Bottom Following for Survey-Class Autonomous Underwater Vehicles

Andrew A. Bennett
abennett@mit.edu

John J. Leonard
jleonard@mit.edu

James G. Bellingham
belling@mitvma.mit.edu

MIT Underwater Vehicles Laboratory
Room E38-300, 292 Main St.
Cambridge, MA 02139
FAX: (617) 258-5730

Abstract

The task of bottom following or feature-tracking is an important vehicle ability which has been well explored (cf. [1, 2, 3]). In the past, the vehicle attempting to bottom follow has generally been a "rover" type vehicle: a vehicle equipped with a variety of thrusters and sensors which enable it to traverse and hover at will. The MIT Underwater Vehicles Laboratory is currently developing bottom following techniques for "survey" type vehicles: vehicles which are optimized to cover large geographic areas efficiently and maneuver by the use of hydrodynamic forces on control surfaces to maintain dynamic control of the vehicle. This places inherent restrictions on the maneuverability of the vehicle and can make maneuvering difficult in a challenging environment. Current research utilizes an incremental approach; starting with the simplest possible bottom-follow, multiple iterations add successive improvements to the system. Results from past and recent field tests are presented, as well as current simulation tests.

Introduction

Bottom following is a highly desired characteristic for underwater vehicles, particularly survey-type vehicles. It is needed for side-scan sonar mapping, photographic surveys, magnetic surveys and for maneuvering in and around both man-made and natural structures. While each of these missions has its own requirements, they all share the general need for operating a stable platform at a mean contour height.

Bottom following, at its most literal, is the task of maintaining a fixed altitude above an arbitrary surface whose characteristics may or may not be known (Fig. 1). There are three aspects to successful bottom following: 1) avoiding catastrophe, 2) executing a good trajectory and 3) operating efficiently. Avoiding catastrophe is simply preventing a collision that might damage or trap the vehicle. Executing a good trajectory involves maintaining the altitude and orientation requirements of the particular sensors employed (e.g. a camera). Operating efficiently is the act of choosing a trajectory which meets the needs of the sensing equipment while at the same time minimizing the power expended. This can be important for a power-limited system such as an AUV, but caution should be exercised to insure that energy conservation does not take precedence over vehicle safety. Our research strategy is to employ models of the environment, the vehicle, and its sensors to improve bottom following safety and performance.

While bottom following may appear to be a simple task, it is made difficult by the uncertainty inherent in operating in complex ocean environments. The simplest bottom follower takes the vehicle's current depth, adds this to the current altitude and then deducts the desired altitude from the total. The result is the depth necessary to maintain the desired altitude. This approach often works well in favorable environments (as illustrated below), but suffers from limitations because it does not model uncertainty in sensor measurements and does not attempt to act in a predictive
manner.

Sensor uncertainty can come from the noise inherent in any sensor system or from confusion about the origin of a reading. Noise from the altimeter and/or from the depth sensor can cause wildly varying depth + altitude totals, which translate to wildly varying desired depths. This can lead to increased fin activity (wear on components and energy consumption) and excessive pitching of the vehicle. Sensor dropouts (missing measurements) can mislead the vehicle into thinking it is far from the bottom, leading to a collision with the bottom if contact is not reestablished quickly. Attitude sensor errors cause the vehicle to compensate for non-existent attitude problems which in turn result in poor bottom following and/or a collision. Likewise, confusion about the origin of a reading can cause poor bottom following behavior. A specular surface may cause dropouts or sonar returns which are really coming from somewhere else (imagine trying to navigate in a dark house of mirrors with a flashlight strapped to your forehead). The resulting signals can confuse the bottom follower into thinking it is further from the bottom than it actually is.

