Optimizing Hidden Markov Models for Ocean Feature Detection

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Abstract

Given the diversity and spatio-temporal scales of dynamic coastal processes, sampling is a challenging task for oceanographers. To meet this challenge new robotic platforms such as Autonomous Underwater Vehicle (AUV) are being increasingly used. For effective water sampling during a mission an AUV should be adaptive to its environment, which requires it to be able to identify these dynamic and episodic ocean features in-situ. We describe the use of Hidden Markov Models (HMM) as a feature detection model used onboard an AUV, an autonomous untethered robot. We show how to build an identification model from data collected during past missions. Then we show how the parameters of the HMM can be optimized using a Genetic Algorithm approach, from models trained with the Baum-Welch algorithm in the initial population.

Introduction

The coastal ocean offers a range of biogeochemical phenomenon of interest to oceanographers. Often these phenomena occur over unpredictable spatial and temporal extents and are difficult to observe using traditional ship-based oceanographic methods. To meet this challenge robotic platforms such as Autonomous Underwater Vehicles (AUVs), an untethered robotic platform, are being increasingly used as a cost effective way for sampling and observation. Robotic platforms such as AUVs are cost-effective, can be targeted towards specific features of scientific interest and are increasingly persistent in the water-column. Their effectiveness however, is often limited by their adaptability since the features in question are often dynamic and episodic and unpredictable in their spatial and temporal extents. To achieve its goals, the AUV must be able to identify whether or not it is within a feature of interest as detected by its sensors. Such identification allows the platform to use the paradigm of sense-plan-act to adapt its navigation and enable targeted water sampling for shore side analysis (McGann et al. 2008b; Py, Rajan, and McGann 2010).

One example of an AUV is Monterey Bay Aquarium Research Institute’s (MBARI) Dorado platform. Fig. 1 shows an image of the AUV with its Gulper water sampling system (Bird, Sherman, and Ryan 2007). Based on sensed data the AUV can decide in-situ whether to trigger a sampler for water acquisition (McGann et al. 2008a). As the AUV is equipped with a small number of samplers (10 in our case) which can be actuated only once per mission sampling comes at a cost. To make an accurate decision the AUV should have precise information about the state of the feature of interest.

The in-situ identification of a given feature is defined as a classification task. Given an observation from the sensors, the aim is to determine the state of the feature of interest. One implication is to detect whether the vehicle is outside, on the boundary or inside some feature such as an INL (Intermediate Nepheloid Layer\(^1\)) or an algal bloom. To detect the state of a feature of interest for the AUV, we first need to build an identification model. Initial work in this area addressed the problem of in-situ identification of water-column features by standard classification (Fox et al. 2007). Such reactive models rely on immediate sensor reading, ignoring the past. More recent efforts in this direction involve generating a systematic identification model based on Hidden Markov Models (HMMs) (Rabiner 1989) for estimating the environments’ state (Py, Celorrio, and Rajan 2010). HMMs exploit the sequential information of the sensor readings and thus provide more robust identification than standard classification.

In this paper we discuss the ocean feature-identification model for AUVs based on HMMs. This model is built using a two step machine learning process. First, semi-supervised clustering is done on the raw sensor data. The clusters thus identified are used, in the second step, as observations for

\(^1\)INLs are fluid sheets of suspended particulate matter that originate from the sea floor
building an HMM which serves as the identification model. The focus of our research here is to come up with the best possible parameter estimation scheme for the HMM. Traditional methods like the Baum-Welch (BW) algorithm (Baum et al. 1970) are unsupervised and offer locally optimal solutions. Furthermore they do not allow us to systematically bias the model easily.

We introduce labeled data and use Genetic Algorithms (GA) to further optimize the HMMs learned by the BW algorithm, aiming to produce models that better fit the data. GA also offers the flexibility to bias the model parameters allowing us to prevent false positive predictions for certain states.

