BathyBoat: Autonomous Surface Command & Control for Underwater Vehicle Networks

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***Abstract*—This paper reports the preparation of two modified Ocean-Server AUV systems and the construction of a new autonomous surface vessel (ASV) for cooperative simultaneous localization and mapping (SLAM) research at the University of Michigan (UMich). The Marine Hydrodynamics Laboratories (MHL) has designed and fabricated the new ASV BathyBoat to serve as a targeted remote sensing platform and a mobile command and control center for underwater search and survey activities performed by UMich Perceptual Robotics Laboratory (PeRL) AUVs. The ASV is outfitted with a suite of sensors including a RadarSonics 250 acoustic depth sensor, Garmin WAAS-enabled GPS, Honeywell HMR3300 digital compass and accelerometer, Vernier CON-BTA conductivity probe, a WHOI Micro-Modem for two-way communication with the AUVs, and other sensors discussed subsequently. Wireless data transmission from the surface offers the ability to monitor, in real-time, the state of the AUVs. In addition, updated mission objectives can be relayed, from ship or shore, through the ASV for mid-mission adjustments. Ongoing scientific and engineering research objectives are discussed, along with an overview of the new autonomous surface vessel and a summary of field trials on the North Slope of Alaska.**

I. INTRODUCTION

Within the last decade, researchers have become increasingly reliant on teams of cooperative autonomous vehicles to survey and search environments more efficiently than using a single vehicle [1]–[3]. Swarm robotics gained a large following in the land-based variant, and heterogeneous vehicle networks soon followed. Current vehicle networks use air, sea (and subsea), and land-based vehicles to achieve various mission goals in ever decreasing time. Some of these networks even organize themselves automatically [4].

As the complexity of these networks increases, reliability becomes an issue. The University of Pennsylvania's General Robotics, Automation, Sensing and Perception (GRASP) Laboratory [5], and the University of Tennessee's Distributed Intelligence Laboratory [6] are actively researching reliability issues of self-organizing teams of heterogeneous vehicles in hostile environments . By leveraging architectural, behavioral, and functional models of groups known to biologists, researchers hope to develop new algorithms for multi-vehicle coordination and control.

Fig. 1. BathyBoat testing at the Marine Hydrodynamics Lab.

Princeton University [7] is experimenting with Webb Research Corporation Slocum Gliders to investigate control of underwater glider fleets. In the field trials, each vehicle relied on inertial navigation (dead-reckoning) techniques, surfacing every two hours to obtain a GPS fix and correct any accumulated drift errors in the position estimate.

Similarly, the Virginia Tech Autonomous Systems and Controls Laboratory (ASCL) is studying coordinated control of multiple vehicles over extremely low bandwidth communication networks such as acoustic modems [8]. The goal of this research is to devise new strategies for message-passing and directive issuance in underwater environments where current technological limitations prevent high-speed communication. The ASCL currently uses small AUVs with a diameter less than approximately 12cm (5in) with onboard GPS, at the surface, and dead-reckoning underwater for navigation in their research.

The University of Portugal and others have constructed and tested several heterogeneous cooperative systems in real-world scenarios comprised of AUVs, ROVs, ASVs, and UAVs. In 2006, the group conducted swarm field trials in Monteray Bay using a Hydroid Remus vehicle and the Naval Postgraduate School's ARIES vehicles [9]. Communication between vehicles was conducted through acoustic links.

The cost of these missions can run into the hundreds of thousands of dollars per deployment due to the logistical requirements to support such large vehicles. Also, environmental factors such as limited access, federally protected land, or hostile environments (extreme temperatures) make the use of these systems at many locations very difficult, if not impossible. The staggering cost of shipboard time ($20k-$40k per day) is enough to halt many projects even before deployment.

Engineers at the University of California San Diego (UCSD) are using a different approach to solve the same class of problems. The UCSD team was recently awarded a National Science Foundation (NSF) grant to explore an underwater, Lagrangian (drifting) buoy network which communicates via acoustic modems. This system has the capability to perform higher spatial and longer temporal scale sampling than conventional methods, but at the cost of deploying tens to hundreds of devices at many locations.