In this paper, we assume the vehicle gathers its information about the environment through a single, high frequency (200 KHz), downward looking sonar altimeter. The performance of the sonar will depend on the complexity of the bottom topography and its acoustical characteristics. One geometric source of error in interpreting the altimeter measurement is that the ray path from the sensor to the bottom will change with the vehicle’s attitude. For example, if the vehicle is steeply pitched, then the ray path will be longer than the true altitude (Fig. 2). Assuming the bottom is flat, this form of error can be compensated for, the true altitude simply being:

\[
\text{True Alt} = \frac{\text{Perceived Alt}}{\cos(\text{roll}) \ast \cos(\text{pitch})}
\]  

(1)

however, when the bottom is not flat this compensation will be in error.

An important feature which the simple bottom follower lacks is prediction. Bottom following with a sonar that only looks down is much the same as trying to walk by only looking at your feet [cf. Fig. 1]. This method works well in gentle, easy environs, but not when the terrain is changing severely. Generally, if the bottom slope can exceed the vehicle's depth-change limits, then the potential for collision exists. Furthermore, by only looking down the vehicle has no knowledge of the terrain surrounding it. If a turn is required, it must be made blindly.
Ideally, the vehicle should be able to look all around itself, using mechanically or electronically scanned sonars. In practice power, payload and cost considerations limit the number of sensors that can be mounted on a vehicle, and only one or a few fixed sonars are available. While scanned sensors may make possible sophisticated feature tracking behaviors [4], with any sensor configuration there are common research issues of how to model the capabilities of the sensors at hand and how to control the vehicle based on sensor information. The key to successful bottom following, then, is to manage the vehicle’s sensory capabilities in the most advantageous fashion.

The Vehicle

In the past, bottom following has been attempted with thruster-equipped vehicles. This type of vehicle is well-suited for hover and traverse maneuvers and is capable of following almost any terrain. In contrast is the AUV Odyssey II: a survey-type vehicle designed to cover large areas as efficiently as possible (Fig. 3). The primary difference (with respect to bottom following) is the Odyssey II’s use of dynamic control via fins and elevator. This requires a minimum speed to maintain pressure on the fin surfaces and thereby control the vehicle. Because of the nature of the design the vehicle has control limits to its velocity, pitch, and turning radius. This in turn places restrictions on the types maneuvers it can perform, making bottom following more difficult.

An important issue is how the bottom follower interfaces to the vehicle’s dynamic controller. We are addressing bottom following as a high-level or intelligent control problem. The output of our algorithm will be the desired path of the vehicle and it is up to the dynamic controller to specify the actuator commands to follow this path. The vehicle’s performance will be limited by the low-level controller’s ability to follow the desired trajectory. It is important to understand the capabilities of the dynamic controller when designing the bottom follower. Recent Charles River field testing of the AUV Odyssey II has been directed at improving our understanding of the dynamics of the vehicle. Using this information, a new controller for Odyssey II is currently being designed by Hover [5]. The results presented below utilize Odyssey II’s existing PID controller which has given satisfactory performance in field experiments over the last two years [6].
Early Bottom Following

As discussed above, the simplest bottom follower is:

\[ \text{Desired Depth} = (\text{Depth} + \text{Altitude}) - \text{Desired Altitude} \]  

(2)

This type of bottom following works very well in certain situations; particularly when the bottom topography is well within the pitch limitations of the vehicle and when the bottom material provides a good sonar target. Our lab's first mission was performed in Sheep Pond, MA on November 9, 1992 using the Odyssey I vehicle and a MesoTech altimeter [7]. Owing to the gentle nature and good acoustics of the sandy pond bottom, the mission went smoothly (Fig. 4).

