MASA: a Multi-AUV Underwater Search and Data Acquisition System

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Abstract. **Nekton Research is developing a cooperative multi-UUV system. This system, MASA, will allow 3-D searches and data collection with high spatial and temporal resolution in both inshore and near-shore environments. This paper discusses MASA's design.**

I. INTRODUCTION

The concept of using N vehicles to execute an underwater task can be traced back to Curtin's seminal work in 1993.[1] The basic premise, that N vehicles can execute a task faster and/or with better spatial resolution than a single vehicle, is a powerful idea whose benefits are expected to be particularly high for time-sensitive missions.

Historically, the two key impediments to implementing an underwater N-vehicle system have been cost and reliability. Due of recent advances in micro-UUV technology, the first obstacle is largely out of the way.[2] The second factor is much less severe now than it was a decade ago, as witnessed by the steady increase in the number of UUV missions per year.[3] With these obstacles out of the way, the time appears ripe for fielding a multi-UUV system.

Spectacular progress has happened in the fields of aerial and terrestrial multi-vehicles systems.[4,5] This progress is the result of combined advances in GNC, path planning, coordination, communication, strategy, and a sustained experimental effort. Given the impact multi-agent systems are having in current military operations, it is easy to imagine the impact they will have underwater.

An example that clearly illustrates these benefits is Mine CounterMeasures.[6-7] Consider the classification problem, where the locations of the targets are known a-priori. A single vehicle could travel to each targets and perform identification. Because the path connecting the mines is one-dimensional, a single of point of failure, for example an unusually long target identification or a vehicle failure, jeopardizes the overall success of the mission. Consider now a group of vehicles that runs an algorithm where every vehicle picks the nearest unvisited target, then signals its choice to the group and proceeds to that target.[7] While a vehicle might be trapped at a target, other vehicles take over the remaining targets. Thus, this way of proceeding is not only faster, but also immune to individual vehicle failures.

It is crucial to realize that the aquatic environment is fundamentally different from the terrestrial or the aerial one: (i) navigation is an uncertain proposition, (ii) communication has a low bandwidth, and (iii) the sensing range is limited by the medium. Thus, it is not clear whether the aerial /terrestrial methodology is appropriate to underwater systems. In fact, all indications are that underwater systems will have to be approached from a fundamentally different direction.

Some recent work in underwater algorithms,[8] software architecture,[9] group behavior,[10] and communication protocols[11] tackles some of these issues. Unfortunately, this work is taking place in the abscence of experimental support,[12] making it near-impossible to measure its relevance.

Nekton is developing a system that will provide concrete answers to some of these questions. This system, the cooperative Multi-AUV Search Array (MASA) is an N-agent underwater system, where each vehicle is not only capable of autonomy, but also of sharing, accepting, and responding to real-time data with/from the other vehicles. This potent combination opens the door to the three fundamental multi-agent handles, i.e. the abilities to control group geometry, to share data, and to react collectively. For this reason, MASA paves the way to a host of underwater applications ranging from distributed search algorithm research (MCM, lost asset search), to formation flying (beam forming and flexible array), and to general oceanography (bathymetry, mixing studies, search/localization/characterization of underwater plumes, etc).

II. DESIGN

The components of MASA are best illustrated on a search and localization scenario (Figure 1). A lost asset lies on the seabed and a standard 27 kHz pinger signals its location. The objective is to locate the asset in minimum time. To accomplish this mission, a groups of micro-UUVs and a set of acoustic buoys are deployed, possibly by helicopter, near the best estimate of the asset's location. The micro-UUVs are each equipped with a pinger detector and each capable of acoustic

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navigation and inter-agent acoustic communication. Each vehicle runs a multi-agent search algorithm, i.e. an algorithm that incorporates each vehicle's own data and all transmitted data. By sharing their data, the vehicles are able to home-in on the pinger faster than a single vehicle would. The location of the asset is then transmitted to the search and rescue team, and MASA is recovered.

