Directed Sensing Strategies for Feature-Relative Navigation

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ABSTRACT

Many important applications of autonomous underwater vehicles (AUVs) require operations in close proximity to man-made objects or natural bottom topography. In these situations, the vehicle must adapt its trajectory on-line in response to current threats and mission objectives. To provide this capability, we are developing a sonar-based navigation technique that emulates the manner in which a person navigates through an unknown room in the dark: by reaching out for and establishing contact with walls, tables, and chairs, managing transitions from one object to the next as one moves across the room. Our intuition here is that, in many ways, sonar is more like touch than vision. It may be possible to build a vehicle that can effectively use its sonar to "grab" an object of interest, say a cylindrical post for docking, and then "reel itself in" by feeding back sonar range measurements from the object to its dynamic controller. We envision an AUV that can establish "virtual tethers" with arbitrary objects in the water column or on the seabed. Fast, local processing can maintain "contact" with the objects or surfaces of interest. Control laws can be established to utilize streams of measurements from these features to achieve local, feature-relative navigation. While our research is driven by the severe challenges of the subsea environment, we anticipate that the approach will also be useful in land robot applications.

1. PROBLEM STATEMENT

Navigating and controlling an autonomous underwater vehicle in the vicinity of obstacles or surfaces in the ocean environment remains a largely unsolved problem. Even human operators of remotely-operated vehicles (ROVs) have difficulty in complex environments, such as inside oil rigs or in regions of severe topography. Only for the simplest cases, for example a vehicle operating over the bottom in a region of mild topography, will existing robotic techniques suffice. Examples of activities of interest which require reliable navigation and control relative to features include:

- Precise bottom following for the purposes of photography or employing some other altitude critical sensor.
- Rendezvous and docking of an AUV with a fixed structure, with a mooring, or with another underwater vehicle.
- Obstacle avoidance.
- Navigating relative to an object of interest for imaging or manipulation of that object or a nearby object.

These activities can easily be placed into the context of search and recovery missions, pipeline inspection, or inspection and maintenance operations in complex environments such as offshore structures or inside fluid-filled ship interior spaces. A wide variety of science missions envisioned for AUVs involve activities such as bottom sampling. Versatile rendezvous and docking capabilities for AUVs would prove extremely useful for recovering vehicles at sea as well as for long duration AUVs which operate out of garages or from moorings. Clearly, a wide variety of important uses of AUVs require the ability to operate in an "intelligent" manner in the vicinity of obstacles or (hard) surfaces.

A useful analogy for the feature-relative navigation problem is the manner in which a person navigates through an unknown room in the dark: by reaching out for and establishing contact with walls, tables, and chairs, managing transitions from one object to the next as one moves across the room. Our intuition here is that, in many ways, sonar is more like touch than vision. It may be possible to build a vehicle that can effectively use its sonar to "grab" an object of interest, say a cylindrical post for docking, and then "reel itself in" by feeding back sonar range measurements from the object to its dynamic controller. To implement this concept in practice requires a capability to detect, identify, and track features of interest, coupled with a higher-level faculty to manage focus-of-attention resources according to current threats and mission objectives. Before describing our technique to achieve such a capability, we first discuss
Figure 1: General arrangement of survey-class AUV Odyssey.

the requirements of typical AUV missions and the physical characteristics of acoustic sensing that place constraints on the solution method.

2. AUTONOMOUS UNDERWATER VEHICLE CONSTRAINTS

While feature-relative navigation is also an important issue in ROV piloting, our approach is driven by the limitations on size, power, computational resources, and cost that are fundamental to the operation of untethered AUVs. For example, size and power constraints render many commercially available sensing devices (developed for the ROV marketplace) inapplicable for AUVs without prohibitive re-engineering. Limitations on size and power in turn limit the computational resources which can be brought to bear for interpretation and control. To operate successfully in the vicinity of obstacles, the sense and control process must be timely. Unlike land robots, underwater vehicles cannot "stop, look, think, and then move" when confronted with a difficult situation.