![Sheep Pond Bottom Following Nov. 9, 1992](image)

**Figure 4**

Bottom Following Using Eqn. 2

This mission was successful because 1) the bottom provided a good reflective surface and 2) the vehicle altitude and orientation was such that the altimeter never lost contact with the bottom. A more recent and extensive mission using the Odyssey II vehicle and a Tritech pencil-beam sonar [6] was conducted at the island of Bermuda in the Spring of 1995 (Figs. 5-8). This mission clearly demonstrates both the advantages and drawbacks of the simple bottom follower.
Figures 5 and 6 show the vehicle path in the water column as it follows along the bottom. The mission was to traverse the sandy-bottomed lagoon in the center of the island of Bermuda and then return to the launch point. At approximately t=1000 seconds, the vehicle turned about and headed home. The sandy bottom provided a good reflective surface which in turn resulted in good sonar contact with the bottom. The altitude is relatively constant, with only minor deviations from the desired path. An analysis of the data shows that the slope of the bottom during the course of the mission never exceeded 10°. This is well within the dynamic limitations of the vehicle and thus the mission posed no difficulty to a simple bottom follower.

This data also shows one of the drawbacks of the simple bottom follower. In an effort to maintain a constant altitude, no effort is made to limit pitch. The resulting pitch oscillations are relatively large when compared to the slope being followed (Figure 7). As an example, consider the vehicle’s behavior around t=635 to t=665 seconds (Figures 6 and 8). The slope at this time is approximately 5° upwards, while the vehicle shows pitching angles on the order of ±10° in order to attain the requested altitude as quickly as possible. Had this been a photographic survey, the pitching would have resulted in degraded picture quality. Clearly a more stable platform would be desirable.

**Dropouts & Noise**

Another important limitation of Eqn. 2 is the susceptibility to dropouts and noise. While the
bottom provided good sonar contact, thereby limiting noise from that source, the pressure transducer which is used to measure depth occasionally provides erroneous data in the form of a “depth spike” (e.g. Fig. 8 at approximately t=635 sec, t = 690 sec and t = 695 sec). This is passed along by the bottom follower to the dynamic controller in the form of a sudden, dramatic change in the requested depth. The controller then attempts to achieve this dramatic depth change by driving the fins to their limit of operation. While these sudden depth change requests have little true impact on the vehicle trajectory (because of the vehicle’s inertia), they do cause excessive wear and power expenditure in the actuators as well as run the risk of placing the actuators in an undesirable position at a moment when quick action may be required. A more drastic form of dropout-induced error can be seen in Figure 9, which is a “yo-yo” mission in the Charles River in Cambridge, MA in April of 1995.

The bed of the Charles River averages 3 to 6 meters deep with a 10 meter trench on the south side. It is composed primarily of an organic silt which is very fine in consistency. While the acoustic characteristics of the muck at the bottom of the river are difficult to determine, our experience has been that specular reflection is predominant with our 200 KHz and 500 KHz sonar altimeters. The sonar employed had a cone angle of approximately 20°. When the pitch exceeded this angle, no portion of the sonar beam was vertical to the bottom. The result was a loss of signal as shown in Figure 9. A simple bottom follower would interpret this drop off as a sudden change in topography: a cliff. The vehicle would attempt to follow this cliff and possibly collide with the bottom as a result. A catastrophic case is when the net slope angle formed between the vehicle and an up-sloping bottom exceeds the sonar cone angle. In this situation the vehicle is confronted with a bottom which is approaching, but invisible. The vehicle promptly dives into rather than pulls away from the slope.

Figure 9
Specular Reflection and Loss of Contact
Predictive Control and Decision Making

A final weak point is predictive control. This weakness takes two forms in the case of a simple bottom follower. First, Eqn. 2 makes no assumption about the dynamic capabilities and limitations of the vehicle. In the case of a thruster-controlled, "rover-type" vehicle, this is a relatively unimportant issue. If the slope approaches 90°, the rover simply moves straight up the cliff to pass over. A survey-type vehicle on the other hand has pitch limits imposed upon it by nature of the design. In the case of the AUV Odyssey II, this limit is approximately ±30°. It is therefore necessary for the vehicle to understand when the slope of the bottom is too steep for it to deal with and take appropriate action, either by turning away, spiraling up (or down) or simply altering the trajectory slightly to avoid a particular feature. This requires a form of predictive control, which in turn requires some form of forward looking sensor(s) with which to gather information about the terrain ahead. Without predictive control, any attempt at trajectory control is only in response to current conditions. This inherent latency in the bottom follower makes the vehicle vulnerable to sudden changes in the topography; by the time the vehicle knows about a cliff or chimney, it has likely collided with it.