This paper is organized as follows. A brief background on HMMs, their exploitation in-situ and the construction of the feature model is provided. We then discuss parameter optimization using GAs, the core of the paper. Experimental evaluation is followed by related work. The conclusion ends on HMMs, their exploitation in-situ and the construction of possible parameter estimation scheme for the HMM. Traditionally, the Baum-Welch (BW) algorithm (Baum et al. 1970) is unsupervised and offers locally optimal solutions. Furthermore, they do not allow us to systematically bias the model easily.

We introduce labeled data and use Genetic Algorithms (GA) to further optimize the HMMs learned by the BW algorithm, aiming to produce models that better fit the data. GA also offers the flexibility to bias the model parameters allowing us to prevent false positive predictions for certain states.

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Hidden Markov Model

A Hidden Markov Model is a state automaton in which the states are not directly visible. Instead we can access a set of observations which are probabilistically dependent on the current state of the system. For a HMM we need to define a discrete set of states \( S = \{s_1, s_2, \ldots, s_N\} \) and a discrete set of observations \( O = \{o_1, o_2, \ldots, o_M\} \).

A state at time \( t \) is denoted by \( q_t \). A HMM uses the Markov assumption that the current state is only dependent on the previous state. Between each pair of states \( i = 1, 2, \ldots, N \) and \( j = 1, 2, \ldots, N \) a transition probability is defined as \( a_{ij} = P(q_{t+1} = j | q_t = i) \)

The transition probabilities among all the states are represented by the square matrix \( A \) whose each element is \( a_{ij} \). Therefore we have the transition matrix:

\[
A_{N,N} = \begin{pmatrix}
    a_{1,1} & a_{1,2} & \cdots & a_{1,N} \\
    a_{2,1} & a_{2,2} & \cdots & a_{2,N} \\
    \vdots & \vdots & \ddots & \vdots \\
    a_{N,1} & a_{N,2} & \cdots & a_{N,N}
\end{pmatrix}
\]

Any transition which does not exist in the model has a zero entry in the transition matrix. Every row of the transition matrix is subject to the constraint:

\[
\sum_{j=1}^{N} a_{ij} = 1 \quad (1)
\]

Each state also has a probability distribution over the possible observations that can be emitted. An observation at time \( t \) is denoted by \( o_t \). Therefore, for each state \( j \in S \), observation \( k \in O \) pair, we have \( b_{jk}(k) = P(o_t = k | q_t = j) \) which gives the probability of observing the symbol \( k \) when in state \( j \) at time \( t \). Hence we define the emission matrix \( B \) as follows:

\[
B_{N,M} = \begin{pmatrix}
    b_{1}(1) & b_{1}(2) & \cdots & b_{1}(M) \\
    b_{2}(1) & b_{2}(2) & \cdots & b_{2}(M) \\
    \vdots & \vdots & \ddots & \vdots \\
    b_{N}(1) & b_{N}(2) & \cdots & b_{N}(M)
\end{pmatrix}
\]

where every row of the emission matrix is subject to the constraint:

\[
\sum_{k=1}^{M} b_{jk}(k) = 1 \quad (2)
\]

The initial state probability vector which gives us the probability of starting in a particular state is defined as \( \Pi = [\pi_1, \pi_2, \ldots, \pi_N] \) where each \( \pi_i \) gives the probability of starting in the state \( i \in S \). Hence a complete HMM can now be defined by the parameter set:

\[
\lambda = (A, B, \Pi)
\]

Exploiting HMM for Feature Identification

HMMs are useful for classifying data which does not appear in isolation but are part of a time series. We use a HMM as an identification model for in-situ identification of ocean features during an AUV mission. The identification is based on the HMM and observed sensor values. More specifically, we are interested in the probability of the feature being in a state \( j \) (for the purpose of robotic actuation) at the current time step \( t \) given an observation \( k \) and a model \( \lambda \), i.e., \( f_{wd}(1 : t, j) \). This probability is recursively computed, taking into account historical observations as:

\[
f_{wd}(1 : t, j) = \alpha_t b_{jk}(k) \sum_i a_{ij} f_{wd}(1 : t - 1, i)
\]

where \( \alpha_t \) is a normalization factor such that \( \sum_j f_{wd}(1 : t, j) = 1 \). The initial state of the HMM is Outside, therefore for the base case of \( t = 1 \), we have \( \Pi = [Outside = 1, Inside = 0, Boundary = 0 \text{ and } Centroid = 0] \).

