

Adaptive Sampling of Algal Blooms Using an Autonomous Underwater Vehicle and Satellite Imagery

Joana Fonseca*, Alexandre Rocha, Miguel Aguiar, Karl H. Johansson

Abstract—This paper proposes a method that uses satellite data to improve adaptive sampling missions. We find and track algal bloom fronts using an autonomous underwater vehicle (AUV) equipped with a sensor that measures the concentration of chlorophyll *a*. Chlorophyll *a* concentration indicates the presence of algal blooms. The proposed method learns the kernel parameters of a Gaussian process model using satellite images of chlorophyll *a* from previous days. The AUV estimates the chlorophyll *a* concentration online using locally collected data. The algal bloom front estimate is fed to the motion control algorithm. The performance of this method is evaluated through simulations using a real dataset of an algal bloom front in the Baltic. We consider a real-world scenario with sensor and localization noise and with a detailed AUV model.

I. INTRODUCTION

We develop an adaptive sampling approach using an autonomous underwater vehicle (AUV) and satellite data to monitor algal blooms. Algal blooms can cause human illness, and large-scale mortality of fish [1]. The scenario is illustrated in Fig. 1, highlighting the AUV and available satellite data. The algal blooms satellite data is obtained from the Copernicus Marine Environment Monitoring Service (CMEMS) [2]. Algal blooms occur naturally in the sea. However, when algae colonies experience abnormal growth, which can result in the production of harmful toxins [3], they are called harmful algal blooms. In the Baltic Sea, this is due to excessive nutrient input mainly attributed to human pollution [4]. The motivation to monitor algal blooms is due to their recent increase in frequency, intensity, and geographical distribution in parallel with the increased utilization of coastal waters for aquaculture [5]. There is a significant scientific and societal interest in developing systems for automated surveillance and monitoring of algal blooms. Traditional methods for observation, such as satellite imaging or ship-towed sensors, are generally unable to provide measurements at the spatial and temporal resolutions required to understand the detailed dynamic ocean phenomena [6]. While remote sensing with satellites can offer a first guess, such data is weather-dependent and prone to false positives in turbid coastal waters [7]. Therefore, we propose using AUVs that can sense water parameters at higher resolutions

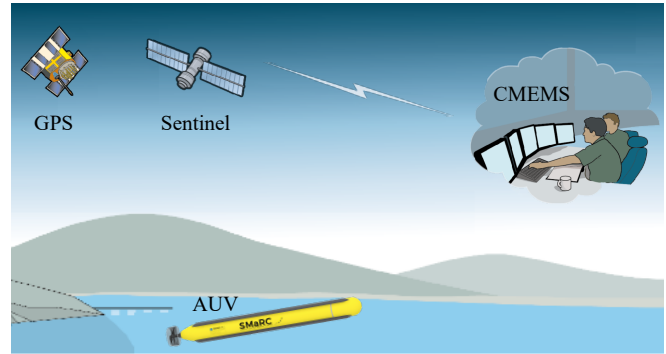


Fig. 1: System overview for algal bloom monitoring based on AUV and satellite imagery.

and coverage than research vessels and buoys at a reduced risk and cost. AUVs can perform measurement runs over a long period at sea [8], making them a suitable choice for oceanographic data collection [9].

