Model-based Adaptive Acoustic Sensing and Communication in the Deep Ocean with MOOS-IvP

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Outline

• The Nested Autonomy Paradigm
  • Integrated Sensing, Modeling and Control
  • Payload Autonomy
• Sensor-based environmental adaptation
  • Noise-interference optimization
• Model-based environmental adaptation
  • Shallow water communication connectivity
  • Deep ocean acoustic environment
  • Autonomous depth adaptation for maintaining connectivity
Undersea Distributed Sensing Networks
Communication Infrastructure

Field Control
- Modeling
- Mission Control
- Planning/Scheduling

Clusters
- Collaboration
- Convergence

Nodes
- Modeling
- Sensor Processing
- Navigation
- Autonomy
- Actuation/Control

Hardware
- Sensors
- Actuators

Operator

Radio Link
- 10 KBytes (/30 minutes)

ACOMMS
- 100 Bytes (/1 minute)

Platform

Ethernet
- 100 MBytes / second

Sensor Process

Artifact Sensor

Environ Sensor

Nav Sensor

Autonomy

Actuation
Nested Autonomy
Command and Control Architecture

• Network Command and Control
  • Managed through communication gateways via RF above sea level and acoustic communication (ACOMMS) underwater
  • The underwater ACOMMS connectivity organized through a slotted MAC scheme with self discovery and organization

• Clusters
  • Autonomous platforms and acoustic gateways with current ACOMMs connectivity will self-organize through distributed control into clusters exploiting collaborative behaviors for improved sensing performance
  • Dynamic clustering topology depending on current ACOMMS connectivity

• Platforms
  • Each platform must be capable of completing mission objectives in absence of communication connectivity
  • Each platform will broadcast status reports at regular intervals in the communication slot assigned by its current cluster
What is Intelligent Autonomy?

Integrated Sensing, Modeling and Control

Automated processing of sensor data for detection, classification and localization of tactical or environmental event

Data-driven modeling for forecasting of tactical and environmental situation

Intelligent decision-making based on situational awareness, adaptive and collaborative strategies (behaviors), and learning, to adapt to forecast for enhanced performance
Payload Autonomy Architecture
Integrated Sensing, Modeling and Control

Main Vehicle Stack
‘Frontseat Driver’
Low-level Control
Navigation

‘Backseat Driver’
Autonomous
Communication, Command and Control

Helm
Autonomous Decision Making

Payload Autonomy System

‘Backseat Driver’

Tracking
Localization
Classification
Detection
Array Processing

Acquisition

NMEA
Data Bus

BF Huxley
Huxley Interface
AcommsHandler
Communication
Expanded CCL

Sensors
Actuators

Sensors

BF Huxley

Autonomous Marine Sensing Systems
Model-based Environmental Adaptation

On-Board Estimation of Ambient Noise Directionality
MOOS-SEALAB Simulation

Objective
Minimize ambiguous beam power
Model-based Environmental Adaptation

Mission Manager

![Graph showing ambient noise vs. depth and range average sound pressure level (SPL)]

Collaborator @ 45 km

![Graph showing depth and incidence angle (θ)]

Modem Configuration

Platform Mode

Mission Constraints

Modem

IVP-Helm

Depth Objective Function

![Graph showing depth (m) vs. utility]
Environmentally Adaptive ACOMMS Connectivity

GProf08 Jul 31 2008 CTD 16:10 UTC | Messages: 12:16-19:41 UTC

“reachable” space given current heading

current position

possible best path (and stay at this depth?)

buoy
Connectivity-Optimal Survey Path
GLINT’10 – Adaptive ACOMMS

In-situ SVP

On-board Ray-trace Modeling (Bellhop)

Topside Situational Display
Exploiting Environmental Acoustics

- Environmental Focusing
- Vertical Beamforming
  - Range scanning
  - Optimize Detection performance
- Depth mobility
  - Synthetic aperture
  - Control range and depth focus
  - Performance/Persistence tradeoff

MIT Laboratory for Autonomous Marine Sensing Systems
Deep Ocean Environmental Adaptation
Communication and Navigation

Environmental Adaptation

ACOMMS

RF

Variable Latency

Environmental Focusing

$c(z)$

0 – 60 km

MIT Laboratory for Autonomous
Marine Sensing Systems
Deep Ocean Environmental Adaptation Persistence

Current profile

Environmental Adaptation

Vertical Mobility

RF
Optimal VLA Depth Analysis

Full Angular Spectrum Signal and Noise Modeling

Array Performance exploiting vertical mobility
Deep Ocean Communication Connectivity

- Adaptive Communication Connectivity
  - Establish Connection: Elevate/dive to depth with minimum ambient noise level and loiter until connectivity is established
  - Maintain Connectivity: After connection established, maintain depth and track collaborator until range exceeds ~15 km, then change depth dynamically to minimum transmission loss predicted for collaborator track.

Transmission Loss

- Target depth: 200 m
- Target speed: 16 kn
- Frequency: 800-1000 Hz
Deep Ocean Communication Connectivity

AUV with Towed array

Collaborator Range 15 km

Collaborator Range 45 km

Upper depth limit 2000 m

Target
16 knots
125 dB
Heading 135
Depth 200 m
Range 15 km

Upper depth limit 2000 m
Depth Utility Function

- Depth-filtering of utility function
  - Avoid non-symmetric caustics – Must stay on ‘good side’
  - Filtering consistent with statistics of environmental acoustics

Deep Ocean Communication Connectivity
Deep Ocean SNR Statistics

SVP/SD Variation:
- Black: Minimum
- Green: Maximum
- Red: Mean

Robust Depth Adaptation
Caustic
Summary

• The deep ocean sound speed is stable temporally and spatially and the associated environmental acoustics is robustly predictable.
  • Below the SOFAR channel, the dominant environmental acoustic effect is the pressure gradient.
  • The near-surface environmental variability is relatively insignificant to the deep refracted acoustic paths, in particular for systems operating below or at the critical depth.
• Significant acoustic system performance gain can be achieved by depth mobility
  • Ambient noise level changes significantly with depth, with minimum below the critical depth.
  • Depth-dependent, vertical noise directionality may also be exploited for sonar and communication performance gain.
• Helm-IvP ideal for developing environmentally adaptive acoustic sensing and communication networks
  • Behaviors based on scaled version of TL, NL or SNR have been developed and validated in both simulation and field deployments.