Contributing to these problems are the poor local area navigation capabilities available for underwater vehicles, especially autonomous underwater vehicles. The range of technologies available includes dead reckoning, inertial navigation, Doppler and correlation speed logs, map matching navigation, and a range of acoustic navigation techniques. Various radio navigation systems are also available for surfaced AUVs. Using a traditional long-baseline navigation system, a position accuracy on the order of a meter or so can be expected (higher accuracy systems exist [19], but they have very limited coverage). In a cluttered environment, acoustic navigation, which is highly susceptible to multipath, may give incorrect positions. None of these techniques represents a broad solution for navigating in the vicinity of obstacles, and the most promising, such as combined Doppler-inertial navigation, are extremely expensive.

These concerns have a particular urgency for our laboratory because of several challenging scientific missions scheduled for our newest AUV, the Odyssey [5]. Odyssey is designed to be a mobile instrumentation platform with actuators, sensors, and on-board intelligence to successfully complete survey and sampling-type tasks without human supervision. The outstanding characteristics of the vehicle are its small size (simplifying operation of the vehicle), large depth rating, and long range. It is a tool for obtaining spatially distributed data, especially at abyssal depths, at a cost low compared to other technologies. A more detailed description of the vehicle is given in Appendix A.

Obstacle avoidance is a difficult problem for a survey class AUV like Odyssey. In the deep ocean, the primary threat of collision is from severe bottom topography rather than mid-water column objects. There are a variety of reasons for a vehicle to operate near-bottom, the most typical being to obtain optical or high-resolution acoustic imagery. Altitudes of 2 to 10 meters would be desired for these applications. In scientifically interesting regions,
such as mid-ocean spreading ridges, a variety of geological features provide collision threats, for example cliffs, lava tubes, and hydrothermal vent mounds.

Obstacle avoidance is complicated by the high efficiency cruising character of torpedo-like survey vehicles, as exemplified by Odyssey. With only a single thruster, and steering provided by hydrodynamic surfaces, such vehicles can only maintain dynamic control under motion. Odyssey’s minimum stable speed is about 0.5 m/sec. Maneuverability of the vehicle is limited, with a turning radius on the order of ten meters. Thus the objective of obstacle avoidance is not merely to stop the vehicle from hitting objects, rather it is to ensure that the vehicle never enters a circumstance from which its limited maneuverability cannot extract it without collision.

Other important commercial and military applications of underwater vehicles, such as operations near oil platforms, in confined spaces, and in very shallow water, also have challenging obstacle avoidance requirements. While these mission are more appropriate for highly maneuverable vehicles, capable of control down to zero speed, the techniques under development here would be highly applicable in these target-rich environments.

Rendezvous and docking is another important concern in using Odyssey for scientific missions. Recovery of vehicles at sea is greatly complicated by rough seas and high winds. For a small vehicle, the primary difficulty is in attaching a line to the vehicle after the mission has been completed. A highly desirable goal is a system in which, well below rough surface water, the vehicle can attach itself to a hook suspended from its host ship. Under-ice operations in the Arctic present an even greater challenge, in which the only reasonable hope for recovery rests on the vehicle’s ability to find, track, and dock with a retrieval mechanism suspended through an ice-hole. At present such systems rely on active homing devices, such as acoustic or optical systems. Clearly, in the long-term, the ability of a vehicle to dock or maneuver relative to a passive mechanical structure is highly attractive.

3. PHYSICAL CHARACTERISTICS OF ACOUSTIC SENSING

There are three basic options for providing an AUV with external sensing of its environment: sonar, passive optical (computer vision), and active optical (laser ranging systems) [22]. Our research is employing sonar for a number of reasons. Passive computer vision is still in an early stage of development for terrestrial applications. While impressive feats of closed-loop visual control such as road-following at 80 km/hr have been demonstrated [11], many fundamental issues of segmentation, representation, and computational complexity remain unsolved by the computer vision research community. A variety of effects such as absorption, scattering, and lighting requirements prevent the straightforward extension of current land-based methods to the underwater setting. Active laser ranging systems suitable for underwater use have recently become commercially available. However, these systems are extremely power-hungry, large, and expensive (at least $250,000).

In contrast, sonar is a well-proven underwater technology. Integrated sonar sensing systems such as side-scan and sector-scan are available over a wide range of cost and performance. An additional motivation for using sonar comes from the sonar ranging capabilities of bats and dolphins, who routinely demonstrate astounding feats of sonar-based prey tracking and obstacle avoidance. For example, in one early experiment, dolphins easily navigated through plexiglas obstacle fields in turbid water and total darkness [14].