The basic challenges each of the above projects are faced with are transportation and logistics, cost of vehicles, and communication between vehicles. In order to meet these design constraints, the UMich MHL has partnered with Michigan Tech. Research Institute (MTRI) to design and construct a small, low-cost ASV (see Figure 1) for remote bathymetric surveys and distributed ocean-sensing. In addition to hosting a full suite of environmental sensors, the new ASV (BathyBoat) also serves as a command and control station for underwater vehicles through the use of its onboard electronics and acoustic communications package. The BathyBoat communicates with the PeRL Iver2 (see Figures 2 and 5) vehicles by sending either mission commands or status requests. Each vehicle can be polled within the status request framework, and the results used to optimize SLAM solutions or to assist in mission decision-making.

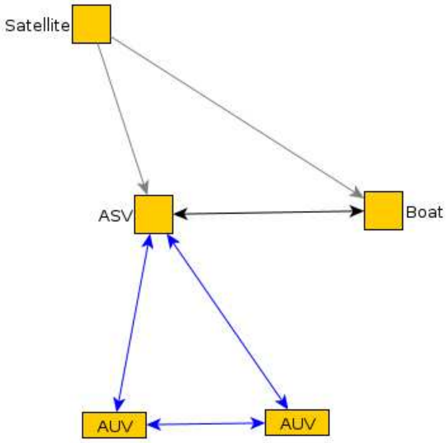

Fig. 2. Autonomous network communication organization.

II. SYSTEM OVERVIEW

BathyBoat. Bathymetric survey costs for a single lake typically range from $10,000 to $25,000 using industry standard techniques. In an effort to reduce these costs, UM, MTRI, and NSSI collaborated to design and build a low-cost ASV sensor platform at a fraction of the cost ($2k, a full order of magnitude), which can survey, log, and transmit real-time data in a fully autonomous mode of operation. In addition, the BathyBoat also serves as a development platform for remote-sensing algorithms and autonomous navigation schemes.

Fig. 3. Moving the BathyBoat from the helicopter for deployment.

In order to support the real-time data collection and transmission objectives, a suite of hydrographic sensors were integrated into a UM-designed hull. A Honeywell HMR3300 electronic compass (including roll and pitch sensors), Garmin 16HVS GPS, RadarSonics 250 acoustic depth sensor, Vernier conductivity sensor, National Instruments temperature sensor, and a Huminbird wireless fish-finder were integrated into the hull of the vessel. Also installed was a Digi International XTend Radio modem. A custom deck and passive directional indicator were added using special composite/aluminum fabrication techniques. The physical envelope of the vehicle was constrained to allow transportation in helicopters (enabling access to remote lakes in the Arctic Circle) and deployment by a single person.

The hull of the BathyBoat is 0.97m (38in.) in length, with a draft of 0.10m (4in.). The interior cavity is lined with expandable foam to provide emergency buoyancy in the case of flooding. The minimal draft, in combination with a recessed propeller, allows the vehicle to operate in extremely shallow or hazardous environments where fouling is a concern. Fully loaded with batteries, the vehicle weighs 32 lbs. and can easily be unloaded, ported, and launched by a single person.

The BathyBoat can be outfitted with a wide range of environmental sensors for different applications. The heart of the BathyBoat is a Digi International Rabbit LP3500 low-power (less than 20mA fully operational) single board computer (SBC) [10]. Software written by the MHL and loaded into the SBC memory controls logging, radio communication, serial communication, autonomous navigation, and autonomous speed settings. A special printed circuit board (PCB) inside the vehicles accepts sensors reporting data via RS-232, RS-485, voltage output, current output, or frequency output, and connects each with the LP3500. The same PCB also provides regulated +5VDC and +12VDC power for sensors from a +12VDC sealed lead acid battery source. The open hardware and software architectures allow new sensors to be integrated with minimal effort. See Table I for standard sensors integrated in the current platform. A future environmental package including chlorophyll, dissolved oxygen, turbidity, and other sensors is currently under review for inclusion on the BathyBoat.