There has been a significant amount of work in developing solutions for autonomous ocean sampling. A common approach in the literature is open-loop techniques with a fixed sampling pattern. A widely used sampling pattern is the lawn-mower [10], which has been used for both single-agent [11] and multi-agent [12] cases. Other relevant methods include the spiral and circular patterns in [13]. While these open-loop strategies guarantee coverage of survey areas, they do not react or respond to changes in the environment or the observed features. In such cases, one needs to close the loop. Adaptive sampling is such a closed-loop control in which an agent autonomously makes decisions during a mission in response to environmental changes [14], [15]. As reviewed in [16], adaptive sampling can be divided into three objectives: source localization, front determination, and tracking and mapping. Different types of targets can be considered: thermoclines, algal blooms, oil spills, etc. In addition, using different vehicles can be deployed: single-agent, multi-agent with leader-follower, cooperative multi-agent, etc. Similar to this paper, an adaptive sampling algorithm that augments a standard Gaussian process (GP) with a nearest neighbors prior is proposed in [17]. Unlike our approach, however, [17] does not use external data to aid the vehicle's decisions. One essential problem is how to aid ocean sampling missions with external data. An early approach uses predictive ocean models to assist in solving the motion planning problem of steering an AUV to a desired location [18]. Here, it is assumed that there is a prediction for the day of the mission, which is not available in this

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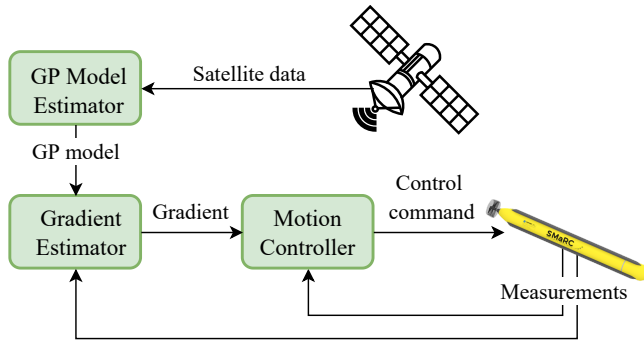


Fig. 2: System architecture and its main components: the satellite data, the GP model estimator, the gradient estimator, the motion controller, and the AUV.

paper’s scenario. Another related result uses knowledge from previous missions to create a model [19].

The main contribution of this paper is a system for algal bloom front tracking comprising a GP model estimator, a gradient estimator, and a motion controller. The GP model estimates the chlorophyll *a* concentration field using satellite data and is updated in real-time by conditioning it on the measurements collected by the AUV. The gradient estimator derives the gradient of the chlorophyll *a* concentration field. The motion controller implements a path-planning guidance law for adaptive sampling using the estimated chlorophyll *a* concentration and field gradient. We run an experimental evaluation in a simulated environment that highlights the performance of the estimators and controller, considering sensor noise and a detailed AUV model.

The paper is organized as follows. In Section II, we introduce the proposed front tracking algorithm. This includes the system architecture, the satellite data, the GP model for the chlorophyll *a* concentration, the gradient estimator, the motion controller, and the AUV model. In Section III, we analyze the algorithm’s performance with simulations considering disturbances and noise. Concluding remarks and future directions follow in Section IV.

II. ALGAL BLOOM FRONT TRACKING

This paper considers algal bloom front tracking as an adaptive environmental sampling problem. The objective of front tracking is to find and track a front with no global information on the front’s location or shape and only use local information collected by the AUV itself as it moves to explore the map. Then, the AUV has to decide where to explore next, given the information it has collected so far. We approach this problem using an AUV with a chlorophyll *a* sensor and remote satellite data from CMEMS. Our solution consists of a novel system architecture containing three main components, as seen in the three green blocks of Fig. 2. In the following subsections, we present the system architecture and its components.

A. System Architecture

The system architecture is summarised in Fig. 2. Here, we illustrate the main components of the proposed system,

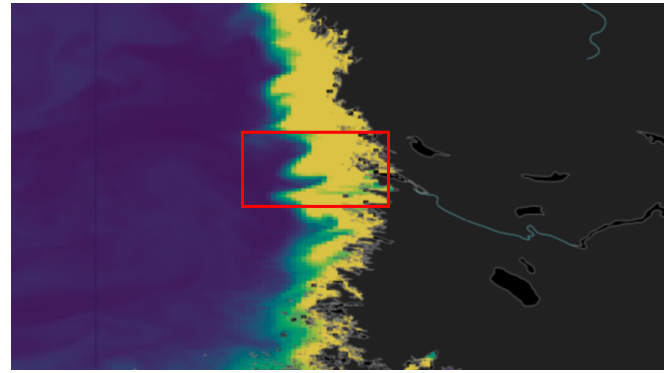


Fig. 3: Optical data available to the AUV before the mission day, with a 2x2km resolution of chlorophyll *a* in the Baltic Sea (blue-yellow) and land (dark grey).

from the AUV to the motion controller, gradient estimator, GP model estimator, and satellite data.