Building the Feature Identification Model

A two-step machine learning process is defined to automatically build the feature identification model for the AUV. The process takes as input the raw sensor data and gives as output a Hidden Markov Model. The output HMM serves as the identification model for the feature of interest. For example, the HMM shown in Fig. 2 can identify four different states within the feature of interest. In this case the states outside the feature, at its boundary, inside or at the centroid are based on studies of INLs and their science requirements (McPhee-Shaw 2006; Ryan et al. 2010).

An overview of the process is shown in Fig 3. The sensor data available is partially labeled with the feature state it belongs to. Complete labeling of sensor data is usually not viable given the size of the datasets. For instance, a one
For a wide variety of problems.

A genetic algorithm is usually given as shown in Fig. 4; we note that to use a GA we need an initial population of solutions, an evaluation or fitness function, a selection mechanism for selecting solutions for crossover, a crossover function which keeps the solutions consistent and a way of mutating the solutions. For optimizing the HMM parameters we encode them as follows:

**Initial Population**

We initialize the population with the seed HMMs and the HMMs learned using Baum-Welch. Each HMM is represented in terms of its parameter set $\lambda = (A, B, \Pi)$. In our case the starting state is always *outside*, hence $\Pi$ does not have any significance. Thus we are left with the matrices $A$ and $B$. Transition Matrix $A$ is of size $4 \times 4$ as we have four states in our HMM. The emission Matrix $B$ is of size $4 \times 87$ as the number of found clusters (observations) is 87. These clusters are found using semi-supervised SOM clustering.

**Evaluation and Selection**

Most of other algorithms for training HMMs like the Baum-Welch, are designed specifically to maximize the log probability of observing the training observation sequence, while GAs offer the flexibility to define an arbitrary evaluation function for which the HMM can be optimized. This is useful to systematically bias the HMM for preventing false positive predictions for certain states. Our AUV takes water samples at the *boundary* and *centroid* states, hence we want to prevent false predictions for these states which are temporally transitory.

Performance evaluation of a model is done using a confusion matrix (Provost, Fawcett, and Kohavi 1998) which allows us to see if the model is confusing between two states and hence giving us a quantitative measure of error. Each row in this matrix indicates actual state instances and each column represents the state predicted by the identification model. For all the identification models the predicted state column represents the state predicted by the identification model. For all the identification models the predicted state is the one with the highest probability of occurrence with a good margin. The additional state *unknown* is predicted otherwise when states cannot be easily disambiguated. Each row of the confusion matrix is first normalized such that it sums up to 100. As a large percentage of our data belongs to the *outside* state, this avoids any bias towards a state which may contain more data points, by giving each state an equal weight.

To compute the final evaluation of a model we initially take the sum of the diagonal values of the confusion matrix.
Values in the diagonal of the matrix indicate the proportion of predictions that were correct. From this we subtract the entries corresponding to false positives for boundary and centroid states. For a model $\lambda$ with $N$ states we have a $N \times N$ confusion matrix $C$ with elements $c_{ij}$. The fitness of the model is calculated as follows:

$$\text{Fitness}(\lambda) = \sum_{i}^{N} c_{ii}^{\lambda} - \sum_{i \neq k_{1}}^{N} c_{ik_{1}}^{\lambda} - \sum_{i \neq k_{2}}^{N} c_{ik_{2}}^{\lambda}$$

where $k_{1}$ and $k_{2}$ are columns of $C$ corresponding to the boundary and centroid states respectively.

Two models from the population are randomly selected for crossover at every cycle of the GA since the models with best fitness tend to have similar parameters.