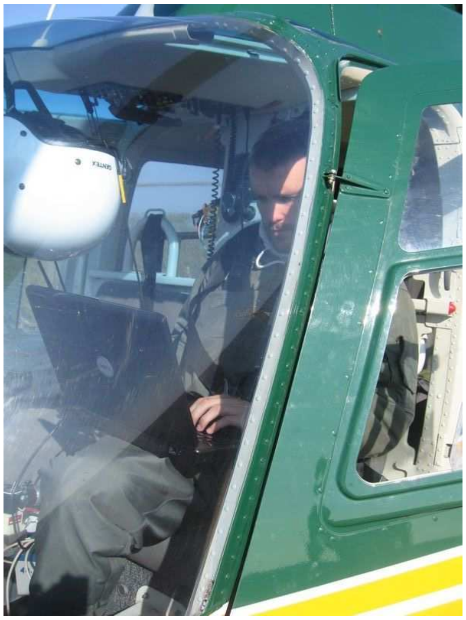

Fig. 4. Control of the BathyBoat from a helicopter in the Arctic National Wildlife Refuge.

The BathyBoat is operated in one of two control modes: autonomous or manual. In autonomous mode, the vehicle follows a predefined bearing or performs GPS waypoint navigation. GPS waypoints, bearing, and sensor options can be modified in real-time through a long-distance radio modem with a range of up to 7 statute miles. Any time the vehicle is within R/C radio range, a field operator can assume manual control by powering a hand-held radio control transmitter. In manual mode, access to the full suite of sensors is still available in real-time through the radio modem (see Figure 4). Both manual control and radio modem control were demonstrated from an airborne helicopter during the most recent missions in Alaska.

Iver2. Two Ocean-Server Iver2 commercial-off-the-shelf (COTS) vehicles (see Figure 5) were purchased by the UMich PeRL to serve as testbed platforms for SLAM research [11]. The vehicles were modified to include a new nosecone with high resolution video cameras in addition to a KVH fiber optic gyroscope, microstrain accelerometer, Desert Star precision depth sensor, and a Woods Hole Oceanographic Institution (WHOI) Micro-Modem.

The Iver2 autonomous underwater vehicle (AUV) has an operational depth of 100m (328ft) and a maximum survey speed of approximately 4 knots (2m/s). The vehicles are typically run at 1 knot for image continuity. One approach to underwater surveys is to use one vehicle equipped with side-scan sonar to swim in the water column to survey large tracts of ground, while another vision-equipped vehicle swims close to the seafloor to capture high-resolution images of areas of interest. In this way, targets of interest can quickly be identified and catalogued by the sonar vessel, while the photographic vessel fully documents each catalogued site and the sonar vehicle moves to other areas.

Fig. 5. Heterogeneous PeRL Iver2 Vehicles.

At 29.48kg (65lbs) each, these AUVs can easily be launched by two people and fit well in a standard pickup truck bed for transportation. Battery life depends on the mission speeds and sensor usage, and typical missions lasts 6-8 hours. At full resolution, the binocular vision system on the Iver2 can produce approximately 42GB of data per hour (not counting other stored sensor data). The BathyBoat, in comparison, stores only ASCII data from its sensors at roughly 1MB per hour (with current sensors).

III. RESEARCH

The UMich MHL robotics group is actively pursuing several research objectives using the BathyBoat and Iver2 vehicles as a test platform. Instrument navigation with restricted environmental information (e.g. loss of GPS during mission), self-organizational behavior (autonomously choose best behaviors to achieve mission goals), and control systems for small, autonomous surface vessels.

In the field of robotics, there is a well known situation known as the kidnapped-robot problem [12]. Imagine a robot which is suddenly placed in a completely unknown environment and must accomplish some goal. The robot must create a map and localize itself within that map for navigation purposes. The solution to this problem is the goal of the PeRL research software onboard the Iver2 vehicles. A related problem, is known as the Urban Canyon problem. Ground-based robots often rely on GPS information for navigation purposes. In urban settings, however, the tall city buildings block or distort the GPS to an unusable state [13]. Without GPS information, most ground vehicles revert to dead-reckoning or state-estimation techniques for localization [14]. In the marine environment, the same phenomena occurs when an ASV passes underneath large bridges. In these cases, we must rely on inertial sensors and state-estimators to guess our location. The MHL is interested in leveraging the PeRL AUV state-estimation research to solve the surface bridge shadow problem onboard the ASV BathyBoat.

TABLE I
INTEGRATED SENSORS ON THE BATHYBOAT.