The AUV has a chlorophyll *a* sensor that measures the chlorophyll *a* concentration at a set frequency as it moves in the field. The AUV movement is dictated by the control command received from the motion controller. The motion controller uses the AUV’s past measurements and an estimation of the field gradient to calculate the control command, closing the adaptive sampling loop. The gradient estimator uses the past measurements taken by the AUV and a model of the chlorophyll *a* concentration field to estimate the chlorophyll *a* concentration field gradient. The GP model estimator uses the previous days of satellite data to train kernel parameters of a GP model that represents the field we want to estimate. Finally, the satellite data consists of remote measurements of the chlorophyll *a* concentration field from a few days preceding the mission and is used in the GP model estimator to generate the GP model estimate of the chlorophyll *a* concentration field.

B. Satellite Data

The satellite provides an optical 2D image and concerns chlorophyll *a* concentration for a given region. We denote this chlorophyll *a* concentration field by $\delta(\mathbf{p})$, where δ denotes the chlorophyll *a* concentration at position \mathbf{p} . In this paper, we consider surface data only. Fig. 3 shows a plot of sample chlorophyll *a* concentration data, where high regions of high concentration are highlighted in yellow and regions of low concentration are highlighted in blue. The dark grey area represents the land. This data has a spatial resolution of 2 km by 2 km and is obtained from CMEMS [20].

The AUV has access to this dataset before deployment, as the data corresponds to days prior to the mission day. The location is on the west coast of Finland, near the coastal city *Pori*. We chose this location because there’s a clear chlorophyll *a* bloom front which we hypothesize is due to the nutrients that the river *Kokemäenjoki* carries into the Baltic sea [21]. In this paper, we’ll focus on the region marked by the red square taken on the 17th of April 2021. We chose April because it is the spring season of algal blooms.

C. GP Model Estimator

The GP model estimator models the chlorophyll *a* concentration field $\bar{\delta}(\mathbf{p})$ for the given region and time, exploiting prior information from satellite data of the previous days and measurements taken by the AUV in real-time. Given this application's slow time scale, we assume that the chlorophyll *a* concentration fields at different days have identical distributions, simplifying model fitting and reducing computational complexity.

To obtain the chlorophyll *a* concentration model, we must define the type of kernel that will accurately depict the process. The kernel represents *a priori* knowledge about the process by specifying how the chlorophyll *a* concentration data is related to the corresponding spatial locations. Among the many kernels described in the literature, only some fit the characteristics of the biogeochemical data we consider. We use the Matérn kernel [22], which is capable of modeling different degrees of smoothness across both vertical and horizontal length scales [23]. The covariance matrix $K \in \mathbb{R}^{N \times N}$ is defined with respect to two points in the field map, x_i and x_j . Each element of the matrix is computed by the kernel function $k(x_i, x_j)$ for which $1 \leq i, j \leq N$. The kernel is defined as

$$K_{i,j} = k(x_i, x_j) = \sigma_k^2(1+r)e^{-r}, \quad (1)$$

where $r^2 = (x_i - x_j)^\top M(x_i - x_j)$, with

$$M = \begin{bmatrix} \left(\frac{\sqrt{3}}{l_0}\right)^2 & 0 \\ 0 & \left(\frac{\sqrt{3}}{l_1}\right)^2 \end{bmatrix}. \quad (2)$$

The kernel hyper-parameters are (σ_k^2, l_0, l_1) , where σ_k^2 is the variance of the chlorophyll *a* concentration process, and (l_0, l_1) define the length scale in each dimension.

