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vehicle interrogates a network of transponders and by listening to the transponder returns figures out the two way travel times and thus its position relative to the net. Multiple vehicles can share a single transponder network only if they time multiplex their interrogations else one would have no way of knowing which return corresponded to which interrogation. This approach however degrades in performance as the number of vehicles increases. Most members of the oceanographic community would consider the degradation in the time between fixes as unacceptable even for the case of two vehicles.

One alternative to that suggests itself for coordinated multiple vehicle operations is to establish one vehicle as the master. This vehicle provides a global reference using LBL navigation while the remaining vehicles servo their position relative to some local beacon that the master provides.

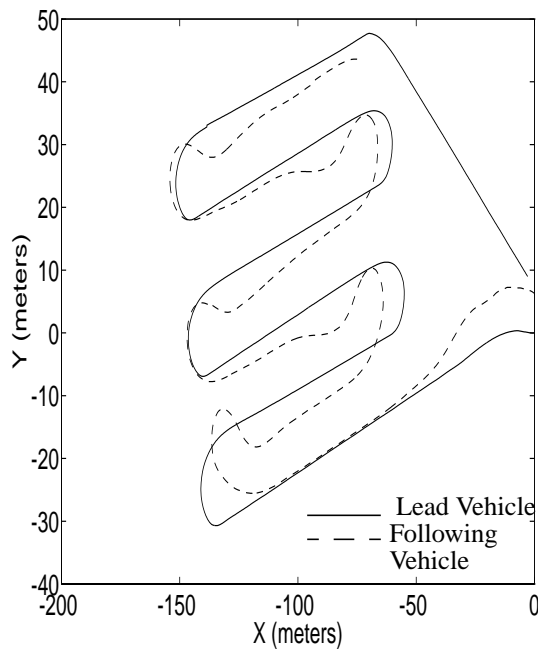


Figure 4. Coordinated Survey Dead Reckoned Tracks

Figure 4 demonstrates one attempt at demonstrating such an approach. The master vehicle was equipped to transmit acoustic pings that were picked up by an Ultra Short Baseline (USBL) receiving array on the second vehicle. In this mission the first vehicle was running a lawnmower pattern while the second vehicle was commanded to follow

dead astern based on its USBL sensor. The first vehicle started at coordinate location (0,0). We see that the second vehicle nulls its bearing to the first vehicle for every leg. We believe that the offset between the lead vehicle and the following vehicle tracks is due to our dead reckoning algorithm which assumes a constant velocity for the vehicles throughout while in reality the velocity does vary during the turns. While these results are encouraging this technique does suffer from a single point of failure in its dependence on the master.

A second alternative which shows even greater promise is the incorporation of common clocks with low drift rates on the LBL acoustic beacons and the vehicles. This would allow the net to ping while an arbitrary number of vehicles could listen in and calculate their positions based on one-way travel times and the common clocks. We would still have to provide some mechanism for re-syncing the clocks as they drift over time but this method does not suffer from the disadvantages of the other methods.

CONCLUSIONS

In this paper we have discussed several theoretical frameworks for optimizing the performance of AUVs in varied applications. We are currently working on analysing the requirements for conducting spatio-temporal sampling for extended autonomous deployments.

In this paper we have also laid out frameworks to accomplish the tasks associated with navigating several vehicles in cooperative tasks and have presented some of our initial results in this regard.

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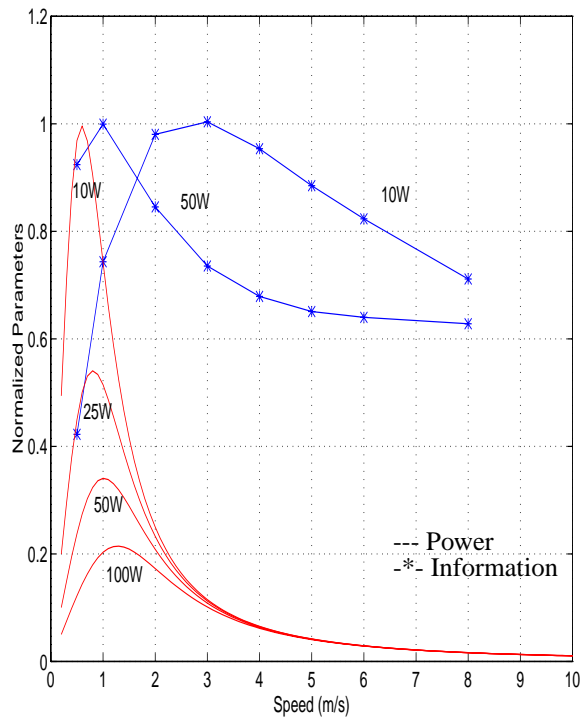