Unfortunately, experience from land robot research makes clear that obstacle avoidance using sonar is a deceptively difficult problem. Early attempts to employ a ring of 12 or 24 sensors as a “sonar bumper” [25], were notoriously unreliable [13]. Figure 2 shows a scan from the 50 kHz Polaroid air sonar system [20] that illustrates the nature of the problem. The slow data acquisition speed, poor angular resolution, gaps in beam coverage, and specular reflection effects that make sonar navigation difficult are unavoidable consequences of the physics of sonar.

Animal sonar sytems, however, confront essentially the same constraints of bandwidth, beamwidth, and wave-length regime as found in robot sonars. For example, the beampatterns of dolphin sonar systems are quite similar to the Polaroid system. (The Atlantic bottlenose dolphin has a 3 dB beamwidth of about 10 degrees [1], as compared to 11 degrees for the Polaroid transducer [20].) Similarly, the acoustic wavelength employed by the dolphin (e.g., 1.4 centimeters for a broadband click with mean frequency of 110 kHz) compares well with the Polaroid air sonar wavelength of 7 millimeters. And data acquisition rates for any sonar system, synthetic or biological, will be orders
Figure 2: Illustration of difficulties in sonar obstacle avoidance [16]. (a) shows 12 returns equally spaced in angle, taken in a simple 3 by 2 meter office scene, using data from the 50 kHz Polaroid airborne ultrasonic ranging system. (c) superimposes a model of the room, while (e) shows the superposition of the entire 612 point scan. (b), (d), and (f) show the drastic effect of rotating the vehicle by 13 degrees, yielding a situation where most of the room is invisible. These effects explain the failures of simple, memory-less approaches to sonar obstacle avoidance that have appeared in the literature, and motivate a more "intelligent" approach in which scanning sonars with a fast local processing capability can acquire and track the nearest threats to the vehicle.
of magnitude smaller than an optical modality. Given that biological sonar systems successfully confront the same “sensing physics”, what lessons can we apply to robot sonar navigation?

From the biological literature, one striking characteristic of cetacean echolocation is its *dynamic* character, in which the oscillating, probing head movements of the animal during its motion through the water play a key role. One noted researcher writes:

One has to wonder whether the various scanning and rocking motions that are associated with dolphins performing certain tasks provide the animal with some kind of advantage…. What kind of information do the animals obtain by rocking about their longitudinal axis or by swimming almost perpendicular to the line-of-sight direction of the target? [1]

Our hypothesis is that the dolphin overcomes the specular reflection effects and gaps in coverage inherent to sonar through the use of purposive, scanning head movements — the selective control of attention-focus. In a similar fashion, the objective of the current research is to provide a feature-relative navigation capability to an AUV through the use of (mechanically or electronically) scanning sonars that can reactively track individual environment features as the vehicle moves.

4. RELATED RESEARCH

A salient characteristic of feature-relative navigation is that the trajectory of the vehicle must be determined online in response to external sensing of environment features. This can be contrasted with traditional vehicle dynamic control research, which has basically addressed the question “how should thruster inputs be controlled versus time so that the vehicle follows a pre-specified trajectory as accurately as possible?” Dynamic control still has an important role to play — our objective here is extend its domain of application to situations where vehicle trajectories cannot be specified in advance.

One method for determining the vehicle trajectory on-line is to apply techniques from computational geometry [15] to plan a path through a “world model” constructed from accumulated sensory information. An extensive literature exists on methods of sensor data fusion to build such a model; Stewart [21] and Cox and Wilfong [10] offer comprehensive reviews. An important issue in sensing is to choose an appropriate representation of sensor information for the task at hand. Possible choices of representation range from occupancy enumeration methods that divide free space into a discrete grid of cells [12, 21] to feature-based methods that employ geometric primitives such as points, lines, and planes and associated covariances for uncertainty management [2, 16]. Generating and updating a world model, however, is a computationally intensive task and is the primary cause of the poor real time performance of most mobile robots. Errors accumulate in the world model with time and in proportion to the complexity of the environment, further degrading the robot’s performance. For these reasons, some argue that mobile robots will fare better by not employing any representation at all [7].