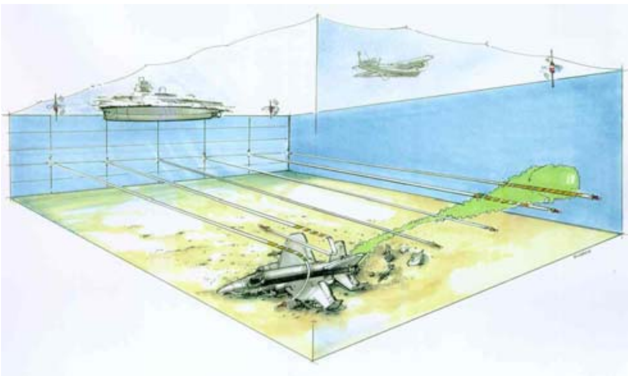

Figure 1: Schematics of MASA. The application depicted here is a search and localization mission. The lost asset lies on the seabed with its 27 kHz pinger on. MASA is deployed, possibly by helicopter, near the best estimate of the asset's location (transponders in cyan and gold, vehicles in yellow). The Rangers then execute a coordinated search, and quickly home-in on the pinger. The XY-depth of the asset is then transmitted to the search and rescue team, and MASA is recovered. The transponders can be either moored of floating: the picture depicts the moored case.

The three key elements of MASA are the micro-UUVs, the localization/communication system, and the search algorithm. We discuss the design of the first two and the command interface.

II.1. RANGER

Ranger was designed to cater to two groups of users: single-vehicle users (Figure 2) - typically environmental monitoring agencies-, and multi-agent researchers (Figure 3). These users have very different needs, portability, ease of use, and sensor expansion in the first case, and communication, reliability, and processing power in the second.

To meet these needs, we have incorporated the following features into Ranger:

Sensors

- CTD standard.
- Options for DO, nitrate/ntrogen, PH,turbidity, chlorophyll α, and rhodamine.
- Reconfigurable logic to allow complete flexibility for sensor expansion (analog i/o, RS232, RS422, IrDA, parallel, synchroneous serial, FireWire; ethernet and USB are being developed).

Software

- The software architecture features an internal and an external layer. The internal layer is state-based, where each state is a collection of behaviors. Behaviors include specific guidance algorithms, vehicle control, navigation, low level control, and condition monitoring. The external layer handles user interfacing.

User Interface

- Graphics User Interface for dynamic retasking, download, upload, monitoring (see Section II.2).
- Same for multi-vehicle systems.
- APIs to permit integration of user-defined algorithms.
- 880Kbps RF link for surface communication.

Processing Power

- 900 MFLOPS DSP chip. The TMS32C60711 runs a RTOS. It has built-in support for threads, C, libraries for image recognition, 32M RAM, 128M disk partitioned into 64M of code space and 64M of data space.
- Low power (1/6 of PC-104).

Reliability

- Modular vehicle: Ranger's three sections, nose, tail, and middle, are independent and free of external wires.
- Internal recharging system.

Portability

- Ranger is 10lbs, 80cm-long, and has a 9cm hull
- The hull is free of control surfaces

Inter-Agent Communication

- WHOI's acoustic micro-modem. This modem is inter-operable, and it supports active and passive SBL/LBL localization, in parallel with 30-100bps acoustic communications.

Figure 2: Ranger is a 9cm hull UUV. It uses a stern-mounted, two-axis vectored-thruster for propulsion and control; otherwise it has no fins. Ranger is passively stable in pitch and roll, and trimmed to have slightly positive buoyancy. Ranger comes equippped wit h CTD sensors, and can accept up to three additional environmental sensors.

Maneuverability

- Ranger features a 2-axis vector thruster that allows is to to turn at 90 degrees/s.

Guidance

- The guidance algorithms currently implemented on Ranger are line-of-sight and track following.