### Crossover

We are working with a non-random population of solutions (HMM parameters) which are subject to constraints in Eqns. 1 and 2. Therefore we only interchange the corresponding rows of the parameter matrices in a crossover. This helps in maintaining the consistency of solutions. For two models $\lambda_{1}$ and $\lambda_{2}$ we define a Transition Crossover $i$ w.r.t. the Transition Matrix $A$ as follows:

$$a_{ij}^{\lambda_{1}} \leftrightarrow a_{ij}^{\lambda_{2}}, \quad \forall j : 1 \leq j \leq N$$

(3)

Each $a_{ij}^{\lambda_{1}} \leftrightarrow a_{ij}^{\lambda_{2}}$ symbolizes the swap of the corresponding entries of matrices $A^{\lambda_{1}}$ and $A^{\lambda_{2}}$. A transition crossover shown in Eqn. 3 is a complete exchange of row $i$ among the transition matrices of models $\lambda_{1}$ and $\lambda_{2}$. There are $N$ such transition crossovers possible. They are numbered from 1 to $N$, corresponding to each row $i$ of transition matrix, for $1 \leq i \leq N$.

Similarly w.r.t. the Emission Matrix $B$ we define the Emission Crossover $N+j$ as:

$$b_{kj}^{\lambda_{1}}(k) \leftrightarrow b_{kj}^{\lambda_{2}}(k), \quad \forall k : 1 \leq k \leq M$$

(4)

Each $b_{kj}^{\lambda_{1}}(k) \leftrightarrow b_{kj}^{\lambda_{2}}(k)$ symbolizes the swap of the corresponding entries of matrices $B^{\lambda_{1}}$ and $B^{\lambda_{2}}$. An emission crossover shown in Eqn. 4 is a complete exchange of row $j$ among the emission matrices of models $\lambda_{1}$ and $\lambda_{2}$. There are $N$ such emission crossovers possible. They are numbered from $N+1$ to $2N$, corresponding to each row $j$ of emission matrix, for $1 \leq j \leq N$.

Consider the case in Fig. 5. Numbers 1 to 4 symbolizes the four rows of the transition matrix in a model, and numbers 5 to 8 symbolizes the rows of the emission matrix. Given the model constraints, we can only exchange rows with the same number between the Model 1 and Model 2 for a valid crossover. An transition crossover would be a crossover between rows 1 to 4 and a emission crossover would be a crossover between rows 5 to 8. From a GA point of view there is no difference between the Transition Crossover and the Emission Crossover. We simply perform a random number of Transition Crossover and/or Emission Crossover in each cycle of the GA.

### Mutation

Mutation is done by running a model through one iteration of the Baum-Welch algorithm. The seed model for this iteration is the current individual. The model resulting from the iteration of the Baum-Welch algorithm is the mutated model. Solutions produced by the mutation step are added back to the population.

The GA loop is terminated when no better individual is found for a constant number of iterations. The best performing individual is selected as the final solution.

### Experimental Evaluation

The data used for the experiments focuses on the detection of INL states from different AUV missions. The data has been divided into two classes; learning missions and test missions. Table 1 highlights the dataset. The learning mission data consists of a set of approximately 500,000 observations from four different AUV missions between the years 2003 and 2005 sparsely labeled at between 7% and 9.7%. This data is used by the Baum-Welch algorithm in mutation and while generating a model for the initial population. Baum-Welch algorithm ignores the labels in the data. The testing data used for model evaluation consists of approximately 150,000 observations from thirteen missions between 2008 and 2010. As the evaluation makes use of labels, more test data is labeled at ~ 21%.

Our experiments compare the performance of HMM models in terms of fitness over test missions. A detailed evaluation is done by using the normalized confusion matrix, used for calculating the fitness of a model. We select models at three different levels of optimization.

**Boot-strap Model** This model is constructed using learning data and serves as a seed model for Baum-Welch. First all unlabeled data points are labeled using a known probability distribution of observations over states. Then model parameters are estimated using a frequency counting technique. Table 2 shows the confusion matrix and fitness score for this model. The fitness value is 134.3 and the classification accuracy for boundary state is very poor.