Our research can avoid many of these difficult issues because of the requirements of the task: feature-relative navigation does not require globally-referenced geometric consistency. Instead, our aim is to exploit a sonar focus-of-attention capability that would act locally and over short time intervals to track those environment features most relevant to the task-at-hand. For the initial research effort described here, we will restrict the class of objects under consideration to well-defined geometries (primarily planes and cylinders), to keep target detection and classification requirements in line with our sensor’s capabilities. This decision is made somewhat reluctantly, for as Stewart points out, grid-based representations can free one from such assumptions [21]. It is not clear, however, how a grid-based representation could support a sonar focus-of-attention capability, as the occupancy grid does not encode distinct objects as separate entities.

A parallel research effort underway in our laboratory is addressing the related issue of scene reconstruction via acoustic data fusion [17]. The two problems of scene reconstruction and navigation are of course closely linked — feature-based navigation can provide motion estimates to enable registration of sonar returns from multiple sensing locations, while multi-look sonar reconstruction can extract richer geometric features to be subsequently employed.

as "beacons" for navigation.

5. OUR APPROACH

The problem of feature-relative navigation can be divided into two parts: sensing the environment, and controlling the vehicle using the resulting information. The basic research issue is dynamic perception — the incorporation of external sensing of object features in a real-time feedback control loop. Our solution to this problem incorporates the techniques of directed sensing to limit the required bandwidth of sensors and state-configured layered control to ensure the vehicle control loop is closed around the pertinent external stimulus.

5.1 DIRECTED SENSING

The basic low-level competence we want to achieve is directed sensing [16]. Directed sensing is a technique by which sensing and computational resources are focused on the object most relevant to the current task. By tracking a given environmental feature, a high bandwidth stream of measurements from the feature becomes available for incorporation in a real-time control loop. In this way, feature-relative navigation can be cast into the same framework as current navigation systems that require pre-deployed acoustic transponders. The basic idea is to use objects and surfaces in the environment as "natural beacons".

Before external object sensing can be put to use for closed-loop control, the correspondence problem must be solved. The key to using a sonar measurement of an environment feature is to identify and track the critical feature. This problem of correspondence or data association is what separates perception and sensor-based control from more traditional estimation and control problems. The fundamental issue is that in addition to uncertainty in the values of measurements (noise), there is also uncertainty in the origins of measurements [9]. Directed sensing strategies substantially reduce the correspondence problem, by using fast local processing to maintain continuous contact with the correct feature. This makes it safe to apply single range measurements from the target of interest for vehicle control, as long as contact is maintained (and loss of contact can be quickly detected).

We envision an AUV that can establish "virtual tethers" with arbitrary objects in the water column or on the seabed. Fast, local processing can maintain "contact" with the objects or surfaces of interest. Control laws can be established to utilize streams of measurements from these features to achieve local, feature-relative navigation.

5.2 INTELLIGENT CONTROL

To manage this low-level capability to acquire and track objects of interest, a higher-level control facility is required. For this purpose, we can draw upon recent advances in the intelligent control of autonomous underwater vehicles. An augmentation of layered control, called state-configured layered control, has been developed at MIT Sea Grant to provide mission planning for underwater vehicles [4]. Layered control is attractive for the low computational requirements it imposes, as well as for the incremental way in which a mission planner can be assembled. Layered control (also called the subsumption architecture) was pioneered by Brooks and colleagues at the MIT Artificial Intelligence Laboratory for the control of fully autonomous land robots [6]. It was first implemented underwater by MIT Sea Grant, in collaboration with the Charles Stark Draper laboratory, using the Sea Squirt AUV [3].

The elementary unit of layered control is the behavioral layer, or behavior. A behavior receives sensory input and generates commands to the vehicle. Each behavior is responsible for a specific mission objective. The objective of layered control is to obtain sophistication through the interaction of many simple behaviors rather than by constructing complicated individual behaviors. The command outputs of the behaviors are resolved into the final command that is sent to the vehicle. Within this layered control framework, directed sensing control algorithms can be implemented as individual behaviors. For example, one behavior might be responsible for identifying a task-critical environmental feature, while a second would be responsible for tracking the feature.

State-configured layered control evolved from a desire to simplify implementation of layered control by minimizing
the number of behaviors active at any given time (Figure 3). CPU resources are concentrated on the specific tasks relevant to the current mission phase. Transitions between different phases of execution, such as target search, acquisition, and tracking can be conveniently sequenced via a state transition table mechanism. This simplifies the job for the programmer, since it is only necessary to consider interactions between smaller assemblages of behaviors. The state table determines which behaviors are active and manages the transitions between subsequent mission phases. For example, once a behavior responsible for identifying critical features has determined targets of interest, the state-table would manage the transition to the target tracking phase. It would accomplish this by activating the target tracking behaviors with the appropriate initialization, and deactivating the feature acquisition behavior.