The kernel hyper-parameters, (σ_k^2, l_0, l_1) , are estimated by maximizing the log marginal likelihood of the prior distribution - using only the available satellite data from previous days. This data is called the training set and consists of a vector of size N containing positions in the chlorophyll *a* concentration field $\mathbf{X} = [\mathbf{p}_1, \dots, \mathbf{p}_N]$, and their respective chlorophyll *a* concentration value $\mathbf{y} = [\delta_1, \dots, \delta_N]$. The log marginal likelihood to maximize is

$$\begin{aligned} \log p(\mathbf{y}|\mathbf{X}) = & \\ & -\frac{1}{2}\mathbf{y}^\top (K + \sigma^2 I)^{-1} \mathbf{y} - \frac{1}{2} \log |K + \sigma^2 I| - \frac{N}{2} \log 2\pi \end{aligned} \quad (3)$$

where K is the $N \times N$ covariance matrix in which each value is created as in (1), and σ is the noise variance of each data point.

Using the trained kernel, the GP model can be fitted with the collected data, using the standard conditioning formulas [22] to obtain the model for the chlorophyll *a* concentration field, which we define as $\bar{\delta}(\mathbf{p})$. To do that, we consider the n most recent measurements taken by the AUV. It contains the AUV's positions $\mathbf{P} = [\mathbf{p}_1, \dots, \mathbf{p}_n]$, and its chlorophyll *a* concentration measurements $\Delta = [\delta_1, \dots, \delta_n]$. Then, the mean of the model $\bar{\delta}(\mathbf{p})$ is denoted by $\bar{\delta}(\mathbf{p})$ and

the covariance by $\text{cov}(\bar{\delta}(\mathbf{p}))$. We can compute the mean and covariance at some point \mathbf{p}_* as

$$\bar{\delta}(\mathbf{p}_*) = K_* (K + \sigma^2 I)^{-1} \Delta \quad (4)$$

$$\text{cov}(\bar{\delta}(\mathbf{p}_*)) = K_{**} - K_* [K + \sigma^2 I]^{-1} K_*^T \quad (5)$$

where $K \in \mathbb{R}^{n \times n}$ corresponds to the covariance between the data in points \mathbf{P} , $K_* \in \mathbb{R}^{1 \times n}$ corresponds to the covariance between the data in points \mathbf{p}_* and \mathbf{P} , $K_{**} = \sigma^2$ corresponds to the variance at the point \mathbf{p}_* , and σ^2 is the variance of the measurement noise. Since the set of the n most recent measurements is changing in time, then our estimate $\bar{\delta}(\mathbf{p}_*)$ is also changing in time.

D. Gradient Estimator

The gradient estimator derives the previously obtained model of the chlorophyll *a* concentration to produce an estimate of the chlorophyll *a* concentration gradient field. From the equation (4), the gradient $\nabla \bar{\delta}(\mathbf{p}_*)$ is obtained by computing the derivative of the predicted chlorophyll *a* concentration with respect to position \mathbf{p}_* ,

$$\nabla \bar{\delta}(\mathbf{p}_*) = \nabla_{\mathbf{p}_*} [K_* (K + \sigma^2 I)^{-1} \Delta]. \quad (6)$$