**Baum-Welch Model** This model is built after running Baum-Welch over the boot-strap model. The learning data are used as a training set, after ignoring the labels.
Table 1: List of AUV missions used for experimentation

<table>
<thead>
<tr>
<th>Mission # (yr-day)</th>
<th>Date</th>
<th>Labeled</th>
</tr>
</thead>
<tbody>
<tr>
<td>Learning missions</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2003-308</td>
<td>Nov 4, 2003</td>
<td>7.0%</td>
</tr>
<tr>
<td>2004-028</td>
<td>Jan 28, 2004</td>
<td>7.8%</td>
</tr>
<tr>
<td>2004-321</td>
<td>Nov 16, 2004</td>
<td>7.1%</td>
</tr>
<tr>
<td>2005-306</td>
<td>Nov 2, 2005</td>
<td>9.7%</td>
</tr>
<tr>
<td>Test missions</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2008-315</td>
<td>Nov 10, 2008</td>
<td>13.0%</td>
</tr>
<tr>
<td>2008-318-1</td>
<td>Nov 13, 2008</td>
<td>16.3%</td>
</tr>
<tr>
<td>2008-318-2</td>
<td>Nov 13, 2008</td>
<td>9.8%</td>
</tr>
<tr>
<td>2009-308</td>
<td>Nov 4, 2009</td>
<td>12.9%</td>
</tr>
<tr>
<td>2009-313</td>
<td>Nov 9, 2009</td>
<td>25.0%</td>
</tr>
<tr>
<td>2009-342</td>
<td>Dec 8, 2009</td>
<td>35.0%</td>
</tr>
<tr>
<td>2009-348</td>
<td>Dec 14, 2009</td>
<td>22.7%</td>
</tr>
<tr>
<td>2010-081</td>
<td>Mar 22, 2010</td>
<td>10.6%</td>
</tr>
<tr>
<td>2010-082</td>
<td>Mar 23, 2010</td>
<td>23.8%</td>
</tr>
<tr>
<td>2010-083-1</td>
<td>Mar 24, 2010</td>
<td>27.4%</td>
</tr>
<tr>
<td>2010-083-2</td>
<td>Mar 24, 2010</td>
<td>29.7%</td>
</tr>
<tr>
<td>2010-118</td>
<td>Apr 28, 2010</td>
<td>28.3%</td>
</tr>
<tr>
<td>2010-119</td>
<td>Apr 29, 2010</td>
<td>22.7%</td>
</tr>
</tbody>
</table>

Table 2: Bootstrap Hidden Markov Model

<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>Out.</td>
<td>93.5</td>
<td>1.5</td>
<td>2.7</td>
<td>1.9</td>
<td>0.4</td>
</tr>
<tr>
<td>Bound.</td>
<td>66.4</td>
<td>2.6</td>
<td>9.2</td>
<td>0.0</td>
<td>21.7</td>
</tr>
<tr>
<td>In.</td>
<td>10.1</td>
<td>12.9</td>
<td>41.5</td>
<td>9.4</td>
<td>26.11</td>
</tr>
<tr>
<td>Cent.</td>
<td>17.3</td>
<td>11.1</td>
<td>33.2</td>
<td>33.5</td>
<td>4.9</td>
</tr>
<tr>
<td>Fitness Score</td>
<td>134.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3: Baum-Welch Hidden Markov Model

<table>
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<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>Out.</td>
<td>73.4</td>
<td>21.2</td>
<td>2.1</td>
<td>3.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Bound.</td>
<td>23.6</td>
<td>54.0</td>
<td>6.6</td>
<td>0.0</td>
<td>15.8</td>
</tr>
<tr>
<td>In.</td>
<td>5.0</td>
<td>4.1</td>
<td>25.8</td>
<td>44.5</td>
<td>20.6</td>
</tr>
<tr>
<td>Cent.</td>
<td>5.2</td>
<td>1.6</td>
<td>18.4</td>
<td>71.0</td>
<td>3.8</td>
</tr>
<tr>
<td>Fitness Score</td>
<td>149.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The confusion matrix for this model is shown in Table 3. Fitness for the model is 149.6 and the classification accuracy is 25.8 for the inside state. There are also large values of false positives for boundary and centroid states.