Rather than have each behavior output actuator commands directly, in our implementation of layered control the behaviors generate commands of the form: heading, depth and speed. These setpoints are then achieved by the vehicle controller. Experience with a variety of control systems has been established on the Sea Squirt, MIT Sea Grant’s first AUV, including classical control, sliding mode control [24], adaptive classical control [8], adaptive sliding mode control [8], and H infinity control [18]. The present research will employ a combination of parameter estimation techniques and sliding mode control [26].

6. EXPERIMENTAL DATA

This section will illustrate the approach with real underwater data acquired in a two-dimensional setting with a 1.25 MHz narrow-beam mechanically-scanned sonar, the Tritech model ST1000 [23]. Figure 4 shows a sequence of sensing locations in the MIT testing tank at which complete 400-point sonar scans were obtained. The tank is approximately 100 feet long, 8.5 feet wide, and 4 feet deep. The sensor was oriented vertically to scan the horizontal plane, and mounted midway in the water column to minimize returns from the tank bottom and the water surface. The tank contains three objects: two water-filled aluminum triangles and a water-filled 7-inch diameter aluminum cylinder. The scan and object locations were hand-measured to a few millimeters of accuracy. The lower tank wall has three glass observation windows that present specular targets at this operating wavelength of 1.2 millimeters. The remainder of the tank consists of surfaces that are acoustically rough to this sensor.

Figure 5 shows circular arc features extracted from the scans for various sensing locations in the run, using the same thresholding algorithm used by Leonard and Durrant-Whyte [16] for air sonar data. In comparison with the Polaroid sonar, the narrow beam of the Tritech sensor makes the circular arcs of each target much narrower, and hence more difficult to extract — each feature has less local support. Another effect prevalent in this data set is that the rough surface of the top wall of the tank produces many responses to our feature extractor at high angles.

Figure 4: Sequence of 39 sensing locations from which Tritech 1.25 MHz profiling sonar scans were obtained.

of incidence. We are encouraged, however, by the success of the feature extractor with the geometric objects in the center of the tank. Algorithms are currently being developed to track these features for similar real and simulated data sets; results will be presented at the conference.

APPENDIX A. AUV ODYSSEY

Odyssey class vehicle characteristics (for more detail see [5]):

- **Size**: 2.15 meters long and 0.59 meters in diameter. Figure 1 illustrates the basic geometry.
- **Dry Weight**: 120-165 kg depending on the amount of batteries used.
- **Range**: 200 km at 7 km/hr, 300 km at 3 km/hr - Ag-Zn batteries. 800 km at 7 km/hr, 1200 km at 3 km/hr - Lithium batteries. The range of Odyssey is a function of such parameters as the amount and type of batteries, the amount of power required by vehicle subsystems and the vehicle speed.
- **Depth Rating**: 6000 meters.
- **Construction**: An external, free-flooded fiberglass structure provides a low-drag faired surface. Internal to the fairing is a pressure hull consisting of glass spheres. Also housed in the fiberglass fairing are a variety of subsystems such as water quality sensors, the propulsion motor, control surface actuators, and sonar transducers.
- **Control**: Odyssey nominally operates without human supervision for the duration of the mission. A computer roughly equivalent to a Macintosh II is used for mission planning and vehicle control.
- **Vehicle Cost**: Hardware costs for Odyssey are under $50,000, not including mission related sensors. This low cost is primarily due to the inexpensive pressure hull and the large number of subsystems developed and constructed in-house at MIT Sea Grant.
- **Status**: Launched August, 1992. Approximately 25 days of testing, including operations in the Charles River, Nahant Bay (north of Boston Harbor), and the Antarctic (off of the NSF Icebreaker Nathaniel B. Palmer).
Figure 5: Circular arc features extracted from various sensing locations in the run. A straight-line segment is drawn from each sensing location to the minimum range value of the arc response. Displaying the features in this manner illustrates the analogy between sonar and touch — by employing target tracking techniques, an AUV can effectively "grab" different geometric features in the environment, using them as local navigation beacons.
REFERENCES