Navigation

- Ranger uses passive acoustic navigation, a depth sensor, and a 3-axis compass accurate to 1, 0.3 and 0.3 degrees in yaw, pitch, and roll respectively. Between acoustic fixes, navigation is done by dead-reckoning. Dead-reckoning accuracy is improved with a 3-state Kalman filter.

Controls

- Ranger is passively stable in pitch and roll, and trimmed to be slightly positively buoyant. Heading, pitch, and depth are all controlled by PID controllers.

Figure 3: A 2-Ranger launch. Because of its light weight, robustness, and processing power, Ranger is well suited to multi-vehicle applications.

Geometry	9cm diameter
Actuators	Vectored Thruster
Guidance	Conventional
Nominal Speed	2 knots
Turning Radius	1.5m
Available Power	172Wh
Range	15+km
Duration	4+hours
Processing	900 MFLOPS
Communication	Acoustic 30-100bps, RF 880kbps
Nav. Sensors	Compass, depth, SBL/LBL
Data Storage	64Mb, expandable to 2Gb
Sampling Sensors	CTD standard. opt'l: DO, nitrate/ntrogen, PH,turbidity, chlorophyll α, rhodamine
Accessories	Lights, closed-hull recharging/RF comm

Table 1. Ranger specifications

II.2. COMMAND INTERFACE

The external layer is called FLICS (Fleet Level Interface and Control Software). FLICS is a GUI that gives the user the ability to monitor and to control the fleet (Figure 4). FLICS has built-in functionality for

- Changing mission parameters on the fly (dynamic retasking).
- Issuing fleet or vehicle-level commands such as START, STOP, GOTO XYZ, ABORT
- Performing software upload, data download.
- Monitoring the state of individual vehicles.

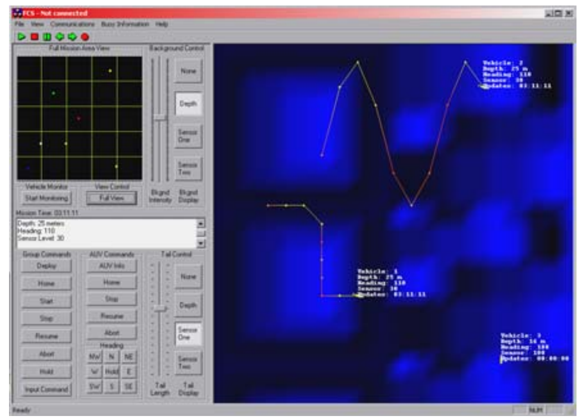

Figure 4. FLICS gives the user the ability to interact with the fleet. FLICS features three master panels: Top left: overall view of all vehicles and objects of interest; Right: zoom and vehicle selection panel; Bottom left: control commands.

II.3. POSITIONING/COMMUNICATION

Currently, the only realistic means of achieving inter-vehicle communication are acoustic. Magnetic communication, although showing rapid progress, is not yet commercially available; it is also too bulky for small UUVs.[13] Blue-green Lasers/LEDs, although theoretically capable of megabaud rates, are range-limited and are still at the conceptual stage.[14]

MASA uses WHOI's C-band 25kHz acoustic micro-modem both for positioning and communication. The accompanying amplifier and processing boards are small enough to fit inside Ranger. The transducer ring is mounted below the hull.

Positioning/communication is done with five buoys, a master and four secondaries (Figure 5). The master has dual usage: (1) it synchronizes nav/comm, and (2) it interfaces with the user, i.e. acts as data relay between the fleet and the user.

Because MASA relies on the C-band, the communication range is limited to 500-1000m; this limitation is not intrinsic to MASA however, since acoustic navigation could be replaced by periodic GPS fixes.

Positioning. One of the requirements on any N-agent supporting technology is that perfomance should not degrade with the number of agents. Thus, we use hyperbolic passive acoustic positioning. The localization protocol is the following: 1) the master pings; 2) the secondaries respond; 3) each Ranger uses the 4 TDOAs and its depth sensor to reconstruct its position. Preliminary tests of the positioning system suggest that the positioning error will be on the order of a few meters.

