$) beamforming
A	amplitude of the LFM pulse
$\mathbf{A}^b_{ll'}(k)$	deconvolution matrix for the b^{th} data block in l' voxel direction when the beam is steered towards l^{th} voxel
α	rate of change of frequency of the LFM pulse in Hz/s
α'	absorption coefficient in dB/km
B	number of data blocks in which the recorded signal at each sensor is divided
$B_{MC_r}(\theta,\phi)$, $B_{MC_{tr}}(\theta,\phi)$	beampatterns of Mills Cross receiver and transceiver array in (θ,ϕ) respectively
$B_{pl}(\theta,\phi)$, $B_{ULA}(\theta)$	beampatterns of planar and ULA receiver array in (θ,ϕ) and (θ) respectively
B_w	bandwidth of the LFM pulse in Hz
c	speed of sound in water in m/s
$c^{(l_\theta,l_\phi)}$	scattering constant of a voxel in (l_θ,l_ϕ) direction based on Rayleigh scattering
$\mathbf{C}^b(k)$	Cross Spectral Density Matrix (CSDM) of dimension $J\times J$ for the b^{th} data block and k^{th} frequency bin
C_1, C_2	constants
d, d_d	distance between the adjacent and diagonally opposite corner sensors of a planar array in meter
$\mathbf{d}_l(k)$	steering vector when the beam is steered towards l^{th} voxel
$E_{(l_{\theta_R},l_{\phi_R})}(l_r)$	normalized energy per sample of the cross-correlated output over the l_r^{th} range cell in $(l_{\theta_R},l_{\phi_R})$
E^b_{lX}	energy in the enhanced beamformer output in b^{th} data block when the beam is steered towards l^{th} voxel
E^b_{lY}	energy in the beamformer output in b^{th} data block when the beam is steered towards l^{th} voxel
η_{ULA}	directivity index of a ULA
f	frequency of the transmit pulse in Hz
f_c	center frequency of the LFM pulse in Hz
f_0	initial frequency of the LFM pulse in Hz
F_s	sampling frequency in Hz
$g^{(l_\theta,l_\phi,l_r)}$	parameter representing the presence of an object whose value is 1 or 0 based on the presence or absence of the object surface at (l_θ, l_ϕ, l_r) respectively

Notation	Description
$g_j[n], G_j^b(k)$	expected signal at j^{th} sensor and its DFT in b^{th} data block for k^{th} discrete frequency bin respectively, where $n, k = 0, 1, 2, ..., N_T - 1$
h	vector containing the scattered values of the enhanced voxels only, otherwise 0
I_i, I_s	intensity of signal incident on a facet and scattered by a facet respectively
I_T, I_R	test image and reference image respectively
J', J	number of projectors in transmitter array and sensors in receiver array respectively
k	frequency bin
l_ϕ	voxel no. in elevation, $l_\phi = \lceil(\frac{\phi-\phi_{min}}{\Delta\phi})\rceil$, l_ϕ = 1,2,...,$\lceil(\frac{\phi_{max}-\phi_{min}}{\Delta\phi})\rceil$
$l_{\phi'}, l_{\phi''}$	denotes the elevation beam and waveform number in the designed waveform set respectively
l_r	voxel no. in the range axis, $l_r = \lceil(\frac{r-R_{min}}{\Delta r})\rceil$, l_r = 1,2,...,$\lceil(\frac{R_{max}-R_{min}}{\Delta r})\rceil$
l_θ	voxel no. in azimuth, $l_\theta = \lceil(\frac{\theta-\theta_{min}}{\Delta\theta})\rceil$, l_θ = 1,2,...,$\lceil(\frac{\theta_{max}-\theta_{min}}{\Delta\theta})\rceil$
L	number of voxels, each voxel is represented by (l_θ, l_ϕ, l_r)
λ	wavelength of the transmit pulse in meter
μ_T, μ_R	local means of test and reference image
$n_{b\tau}^{j',(l_\phi)}$	number of samples corresponding to beamforming delay at j'^{th} projector for l_ϕ^{th} elevation beam
$n_{b\tau}^{j,(l_{\theta_R})}$	number of samples corresponding to beamforming delay at the j^{th} sensor when the beam is steered towards the $l_{\theta_R}^{th}$ direction
$n_{T\tau}^{j',(l_\phi,l_r)}$	number of samples corresponding to beamforming delay for l_ϕ^{th} elevation beam