Figure2: Optimizing Speed for Power and Information

We note in passing that one other very interesting scenario arises when we consider the case of an AUV engaged in gradient following one of its sensors to a global maxima or minima. Here the information content of a particular mission is quite low as we are only interested in locating the coordinates of the minima or maxima. One could argue for optimizing around a power-based metric but one needs also to consider the cost associated with missing the global maxima while getting stuck in a local minima. Clearly this will depend upon the sensor and other issues at hand.

It is obvious from the preceding discussion that the design and deployment of an AUV is of a complex multi-dimensional nature.

NAVIGATION

Let us now move away, somewhat, from the theoretical to the more practical demonstrations of the principles discussed in the preceding sections. We begin in this section by looking at one example of optimizing the trajectory of the ABE vehicle for power as it transits from the surface to the spot where it must begin its survey patterns. We will later look at the issue, in some depth, of navigating

multiple vehicles in an acoustic net.

In deploying a typical vehicle one might choose to drive to the bottom maintaining a steady course to the starting point. However, this might easily involve using up a significant portion of the power budget in a deep ocean deployment. On the other extreme one could deploy by tossing the vehicle overboard with a descent weight which is jettisoned once the vehicle approaches or is on the bottom. However this too is not completely satisfactory as the vehicle could drift away and this might imply a long transit for the vehicle to its starting point.

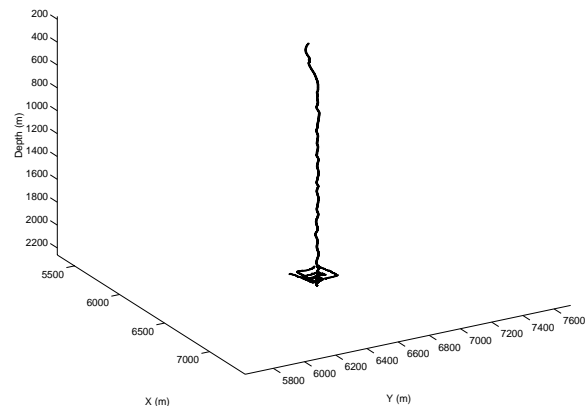


Figure 3: ABE Low Energy Descent

The solution we chose for deploying ABE utilizes a hybrid scheme based on the dynamics of the vehicle and an descent weight. A descent weight is added to the aft section of the lower pod causing the vehicle to glide forward in a slow spiral. The spiral arises due to asymmetries in ABE's top hulls. The vehicle only makes heading corrections every tens of seconds while it is away from its targetted spot on the bottom. Once it approaches within a tolerance of the desired spot it does nothing. The results of such a descent are shown in figure 3. The vehicle headed to and attained the desired spot quite easily and then did not have to run its thrusters at all which resulted in a very efficient, low power approach to the bottom while not sacrificing the navigational accuracy required by our oceanographic clients.

Let us now turn our attention to one of the major issues connected with deploying several vehicles simultaneously - multiple vehicle navigation. The desired position accuracy required for oceanographic surveys with these vehicles dictates the use of externally referenced navigation, such as an acoustic long-baseline (LBL) system. In such a system the

Following the previous analysis the range then becomes

$$R = \left(\frac{2(1-\sigma)V_0}{C_d S_0 + \left(\frac{2P_H}{\rho L^2 u^3} \right)} \right) \frac{B_0 L}{u^2} \quad (10)$$

We can maximise R in (10) with respect to u , to see that there is only one maxima and that that maxima occurs at a velocity

$$u = \left(\frac{P_H}{2C_d S_0 \rho L^2} \right)^{1/3} \quad (11)$$

These are interesting results. Equation (10) states for a given hotel load the speed and the hotel load intimately determine the range. Equation (11) states the exact relationship between these two quantities for achieving a maxima in range which is seen to be independent of factors such as motor efficiency and motor propeller efficiency.

In Figure 1 we plot out range versus speed curves for an Odyssey like AUV. These show the kind of ranges that are theoretically possible in an ideal world. They also point out the importance of moving slowly for maximising range. In reality, other effects such as the ability to work against ocean currents will also effect the speed at which we may wish to fly the vehicle. This analysis is excellent for designing vehicles whose missions include long transits but as we shall show in the next section slow speed may not be optimum for other kinds of missions.