SENSOR	VARIABLE	UPDATE RATE	ACCURACY	RANGE
Honeywell HMR3300 Compass	Heading, Roll, Pitch	8 Hz	1° (Heading), $.5 - 1.2°$ (Roll, Pitch)	360°, ±60
GarminGPS-16LVS	Time,Position,Track	1Hz	3-10m	—
RadarSonics Model 250 Sonar	Water Depth	1 Hz	0.1m	0.4-135m
National Instruments LM35	Temperature	1 Hz	$\pm\frac{3}{4}^{\circ}$	-55 to +150 °C
Vernier Con-BTA Probe	Conductivity	.2 Hz	± 1%	0-2000μ S/cm
Huminbird RF15 Wireless Fish Finder	Depth, Fish	125kHz	—	30m

Another field of ongoing research at the MHL is that of self-organizing networks of autonomous vehicles. Many scientific missions include several objectives and often require surveys of large areas of seafloor. Standard practice is to focus on each objective in turn and once accomplished, move to the next. The MHL is working on algorithms to allow the vehicle network to adapt in real-time to dynamic environmental conditions to best achieve mission targets. A surface vessel such as the BathyBoat is an ideal platform to serve as a command and control center for underwater activities (see Figure 2). Radio communication with the surface vessel from shore (or manned vessels) can issue updated mission parameters and the ASV can then relay that information to the underwater vehicles via acoustic modems.

The third research focus of the MHL robotics group is that of ASV control. Marine vessel control algorithms typically are based upon a 6 degree of freedom (DOF) model. The MHL is currently working to build accurate vessel models and construct new control algorithms to dynamically position and navigate the BathyBoat along mission parameters using limited sensor feedback. A combination model using information from SLAM techniques and more traditional control algorithms is currently being explored in conjunction with the BathyBoat system.

IV. BATHYBOAT FIELD TRIALS

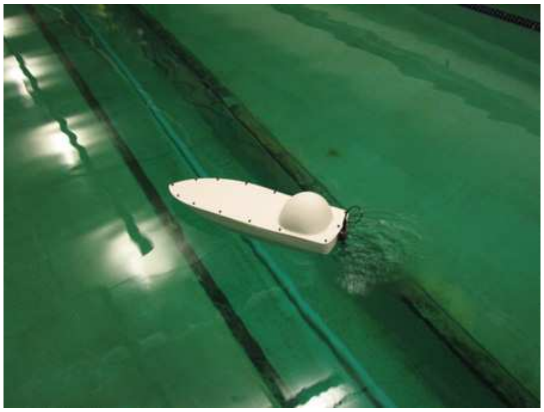

Fig. 6. BathyBoat trials at the MHL Physical Modeling Basin.

A. Michigan

Initial testing of the BathyBoat ASV was conducted at the MHL Physical Modeling Basin (see Figure 6) and Wild Pond in Ann Arbor, MI in 2007 and 2008. Basic hull integrity, propeller sealing, and manual control were thoroughly tested and verified at the UMich MHL before moving to an outdoor setting. Autonomous navigation, radio communication, and remote tasking were verified through a variety of trials on Wild Pond. Steering ranges were characterized and algorithm parameters were identified experimentally to achieve the best performance at a spectrum of speeds. A depth map of the pond was produced under manual control, and autonomous heading following was also demonstrated (see Figure 7). A contour map was then constructed using the bathymetry data collected during the trials (see Figure 8).

Similarly, the Iver2 vehicles have been field tested in several local Ann Arbor, MI lakes as well as in Lake Huron. Developmental testing of the vehicles was conducted at Argo Pond, Ann Arbor, in 2008 to finalize physical modifications and control software. The vehicles were then field tested during their first real-world mission at the Thunder Bay National Marine Sanctuary in Alpena, MI. During this mission, the Iver2 located a shipwreck via side-scan sonar which was then used successfully as evidence for enlargements to the sanctuary boundary. The vehicles were programmed to follow a standard mowing-the-lawn search pattern encompassing the suspected area of the shipwreck. When the AUV returned to the surface, data recorded during the mission was wirelessly downloaded for review. Inertial navigation techniques were used during this phase to determine the actual location of the shipwreck and align the sonar maps with GPS coordinates.