Since the second and third terms inside the gradient in (6) are constant relative to \mathbf{p}_* , we only need to compute $\nabla_{\mathbf{p}_*} K_*$. Each element of the K_* matrix is given by (1), in which x_i corresponds to \mathbf{p}_* and x_j corresponds to $\mathbf{p}_j \in \mathbf{P}$. So we take the derivative of $k(\mathbf{p}_*, \mathbf{p}_j)$ with respect to \mathbf{p}_* ,

$$\nabla_{\mathbf{p}_*} k(\mathbf{p}_*, \mathbf{p}_j) = -\sigma_k^2 e^{-r} M(\mathbf{p}_* - \mathbf{p}_j),$$

where M and r are as in subsection II-C. Note that the gradient of the kernel equation is not defined when the test point in \mathbf{P} is equal to the current position \mathbf{p}_* . To account for this, the current position \mathbf{p}_* is not included in \mathbf{P} when computing (6). Then the gradient estimate at position \mathbf{p}_* is

$$\nabla \bar{\delta}(\mathbf{p}_*) = \nabla_{\mathbf{p}_*} K_* (K + \sigma^2 I)^{-1} \Delta. \quad (7)$$

E. AUV

The AUV receives the control command \mathbf{u} from the motion controller, which is the reference for direction and velocity. Then, using its internal lower-level controller, the AUV turns this reference \mathbf{u} into thrust commands to its thrusters τ_C . For this AUV, we consider the 6DOF model in which the state is the velocity vector given by $\boldsymbol{\nu} = [u \ v \ w \ p \ q \ r]^T$ containing the translational and rotational velocities. Note that these velocity vector elements directly influence the AUV's position \mathbf{p} .

The dynamics of the AUV can be formulated as a nonlinear system represented by a vectorial notation presented by Fossen [24] as follows:

$$\begin{aligned} (M_{RB} + M_A)\dot{\boldsymbol{\nu}} + (C_{RB}(\boldsymbol{\nu}) + C_A(\boldsymbol{\nu}))\boldsymbol{\nu} + \\ D(\boldsymbol{\nu})\boldsymbol{\nu} + \mathbf{g}(\boldsymbol{\eta}) = \boldsymbol{\tau}_C, \end{aligned} \quad (8)$$

where M_{RB} is the rigid body mass and inertia matrix and C_{RB} is the matrix of Coriolis and centripetal terms on the left-hand side. M_A and $C_A(\boldsymbol{\nu})$ represent the effect of added

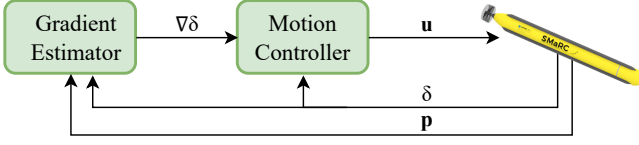


Fig. 4: Control architecture with the motion controller, the gradient estimator, and the AUV.

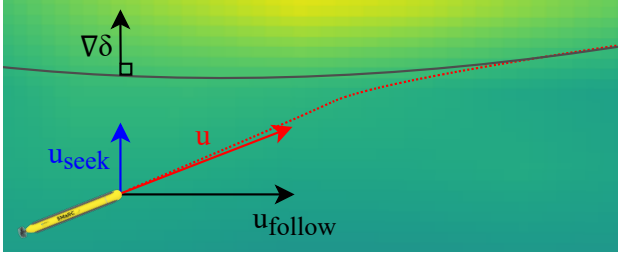


Fig. 5: Visualization of the seek and follow components of the control law and the gradient of the chlorophyll a concentration field.

mass, $D(\nu)$ represents the damping matrix, and $g(\eta)$ is the vector of gravitational and buoyancy forces and moments. τ_C is a vector of external control forces based on the AUV's actuator configuration.

F. Motion Controller

The control law we propose is summarised in Fig. 4. It relies on the chlorophyll a gradient $\nabla\delta$ and the latest chlorophyll a concentration measurement δ to produce a control command \mathbf{u} . First, we define a front as a level set of a time-varying scalar field $\delta: \mathbb{R} \times \mathbb{R}^2 \rightarrow \mathbb{R}$:

$$F(t) = \{\mathbf{p} \in \mathbb{R}^2 : \delta(t, \mathbf{p}) = \delta_{\text{ref}}\}, \quad (9)$$

where δ_{ref} is some reference value, \mathbf{p} the position and t time.