$n_{R\tau}^{j,(l_\theta,l_r)}$	number of samples corresponding to the travel time from the voxel at (l_ϕ, l_r) to the j^{th} receiver sensor
$n_{\tau(l_{\theta_R},l_{\phi_R})}^{j}$	number of samples corresponding to the beamforming delay at j^{th} sensor when beam is steered to $(l_{\theta_R}, l_{\phi_R})$
$n_\tau^{R_j,l_{r(l_\theta,l_\phi)}}$	number of samples corresponding to travel time from a voxel at range l_r in (l_θ, l_ϕ) direction to j^{th} receiver sensor
n_τ^{T,l_r}	number of samples corresponding to travel time from the transmitter T to the voxel at range l_r
N	number of samples in each data block, such that $N.B = N_T$, assuming no overlapping of data blocks
N'	number of samples in the transmit pulse
N_T	number of samples in the signal recorded at each sensor
O	number of samples in the compressed pulse
P_{Watts}	acoustic power output of a projector array in watts
p	proportionality constant for Rayleigh scattering
ϕ, $\Delta\phi$	elevation angle in degree, between ϕ_{min} and ϕ_{max} and elevation angular resolution of a voxel in degree respectively
ϕ_{min}, ϕ_{max}	minimum and maximum elevation angle respectively in the field of view in degree
ϕ_p	initial phase of the LFM pulse
ψ	solid angle defined by the transmit and receive beamwidths

Notation	Description
Q	number of voxels above a fixed threshold chosen for enhancement
r, Δr	range of voxel in meter, between R_{min} and R_{max} and range extent of a voxel/ range resolution in meter respectively
r_1, r_2	distance of the facet from the acoustic projector and from the middle sensor of the hydrophone array respectively
$r_{vv}[n]$	cross correlation of LFM with its delayed version
R_{min}, R_{max}	minimum and maximum imaging range respectively in meter
$s_j[n], S_j^b(k)$	recorded signal at j^{th} sensor and its DFT in b^{th} data block for k^{th} discrete frequency bin respectively, where $n, k = 0, 1, 2, ..., N_T - 1$
S_v	volume scattering strength
$\sigma_T, \sigma_R, \sigma_{TR}$	local variances and local covariance between test and reference image
τ	time delay in sec
τ_d	time delay in the received signals at diagonally opposite corner sensors of the planar array from the edge of the azimuth and elevation field of view in sec
θ, $\Delta\theta$	azimuth angle in degree, between θ_{min} and θ_{max} and azimuth angular resolution of a voxel in degree respectively
θ_1, θ_2	angle between the direction vector of the incident signal and the normal to the facet, and scattered signal and the normal to the facet respectively
$\theta_{min}, \theta_{max}$	minimum and maximum azimuth angle respectively in the field of view, in degree
$u_{(l_{\theta_R}, l_{\phi_R})}[n]$	cross correlation output when beam is steered to $(l_{\theta_R}, l_{\phi_R})$
V	set of designed waveforms
V'	logarithmic volume of the insonified region
$v[n']$	transmit pulse of N' sample length, $n' = 0, 1, 2, ..., N' - 1$
$w_j, w_{j'}$	beamforming weight at j^{th} sensor and j'^{th} projector respectively
$x^{(l_\theta, l_\phi, l_r)}[n']$	signal incident on a voxel at (l_θ, l_ϕ, l_r)
$X_l^b(k)$	DFT of enhanced beamformer output in b^{th} data block when the beam is steered towards l^{th} voxel
$y_j^{(l_\theta, l_\phi, l_r)}[n]$	signal received at j^{th} sensor of the receiver array from a voxel at (l_θ, l_ϕ, l_r)
$Y_l^b(k)$	DFT of beamformer output in b^{th} data block when the beam is steered towards l^{th} voxel
$z_{(l_{\theta_R}, l_{\phi_R})}[n]$	beamformer output when beam is steered to $(l_{\theta_R}, l_{\phi_R})$