Communication. Agents talk to each other acoustically. In anticipation of very shallow conditions, we are purposefully using a low inter-agent communication rate. In these conditions, the key communication problems are noise and reverberation; to further exacerbate the problem, the bandwidth has to be shared amongst agents. To maximize communication reliability, MASA uses the following scheme: 1) the master buoy selects and broadcasts the identity of the next vehicle to transmit data; 2) all vehicles are quiet unless instructed to talk.

We note that except for the convenience and reliability of having constant line of sight with the master, there are no conceptual problems giving communication authority to the fleet.

Communication and localization are done with the same hardware, i.e. the modem. Given the existing transmission rate and packet size of the model, data transmission bursts take 4s. Localization takes approximately 2s. Consequently, the rate of data acquisition is ~5000 points per hour, and the rate of localization is ~ once per 6s.

III. STATUS

As of this writing, the status of MASA is the following:
(1) Three of the 10 Rangers have been built, assembled, and tested; the other seven are now being assembled.
(2) The C-band ping detection software is being tested by WHOI and is slated for integration to the system shortly.
(3) A multi-agent search and localization algorithm has been designed by Sandia National Laboratory and is being tested in simulation. This proprietary algorithm grafts the features of extended spatial coverage onto the gradient search methodology.
(4) System integration tests are slated to take place during Fall 02/Spring 03.

MASA is to our knowledge the first system of its kind; as a consequence, its potential is still largely unknown. This offers innumerable opportunities for investigation, particularly in the areas of mine localization, mine identification, ship and port patrolling, networking, adaptive array forming, adaptive mapping, autonomous navigation, multi-agent strategy, including symmetric and asymmetric asset properties, ocean characterization (bathymetry, mixing studies, localization and characterization of underwater plumes, etc), plasticity of social structure, etc. Nekton strongly welcomes opportunities for collaborative research in all areas of impact of this fascinating new tool.

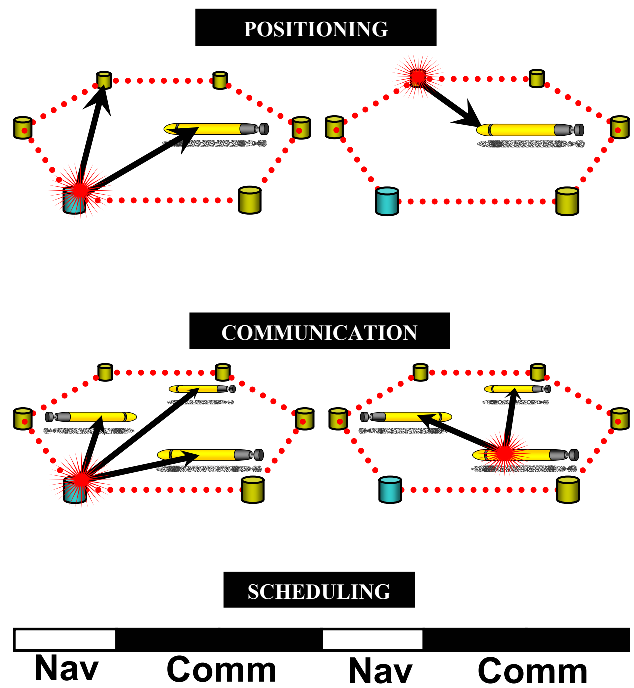

Figure 4: Positioning/communication protocol. Top: positioning. The master (cyan) transmits a primary broadcast, which triggers a secondary broadcast by the slaves (gold). These broadcasts are all received by the vehicles. Middle: communication. The master selects a vehicle for data sharing and broadcasts its choice. The vehicle that is selected broadcasts its data to the other vehicles. Bottom: scheduling. Positioning bursts (white) are interspersed between communication bursts (black).

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