Second, the lack of side-looking sonar means that even if the vehicle encounters severe terrain and manages to turn in time to avoid it, it may simply collide with some feature out of sight to one side. With some knowledge of the terrain off to either side, the vehicle has the information needed to make decisions about which way to turn and how much. Because a survey-type vehicle has a non-zero turning radius, it is important for the bottom follower to understand what potential turning space exists. This can only be safely achieved with the addition of a side-looking capability. Without it, the vehicle could be "blind-sided" when making a turn and collide with some unknown obstacle. This occurred with the Odyssey II vehicle while performing a bottom following mission in the Charles River in the Spring of 1995.

A simple bottom following mission was programmed into the vehicle: head south across the river for a specified time then turn around and return to the launch point. Unfortunately, the turn around time coincided with the point where the vehicle had just entered the trench. Figures 10-13 graphically describe the mission. Figure 10 is a bathymetric view of the vehicle vs. mission time and the corresponding vehicle altitude, as reported by the sonar. The mission proceeded normally, with good bottom following behavior exhibited from the launch until approximately T = 460 seconds. At that point, the vehicle passed over one lip of the trench, as evidenced by the sudden upsurge of the bottom. The vehicle passed over this lip without incident, and proceeded into the trench proper in an attempt to maintain a constant altitude. At T = 475 seconds, the vehicle begins to turn around to head home. Unfortunately, it is now well within the trench and its turn is heading the vehicle directly into the side. At this point, the vehicle is handicapped both by the altimeter location (looking straight out the bottom of the vehicle) and by its current attitude. Since the vehicle is pitched nose-down, the altimeter is looking slightly behind its current position (as demonstrated in Fig. 2). Consequently, the vehicle is completely blind to what is happening both directly beneath and in front of it. The altimeter returns begin to break up due to the pitch angle of the vehicle and the specular nature of the river bottom, as evidenced by Fig. 11 at T = 485 seconds. The simple bottom follower is not designed for such contingencies and the maneuver results in an impact with the trench wall at approximately T = 500 seconds. The vehicle continues to thrust into the bottom until T = 620 seconds, when handlers on the surface manage to pull it free of the mud (using its tow float). Figure 13 is a three-dimensional projection of the vehicle track up to the time of impact.
Current Bottom Follower

The current bottom follower is based upon a three-phase design cycle (Figure 14). Using past tests performed in the field, a model-based simulation system is designed and improved. The simulator is then applied to the current bottom following software to expose any weaknesses or problems. Once the system has performed satisfactorily in the simulator, the software is run in the vehicle for field tests. The simulator is a model-based system, incorporating four separate components: the vehicle, the sensors, the environment and the bottom follower (Figure 15). One advantage of this modularization is that each component can be improved incrementally in isolation from the others as more information becomes available; it is not necessary to recreate the system each time. This allows each model to be worked upon independently of the others, allowing experts in each area to work together on the whole without disruption.

The vehicle dynamic model is used to simulate the vehicle's behavior in the simulated environment and to provide a source of vehicle sensory data (e.g. pitch, yaw and roll). The dynamic controller and high level control software are all actual vehicle code, thereby insuring that the software interface remains consistent. The sensor model is also interrogated by the original vehicle sensing software, taking the information provided by the environment model and adding in simulated noise, dropouts, etc. according to the sensor type and conditions. The environment model
supplies the appropriate information according to the type of sensor that interrogated it and the location of the vehicle in the environment at that time.

