MICRO-AUVS I: PLATFORM DESIGN AND MULTI-AGENT SYSTEM DEPLOYMENT

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1. Introduction

Distributed AUV systems present unique opportunities and challenges arising from exploiting the massively parallel nature of data collection. These challenges come from having to coordinate a swarm of distributed nodes with limited flexibility with regards to bandwidth, power, mobility, payload, and processing.

Starting in 1998 under DARPA support, Nekton Research has worked toward the deployment of an underwater multi-agent system (MAS). This effort is partitioned into two phases. The first phase, now complete, focused on the development and testing of underwater distributed robotic platforms. The second phase, now underway, is aimed at the deployment of the underwater MAS.

This article is an interim report, and is organized as follows. In section 2 we discuss the design and performance of MicroHunter™, a helically traveling, single-actuator MicroAUV. In section 3, we discuss the design of Ranger™, a vectored-thruster MicroAUV. Our on-going efforts toward deploying an underwater multi-agent system are discussed in Section 4.

2. MicroHunter

A central factor in the design of any underwater multi-agent system is system cost. System cost is determined by the cost per agent and by the cost of deployment of the system. Cost per agent is important because it determines the number of agents that are deployed, which in turn determines speed and resolution of the data collected. In order to reduce the logistical overhead and minimize the individual agent cost, a decision was made to minimize vehicle size while maintaining functionality.

Reducing the size of each agent introduces many technical challenges:

- *Actuators*: size affects the number and efficiency of actuators that can fit inside the vehicle.
- *Availability of COTS components*: size affects the number of commercially available components that will fit inside the hull.
- *Sensors*: size severely limits the number and accuracy of sensors, both for navigation and for data acquisition.
- *Power*: available power scales as the third power of hull diameter.
- *Processing*: reducing processor size decreases the processing that can be done on-board.
- *Packaging*: the difficulty associated with fitting actuators, sensors, batteries, and processors inside the hull increases substantially when size decreases. For small AUVs, the difficulty is compounded by the constraint of maintaining vehicle trim.
- *Noise Interference:* noisy motors, amplifiers and acoustic transmitters are

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very close to sensitive sensors, e.g. compass.
- *Control*: the degree with which MicroAUVs can be controlled depends on the number of actuators, quality of sensor feedback, and magnitude of disturbances.

As size decreases, the coupling between these factors increases. We have found that below a certain threshold, a departure from conventional AUV design approaches is needed in order to accommodate these factors. The key to our size-reduction effort is to: 1-reduce the number of actuators, 2-use custom-electronics to minimize the footprint, and 3-to use underactuated vehicle control algorithms.

2.1. Design

A helically traveling object is able to change its heading by simply modulating propeller speed [1-5]. This observation can be turned into a guidance algorithm by appropriately coupling external stimulus to propeller speed. This is the heart of Helical Klinotaxis (HK), Nekton's proprietary single-actuator guidance algorithm (Figure 1).

Figure 1: From left-to-right, M3, M4 and M5 MicroHunters.

Because MicroHunters use a single actuator, we have been able to shrink hull size considerably. We have built three versions: the *M3* is a 2.5cm diameter hull vehicle aimed at demonstrating that guidance with a single actuator is possible; the *M4*, a 5cm diameter vehicle, aimed at showing that data collection at a controlled depth and heading is possible; the *M5*, a 1cm diameter vehicle used for dynamic performance evaluation.

Geometry	<5cm diameter
Actuators	One Propeller
Guidance	Helical Klinotaxis
Gross Trans'l Speed	1-1.2m/s
Turning radius	Body length
Available Power	29Wh
Range	17-30km
Duration	4-20hours
Payload	Variable
Processing	20MHz PIC
Communication	Acoustic 30-100bps, RS232 thru-hull
Nav. Sensors	Compass, depth
Data Storage	8Kb, expandable to 256Kb
Sampling Sensors	CTD, light, other sensors opt'l
Accessories	Lights,SBL and LBL tracking

Table 1: Technical description of MicroHunters.