SENSING

AUVs can fundamentally be considered to be information gathering agents. While deriving our range versus speed estimates in the previous section, our underlying assumption was that the rate of useful information coming from the sensor does not change as the speed of the vehicle changes. From a slow speed standpoint, unfortunately this assumption is not true for most sensors. As an example, we focus in this section on deriving an optimum speed for an AUV using a sonar.

We use a grid-based occupancy method for backprojecting probabilistic values into a global

grid[8]. The probabilistic values are calculated by using a physics-based model of the acoustic sensing modality[9] which take into account the sonar receiving and transmitting beam patterns, the source level, and the transmission and absorption losses.

Now if we consider that the sonar sensing modality is a stochastic process we can derive the rate of information arriving from the sonar by defining an entropic measure H , similar to that defined by Shannon[10] for use in communications systems.

$$H = -p_1 \log p_1 - (1 - p_1) \log(1 - p_1) \quad (12)$$

where p_1 is the probability associated with our belief in occupancy and emptiness for a pixel.

Eqn 12 translates our probabilistic beliefs into a quantitative measure of information which can provide useful insight into the performance of our sensor. By looking at the entropy associated with all the pixels ensonified by a sonar ping we obtain a measure of the information rate of the sensor. If we look at the information rate associated with successive pings over the same area we see that the rate peaks and then recedes in the amount of information being conveyed by each successive ping. Thus there is seen to exist an optimum redundant mapping for a particular sonar sensor which is a function of its characteristics. We can now extend this simple analysis to the case of an AUV moving over terrain at different speeds and calculate the rate of information for each case. The values obtained from such a simulation for two different sensors, a 10W Echo Sounder and a 50W Pencil Beam sonar are plotted in Fig 2. The differences in the two curves are primarily due to the differences in the beam patterns for the two sensors. The curves derived from power considerations are also plotted (dotted lines) for comparison. We have normalized the two sets of curves about their maximum values. Fundamentally, the two sets of curves are radically different as they are optimized for two very differing sets of circumstances - the power curves having been optimized for long transits while the information curves have been optimized for sonar mapping with particular sensors.

Canadian northwest border. Work is continuing towards the eventual deployment of these vehicles for multiple autonomous missions for studying deep ocean convective overturning in the Labrador Sea.

In looking at such missions it is not immediately obvious how one might best serve the oceanographers in acquiring their data. Even missions on small AUVs are a complex interaction between a number of quantities and so the focus of this paper is to try and arrive at some understanding of the interaction of quantities such as power, navigation and sensing strategies based on our past and continuing work with ABE and the Odyssey IIB class vehicles.

POWER

It seems obvious that the power available on an AUV will have important consequences in the eventual performance of the vehicle. This is especially true for the case where the vehicle may be transiting large distances to the site of interest. To look at the limits of the ranges achievable with current technologies we first derive and elaborate on the relation between range and other vehicle characteristics such as speed, propulsive power and the so-called hotel load, which is the power required to drive the sensors and computers on the vehicle. This derivation follows that given by Bradley[7].

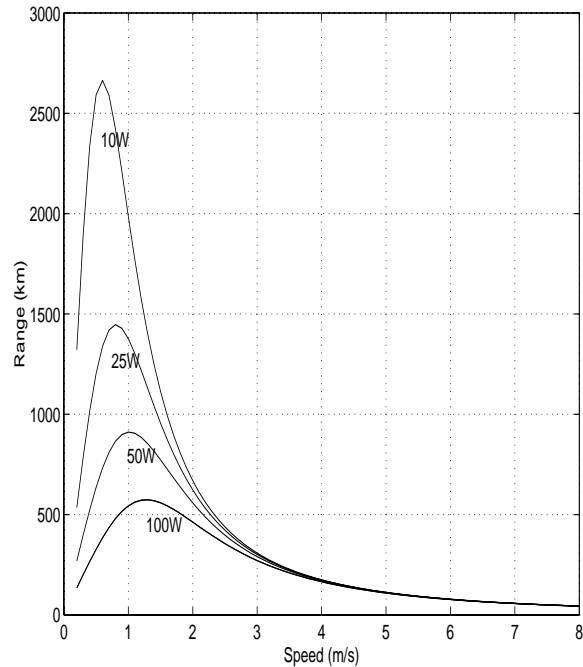


Figure 1: Range vs Speed Curves

We begin by assuming that the drag force F_d on the vehicle is

$$F_d = (1/2)\rho C_d S u^2 \quad (1)$$

where ρ is the density of water, C_d is the drag coefficient, S is the surface area for the body, and u is the speed at which the vehicle is travelling.