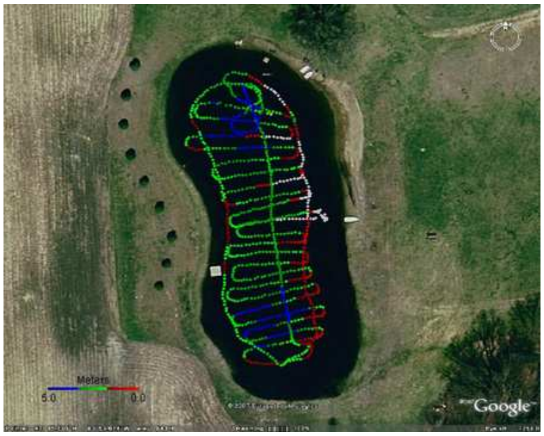

Fig. 7. Bathymetry data taken during 2008 Wild Pond survey.

Fig. 8. Contour map of Wild Pond from bathymetry data.

B. Alaska

Field trials of the BathyBoat continued during a July 2009 deployment to the North Slope of Alaska. The mission included sites located near Helmerick's, Deadhorse, and inside the boundaries of the Arctic National Wildlife Refuge. The team was airlifted to specific sites via helicopter with GPS and then programmed the BathyBoat to perform one or more tracks across the width of the lake to sample water depth, temperature, and conductivity (see Figure 10). In addition to the bathymetry data for each lake, environmental sampling was conducted to characterize local habitats near the lakes in efforts to preserve many of Alaska's endangered species like the Yellow-billed Loon. Water depth information is of vital importance to the oil industry in selecting lakes for the removal of water for ice-roads during the winters. Many of the detached facilities are inaccessible without the annual construction of ice-roads, and workers rely on the roads for equipment, food, and, in emergencies, rescue.

Testing continued for ten days as the BathyBoat surveyed over 14 lakes on the North Slope. Bathymetry data from the autonomous survey was used as a baseline for computational models built by MTRI to predict lake depths and volumes based solely on satellite imagery. The aim of this research is to reliably identify ideal lakes for the extraction of water for ice roads without the need to send advance teams to each potential site and drill test holes ahead of the extraction team.

MTRI has established a comprehensive database containing all available spatial GIS data pertaining to the North Slope of Alaska (see Figure 9) and has made it available through a web portal to managers, planners, scientists, and the general public.

The BathyBoat ASV maintained 2kts (1m/s), and sampled at 1Hz during this phase of testing, while surveying over seven miles of lake tracks. Post-processing of mission data resulted in Google Earth KVH files which can be downloaded and viewed by scientists around the world using the free Google Earth software. The data is georeferenced and displayed at the sample locations around the globe (as in Figure 7).

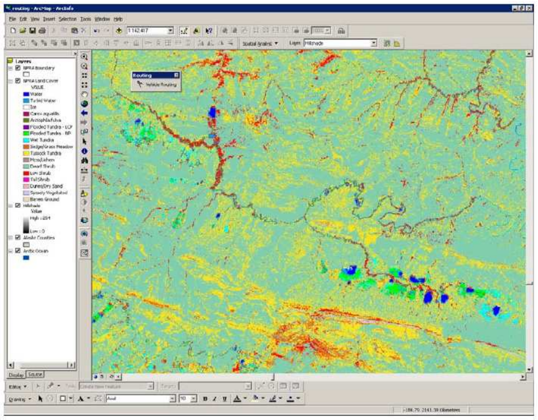

Fig. 9. North Slope GIS information made available to the public by MTRI.

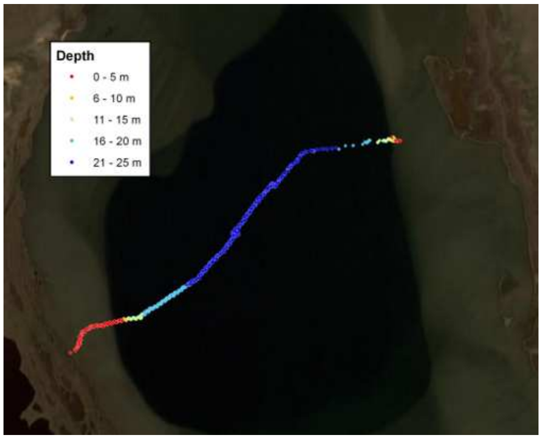

Fig. 10. Bathymetry map of remote lake in the Arctic National Wildlife Refuge, Alaksa.