2.2. M3

The M3 has a 2.5cm hull and weighs 75g. Its nominal cruise speed is 1kt. Its mission duration per charge is 20h. The M3 is a proof-of-concept proof of concept vehicle, built to demonstrate the validity of single-actuator guidance. To achieve this, the M3 was equipped for light tracking.

The performance of the M3 was assessed during DARPA-supervised pool trials. Pool dimensions were 20mx10mx3m. Tests were performed to measure the vehicle's ability to 1) detect-and-home, 2) detect-and-home to a degraded signal, 3) penetrate a guarded volume, and 4) escape from a trap. Test outcomes were as follows:

1) *Detect-and-Home.* Multiple M3's were released in a 10m×10m×3m volume, for more than 100 trials, at initial orientations including on-heading, ±30° off-heading, ±45° off-heading, ±90° off-heading, and 180° off-heading with respect to an 800W Thallium light source placed along the volume's perimeter, aiming into the volume. Initial tests showed that the M3 reliably and repeatedly homes in on the light source with an accuracy of ±0.3m within ±2-sigma. Approximately 25% of the trials were conducted with obstacles and traps in the volume. Refined algorithms improved the accuracy to ±0.1m.

2) *Detect-and-Home to a Degraded Signal*. This test measured the M3's ability to find and maintain a light-intercepting trajectory to a degraded source. The degraded light source, a 250W Halogen light encased in a diffuser, exploited less than 10% of the sensor's dynamic range. Our tests showed that even in this case, the M3 homes-in on the target 90% of the time (compared with 100% in test 1).

3) *Penetration of a Guarded Volume*. We set up two concentric circles, (inner circle radius = 1m; outer circle radius = 2m) and put the degraded light source inside the inner circle. A US Navy SEAL was charged with protecting the light while remaining between the two circles. Upon interception of a vehicle, the SEAL could throw it back in the water, >8m away. Each trial could last until any one of four M3s penetrated the inner circle or 180 seconds have elapsed. The SEAL was allowed a 120 second rest period between trials. We find that the percentage of successful penetrations was 50%. Interestingly, this is achieved without agent coordination. Substantially higher rates are expected with coordination, longer trial times or additional agents.

4) *Escape from a Trap*. This test measured the M3's ability to escape from a trap. We placed multiple 5-gallon traps (horizontal buckets) at the bottom of the pool, and release M3s into their interiors 50 times. We recorded the probability of escape and the time to escape. Our tests showed that the escape rate is 100%, and that the escape time is, on average, 20s.

2.3. M4

After successful demonstration on the M3, vehicle capabilities were augmented to incorporate the ability to swim at depth and heading, collect environmental data and support acoustic tacking and communication. The M4 has a 5cm diameter hull and weighs 700g. Like the M3, the M4 uses HK, however, in addition to the ability to detect-and-home to a light source, it also uses inputs from a 3-axis magnetometer, a 3-axis accelerometer, and a depth sensor. It supports SBL and LBL tracking, is outfitted with temperature and conductivity sensors, and is capable of logging CTD data. Vehicle trim (displacement, pitch and roll) can be adjusted externally. Technical details are shown in Table 1.

Field trials were performed in an inland lake that is roughly 200m x 300m x 30 m deep. Test results are as follows:

- Tracking Maintenance. The M4 repeatedly maintains target depth and heading with an accuracy of 30cm and 2º respectively.
- Target Acquisition. The turning speed at 2 knots is 20º/s. The maximum diving angle is 90º (a sharp contrast to conventionally controlled AUVs).
- The M4 was able to successfully navigate a number of set trajectories

(alternating depth on-heading, alternating heading on-depth, etc).

- We were able to track the vehicle acoustically from the surface.
- We were able to log CTD data.

Due to its electro-mechanical simplicity, the M4 has proven to be a reliable and simple system to operate. In the near future, as sensor size decreases, we expect the M4 class of MicroHunters to become a valuable vehicle platform.