Genetic Algorithm Model This model is learned by using a GA with Boot-strap and the Baum-Welch models as the initial population. The confusion matrix for this model is shown in Table 4. The fitness for this model is 199.4. The percentage of false positives for the boundary is 5.0, 0.8 and 0.0 and for a centroid at 1.8, 0.0 and 8.8. This is low when compared to other models.

Table 4: GA Hidden Markov Model

<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>Out.</td>
<td>89.0</td>
<td>5.0</td>
<td>3.7</td>
<td>1.8</td>
<td>0.4</td>
</tr>
<tr>
<td>Bound.</td>
<td>45.8</td>
<td>23.9</td>
<td>8.8</td>
<td>0.0</td>
<td>21.4</td>
</tr>
<tr>
<td>In.</td>
<td>3.6</td>
<td>0.8</td>
<td>63.4</td>
<td>8.8</td>
<td>23.3</td>
</tr>
<tr>
<td>Cent.</td>
<td>3.0</td>
<td>0.0</td>
<td>52.8</td>
<td>39.6</td>
<td>4.5</td>
</tr>
<tr>
<td>Fitness Score</td>
<td>199.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The confusion matrix for this model is shown in Table 4. Fitness for the model is 199.4 and the classification accuracy is 25.8 for the inside state. There are also large values of false positives for boundary and centroid states.

Related Work

HMMs are a common approach for handling sequential data with various applications in the field of speech processing and analyzing biological data. The idea of using Genetic Algorithms (GA) to learn HMMs has been used earlier. These attempts can be categorized into three classes (Volkert 2006).

Model parameter evolution Earlier work of Chau et al. (Chau et al. 1997) using GA for optimizing HMM parameters started with a random population of solutions. Their objective was to maximize the log probability of observing the training sequences, $\log P(O|\lambda)$. Experiments showed improved performance over the Baum-Welch algorithm.

Slimane et al. (Slimane et al. 1996) conducted a series of experiments to study the use of genetic algorithm for optimizing HMM parameters. Their findings suggested that HMM trained by Baum-Welch using seeds generated by GA gives the best quality models. Kwong et al. (Kwong and Chau 1997) optimized HMM parameters for speech recognition using GAs.

Evolution of model parameters and structure Kwong et al. (Kwong et al. 2001) also developed a hybrid-GA to evolve both the topology and the model parameters of a left-right HMM for speech recognition.

A genetic algorithm training approach combined with Baum-Welch has been used by Yada et al. to train HMM models representing signal patterns in DNA sequences (Yada et al. 1994; Yada 1996). It evolved both the topology and model parameters.

HMMs evolved both for topology as well as model structure have been used by Thomsen (Thomsen 2002) for solving the problem of predicting the secondary structure of protein sequences.

Model structure evolution Recent work on optimizing the structure of HMM for biological sequence analysis and secondary structure prediction also use the GA approach. Won et al. (Won, Prgel-Bennett, and Krogh 2004; Won et al. 2005) have focused their efforts on evolving only topology, while the task of learning parameters is left to the Baum-Welch algorithm.

Our work is within the first class, most closely related to the approach of Slimane et al. We also use a combination of Baum-Welch and Genetic Algorithm to optimize the HMM parameters. Our approach differs from the above, as we try
to optimize the model found by Baum-Welch using GA instead of using it for producing seed models for Baum-Welch. We do this because, first we have partially labelled data for producing good seed models for Baum-Welch. And second, because our evaluation function is also different. Given that in our work data examples are typically unbalanced, our evaluation function aims to maximize the normalized accuracy taking into account the cost of false positives for certain states, whereas most other algorithms try to optimize log probability of observing the training sequences \( \log P(O|\lambda) \).

**Conclusion**

This paper presents an approach for in-situ identification of dynamic ocean features using a Hidden Markov Model. We present the use of Genetic Algorithms to further optimize the solution found by the Baum-Welch algorithm. Tables 3 and 4 show that more refined models can be found by using GAs over already optimized models. Additional optimization is not the only benefit of using GAs; the flexibility to design an arbitrary evaluation function allows introduction of systematic bias into the model where necessary. This is helpful in preventing false positives for certain states important in scenarios such as ours where the AUV has limited sample acquisition capability.

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**References**