Our current generation of bottom follower incorporates noise filtering and outlier rejection. Outlier rejection was added in response to spurious pressure sensor readings of the type observed at Bermuda. Noise filtering was first incorporated as a “moving window” scheme; this reduced noise-induced error but resulted in further latency in the system. As a moving window lends weight to past returns, this latency was to be expected. The moving window will soon be eliminated in favor of a superior filtering scheme.

![Figure 14](image)

**Figure 14**
Bottom Follower Design Cycle

![Figure 15](image)

**Figure 15**
Bottom Following Component Models

To prevent the vehicle from grounding itself or attempting to follow up slopes which are too steep for it, an adjustable slope estimator was incorporated which uses past bottom locations and the current bottom location to reconstruct an estimate of the current slope beneath the vehicle. If the slope is too steep, the bottom follower slows the vehicle down to allow more time for the vehicle to pull away from the bottom. This method has proven only partly successful due to the minimum speed that is needed to maintain dynamic pressure on the vehicle control surfaces. To prevent “shoaling” (running aground in shallow water), the bottom follower monitors the current water column (current depth + current altitude). If the water becomes too shallow, the vehicle shuts off and surfaces.

Finally, the vehicle has been programmed to “distrust” sudden increases in altitude which were likely to be caused by sonar error rather than a true change in depth. This is achieved by examining both the sonar input and the recent history of the bottom. The sonar updates at a rate of 5 Hz, while the vehicle moves at velocities of approximately 1-2 meters/second. If the altitude is gradually decreasing and the range suddenly increases over a period of 1-2 returns (or 0.2 to 0.4 seconds), then it is highly unlikely that the bottom has truly dropped away so abruptly and it is far more plausible that the sonar is losing returns. The bottom follower therefore pulls away in order to reestablish contact. The value of the sonar returns are used as a further check on the sonar. The sensor characteristics are pre-programmed into the bottom follower: minimum reliable range, maximum or “infinite” range value and beam width. If the returns are on the order of the “infinite” range, then the sonar is assumed to have failed and the bottom follower will continue to pull away until either the returns are no longer “infinite” or enough time has elapsed that the bottom follower aborts the mission.
Conclusion

Bottom following, while simple in concept can be quite difficult to implement in practice, particularly for a survey-type vehicle relying on fins for control. Problems such as vehicle controllability, sensor noise, dropouts and collision avoidance each pose challenges to successful bottom following. The results presented above show that a straightforward approach can succeed in favorable environments, however the potential pitfalls of reactive bottom following are also apparent. We believe that a model based approach can yield increased performance with less risk to the vehicle. Experimental results to support this conclusion are the goal of our current bottom following experiments with the Odyssey II AUV. Data from field tests are being analyzed to improve the realism of the model-based simulator and to evaluate different bottom following strategies.

While our current field tests will be confined to the use of a single downward-looking altimeter, the simulator allows for multiple sonars to be placed in arbitrary locations on the vehicle. This will permit us to evaluate new sonar configurations making use of one or two additional units. For example, a sensor looking forward at 30° from perpendicular could help with predictive control and provide increased performance. Ultimately, it would be desirable to use a steerable sonar to allow the bottom follower to locate and “focus attention” on specific bottom features [4]. This will be a continuation of the work of Moran, Leonard and Chryssostomidis [8], allowing to vehicle to not only follow the bottom but also to use distinctive features to act as natural “beacons” for navigation. Once expanded sensing capabilities have been added, higher level capabilities such as trajectory planning can be incorporated.

Acknowledgements

The authors would like to acknowledge fruitful discussions with our colleagues at the MIT Underwater Vehicles Laboratory. Special thanks are due to J. W. Bales and B. A. Moran for their hard work during the Bermuda field deployment. The work described here was supported by the MIT Sea Grant College Program (grant number NA46-RG-0434), the NASA Student Fellowship Program (NASA contract NGT-30232), and the Office of Naval Research (grant number N00014-92-J-1287).

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