3. Ranger

In an effort to provide increased user payload and improve sensor accuracy, we developed a second class of MicroAUVs. Rangers are MicroAUVs aimed at performing massive decentralized data collection (Figure 2). Ranger has a 9cm diameter hull and weighs 3.5kg. It is passively stable in pitch and roll, and trimmed to be slightly positively buoyant. Ranger is equipped with an off-the-shelf (OTS) compass and a YSI multi-sensor array. Ranger is equipped with WHOI's acoustic micro- modem, which supports both active and passive SBL/LBL localization in parallel with acoustic communications at 30-100bps. It is also equipped with an 880kbps RF link for surface communication. Technical details on Ranger are shown in Table 2.

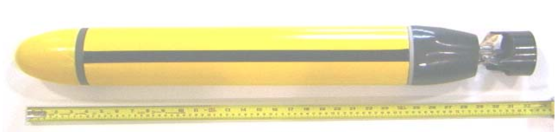

Figure 2: 9 cm-diameter Ranger.

The 9 cm diameter hull of Ranger opens the door to a wider palette of actuator/control strategies. In anticipation of multiple vehicle deployments, we tried to avoid outboard control surfaces, which would reduce the packing factor of clusters of vehicles. Additionally, concerns over low speed maneuverability and the risk of entanglement weighed against control surfaces. A single, stern-mounted, two axis vectored-thruster was chosen. A comparison of vectored thruster control with HK is shown in Table 3. The table shows that the turning/speed/disturbance rejection performance of a passively horizontal, vectored thruster vehicle is superior to that of a HK based vehicle.

Ranger is currently undergoing performance testing. Data will be reported as it becomes available.

Geometry	9cm diameter
Actuators	Vectored Thruster
Guidance	Conventional
Gross Trans'l Speed	1-1.5m/s
Turning radius/speed	< body length
Available Power	172Wh
Range	30+km
Duration	8+hours
Payload	Variable
Processing	150MHz DSP
Communication	Acoustic 30-100bps, RF 880kbps
Nav. Sensors	Compass, depth, SBL/LBL, opt'l IMU
Data Storage	64Mb, expandable to Gb
Sampling Sensors	CTD, YSI sensors opt'l (DO, nitrate/ntrogen, PH, turbidity …)
Accessories	Lights, closed-hull recharging/RF comm

Table 2: Technical description of Ranger

4. Multi-Agent System Deployment

The rationale for using MicroAUVs in distributed data collection is to exploit their small size and low cost in order to improve the speed and resolution of data acquisition. The first phase of our MicroAUV effort has served to demonstrate that reliable MicroAUVs can be fielded. The next phase is a demonstration of multi-agent behavior.

Attribute	Helical Klinotaxis	Vectored Thruster
Sensor Arrays	• Minimum # of elements (including single pixel) • Scan & mosaic in roll, pitch & yaw	•Sufficient elements to achieve desired static field of view • Scan & mosaic limited mostly to yaw
Control	• 1 actuator – screw • Minimal; analog electronics • Reactive, low-level	• 3 actuators – screw/2 servos • Digital electronics • Low- & high-level
Size/Cost	• Extremely small/low-cost • Permits high-density MAS	• Very small/low-cost • Permits mid-density MAS
Ideal mission type	• Fire-and-forget • Moderate range • Low ded-reck'g reliance • Anti-submarine warfare, psy-ops, illumination, Real-time ISR, enemy asset tagging & neutralization, etc.	• Launch & recover; round trip • Medium- to long-range reliance • Real-time & remote ISR, psy-ops, in-port-ship-protection, lost survivor & asset location, etc.
Logistics	• High sensitivity to trim (pitch & roll) & buoyancy	• Long-term dive angle limited to <90°
Telemetry	• Required if tracking & real-time DAQ	• Aids tracking & real-time DAQ

Table 3: Comparison of Helical Klinotaxis with Vectored Thruster control.

The Lost Survivor and Asset Location System (LSALS) program is a DARPA-sponsored collaboration between Nekton, Sandia Labs and WHOI. The objective of the program is to develop a multi-agent system capable of localizing the source of an underwater plume, such as the fuel trail coming from a downed helicopter. The system consists of multiple Rangers (8-15), each capable of passive acoustic localization, sensing, & inter-agent communications, acting cooperatively to accelerate the mapping of a plume.

This program is currently underway. Data will be reported as it becomes available.

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