V. CONCLUSION

This paper describes the design and construction of a new ASV, BathyBoat, and the integration with two modified Iver2 vehicles to form a heterogeneous multi-vehicle network for both fresh and salt water environmental surveys. The goal of this work is the development of new navigation and control algorithms while streamlining the operational logistics of a complete, low-cost, underwater survey system. Testing in Michigan and Alaska has afforded the opportunities to work in both ideal and extreme environments. These trails highlighted certain design aspects and provided insight into systems design for remote deployments. Based on the encouraging results of the field trials, updated autonomous navigation schemes will be in place for testing in early spring.

Upcoming missions will merge the SLAM software onboard the Iver2 vehicles with the surface capabilities of the BathyBoat to enable high-precision subsea sampling in areas of reduced or no GPS data available at the surface, as well as testing the ability to perform high-speed riverine reconnaissance.

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REFERENCES

[1] D. Cronin, G. Landrum, and K. Sharp, “Application of autonomous underwater vehicle systems in distributed ocean observing networks,” in OCEANS 2008, Sept. 2008, pp. 1–3.

[2] R. Madhavan, K. Fregene, and L. E. Parker, “Distributed heterogeneous outdoor multi-robot localization,” in ICRA, 2002, pp. 374–381.

[3] L. Barnes, M. Fields, and K. Valavanis, “Unmanned ground vehicle swarm formation control using potential fields,” in Control & Automation, 2007. MED ’07. Mediterranean Conference on, June 2007, pp. 1–8.

[4] J. Werfel, D. Ingber, and R. Nagpal, “Collective construction of environmentally-adaptive structures,” in Intelligent Robots and Systems, 2007. IROS 2007. IEEE/RSJ International Conference on, 29 2007-Nov. 2 2007, pp. 2345–2352.

[5] K. Pimenta, N. Michael, R. Mesquita, G. Pereira, and V. Kumar, “Control of swarms based on hydrodynamic models,” in Robotics and Automation, 2008. ICRA 2008. IEEE International Conference on, May 2008, pp. 1948–1953.

[6] L. Parker and F. Tang, “Building multirobot coalitions through automated task solution synthesis,” Proceedings of the IEEE, vol. 94, no. 7, pp. 1289–1305, July 2006.

[7] E. Fiorelli, N. E. Leonard, P. Bhatta, D. A. Paley, R. Bachmayer, and D. M. Fratantoni, “Multi-auv control and adaptive sampling in monterey bay,” Oceanic Engineering, IEEE Journal of, vol. 31, no. 4, pp. 935–948, Oct. 2006.

[8] A. Gadre, D. Maczka, D. Spinello, B. McCarter, D. Stilwell, W. Neu, M. Roan, and J. Hennage, “Cooperative localization of an acoustic source using towed hydrophone arrays,” in Autonomous Underwater Vehicles, 2008. AUV 2008. IEEE/OES, Oct. 2008, pp. 1–8.

[9] E. Marques, J. Pinto, S. Kragelund, P. Dias, L. Madureira, A. Sousa, M. Correia, H. Ferreira, R. Goncalves, R. Martins, D. Horner, A. Healey, G. Goncalves, and J. Sousa, “Auv control and communication using underwater acoustic networks,” in OCEANS 2007 - Europe, June 2007, pp. 1–6.

[10] D. I. Inc., Rabbit LP3500 Fox User’s Manual, 081121st ed.

[11] H. Brown, A. Kim, and R. Eustice, “Development of a multi-auv slam testbed at the university of michigan,” in OCEANS 2008, Sept. 2008, pp. 1–6.

[12] S. Engelson and D. McDermott, “Error correction in mobile robot map learning,” in Robotics and Automation, 1992. Proceedings., 1992 IEEE International Conference on, May 1992, pp. 2555–2560 vol.3.

[13] C. Vicek, P. McLain, and M. Murphy, “Gps/dead reckoning for vehicle tracking in the urban canyon environment,” in Vehicle Navigation and Information Systems Conference, 1993., Proceedings of the IEEE-IEE, Oct 1993, pp. 461, A–34.

[14] Y. Cui and S. S. Ge, “Autonomous vehicle positioning with gps in urban canyon environments,” Robotics and Automation, IEEE Transactions on, vol. 19, no. 1, pp. 15–25, Feb 2003.