Assuming that the reference value δ_{ref} is known, we used the previously developed control law as in [25]. There, we define the control law as

$$\begin{aligned} \mathbf{u}(t, \mathbf{p}) &= \mathbf{u}_{\text{seek}}(t, \mathbf{p}) + \mathbf{u}_{\text{follow}}(t, \mathbf{p}) \\ \mathbf{u}_{\text{seek}}(t, \mathbf{p}) &= -\alpha_{\text{seek}}(\delta(t, \mathbf{p}) - \delta_{\text{ref}})\nabla\delta(t, \mathbf{p}) \\ \mathbf{u}_{\text{follow}}(t, \mathbf{p}) &= \alpha_{\text{follow}}R_{\pi/2}\nabla\delta(t, \mathbf{p}), \end{aligned} \quad (10)$$

where $\nabla\delta$ is the gradient of δ with respect to \mathbf{p} , $R_{\pi/2}$ is a mapping which rotates vectors by 90 degrees, and α_{seek} and α_{follow} are tunable parameters.

As seen in Fig. 5, the control law consists of two components: \mathbf{u}_{seek} , which controls the AUV towards the front by following the gradient field, and $\mathbf{u}_{\text{follow}}$ which controls the AUV to move along the front, perpendicularly to the gradient field. We ensure convergence to the front [26] by designing the control law with these two components. Namely, note that if $\delta(t, \mathbf{p}) \neq \delta_{\text{ref}}$, the \mathbf{u}_{seek} component grows proportionally to this difference, making seeking the front a priority, comparing to following the front. On the other hand, if the AUV is on the front, the most prominent component becomes the $\mathbf{u}_{\text{follow}}$.

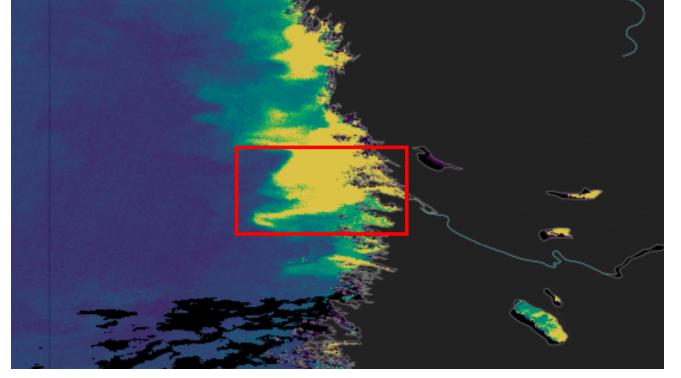


Fig. 6: Optical data not available to the AUV, used only for simulations purposes to emulate the field on the mission day, with a 300x300m resolution of chlorophyll a concentration in the Baltic Sea (blue-yellow), clouds and cloud coverage (black), and land (dark grey).

III. EXPERIMENTAL EVALUATION

In this section, the proposed system architecture and its corresponding control and estimation components are tested in a scenario of an algal bloom front tracking mission. We first define the experimental setup for this section and then present and analyze the numerical results.

A. Experimental Setup

For this scenario, we consider the environment illustrated in Fig. 6 in which we will deploy the AUV and track the algal bloom front. Here, the chlorophyll a concentration is represented by a map that goes gradually from a high concentration in yellow to a low concentration in blue; these values will be measured by the chlorophyll a concentration sensor mounted on the AUV. More specifically, the simulated mission will occur inside the red square. The data we use to simulate this environment has a spatial resolution of 300 m by 300 m [27], and the location is in Pori, Finland, the same location as the satellite data we considered earlier in Fig. 3. Note that this high-resolution dataset is the ground truth environment in which the AUV will be deployed and track the algal bloom front during the simulation. The AUV does not have access to this dataset beyond the sensor measurements it takes while tracking the front. It is of higher resolution than the dataset presented in Subsection II-B, which the AUV has access to and uses to train its GP hyperparameters.