The energy E to travel a distance R is just

$$E = F_d R \quad (2)$$

For a battery pack of mass m_b and motor propeller efficiency η , the energy available for propulsion is

$$E = \eta B_0 m_b \quad (3)$$

where B_0 is the energy density of the batteries in J/kg.

With a floatation material having a specific gravity σ , the mass that can be carried is

$$m_b = V\rho(1 - \sigma) \quad (4)$$

where V is the volume of the floatation material. We can express the volume V and the surface area S of the AUV as functions of its length L .

$$V = V_0 L^3 \quad (5)$$

$$S = S_0 L^2 \quad (6)$$

where V_0 and S_0 are non-dimensional parameters which depend upon the shape of the vehicle.

Substituting values from (1), (4), (5), and (6) into (2) and (3) we get

$$\eta B_0 V_0 L^3 \rho(1 - \sigma) = (1/2)\rho C_d S_0 L^2 u^2 R \quad (7)$$

which reduces to

$$R = \left(\frac{2(1 - \sigma)V_0}{C_d S_0} \right) \frac{B_0 L}{u^2} \quad (8)$$

Equation (8) gives the range for an AUV when we consider the propulsion load alone. If we consider the hotel load P_H for sensing then (2) is modified to

$$E = F_d R + P_H(R/u) \quad (9)$$

Issues in AUV Design and Deployment for Oceanographic Research

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ABSTRACT

We look at some of the important requirements for making Autonomous Underwater Vehicles (AUVs) more ubiquitous in their role in Oceanographic research in the deep ocean. We show how some of the constraints in working underwater lead to unique solutions for complex multidimensional sets of design possibilities for working with real vehicles in the deep ocean. We identify three components in elaborating on our system optimization concepts - the use of power, sensing strategies, and navigation. We analyse several possible deployments from a theoretical and practical standpoint in which the effects of each of these components interact. We look at the tasks associated with long distance transits, with conducting a sonar survey as well as the task associated with navigating multiple vehicles in the same acoustic network.

INTRODUCTION

A number of AUVs are presently on the drawing board or in various stages of design or testing, with the eventual goal of being used as platforms for oceanographic research. Some of these vehicles are being designed for coastal oceanography, others for work in the deep ocean in the mid-water column, and still others for working in the deep ocean near the bottom[1][2][3][4]. The list of capabilities being developed for use with these vehicles is long and varied. It includes using them for long-term untended deployments where they would serve as platforms for spatio-temporal sampling; using multiple vehicles in combination for mapping out rapidly evolving phenomenon; and transitting long distances to a site for making observations as part of a first response team at the site of interest. In looking at these proposed missions it becomes

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obvious that the use of AUVs for oceanographic research is actually complementary to the use of manned submersibles and remotely operated vehicles. AUVs are seeking to evolve a niche where they serve as a cheap mechanism for doing spatio-temporal sampling. Their capabilities do not overlap with the manipulative capabilities of manned submersibles or with the very intensive multi-sensor, multi-scale survey capabilities of remotely operated vehicles.

Despite the various applications for which AUVs are intended it is interesting to note that most vehicles being designed for oceanographic research share some common characteristics. The most obvious being the relatively small size of these vehicles as compared to those vehicles being designed for military purposes[5] or for use in the offshore industry[6]. This is largely a function of the financial constraints placed by the oceanographic research community but is also driven by a need for ease in deployment and recovery. The other common characteristic, although there are several exceptions to this, is the shape of the vehicle. Given the small size of these vehicles and their limited payload capabilities, most vehicles are torpedo shaped in an effort to minimize drag and thus minimize the energy required for vehicle propulsion. This comes at a cost, however, as torpedo shaped vehicles do not have the ability to hover at a spot. Such vehicles are also inherently less stable in pitch and roll. While the attitude stability issues may be compensated by good control design techniques, the lack of a hovering capability translates to an inability to work very close to the bottom in harsh or very rugged terrain.

Only very recently have AUVs actually being doing real oceanographic research. The Autonomous Benthic Explorer (ABE) was deployed last year in the Juan de Fuca region off the coast of Oregon to help map out the magnetic characteristics of a new lava flow. It is currently scheduled to return to that site in the fall of this year. Two of the Odyssey IIB class vehicles from MIT were used to study the convective overturning associated with the mixing of fresh and salt water in the Haro Strait on the US-