The source code that implements the algorithm is available as an open-source contribution on two repositories. The first one is the Gaussian Processes for Adaptive Environmental Sampling (GP4AES) library, which includes the GP model estimator, the gradient estimator, and the motion controller <https://github.com/JoanaFonsec/gp4aes>. The second one is the ROS [28] interface, which uses the GP4AES library and handles the connection with the AUV's software <https://github.com/JoanaFonsec/algalbloom-tracking>.

The simulation starts by deploying the AUV close to the front and providing it with an initial gradient estimation. When the AUV is near the front, the gradient estimation is

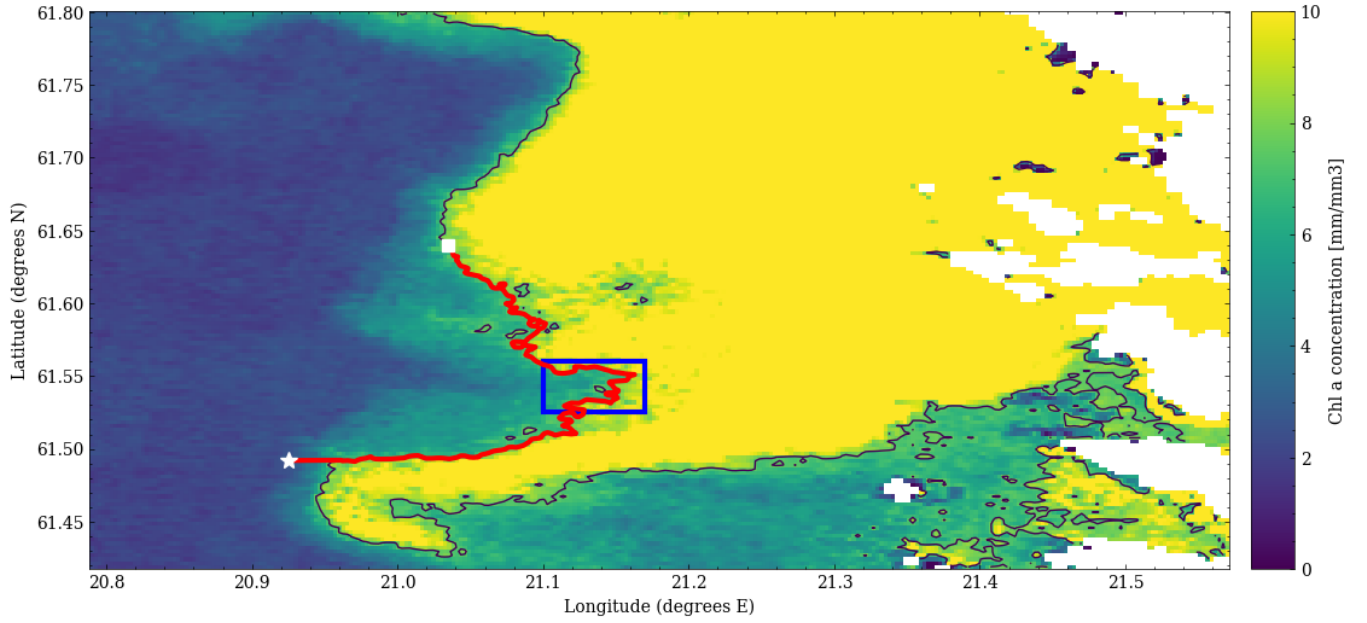


Fig. 7: Overview of the complete mission with the trajectory of the AUV (red) tracking the front (black) in the chlorophyll *a* field (blue-yellow). The white star indicates the initial position, and the white square the final position. The blue rectangle indicates the area that will be further analyzed.

triggered. The AUV speed is fixed at 1 m/s. For that reason, we are interested only in the ratio of α_{seek} and α_{follow} , and thus the latter is set to 1. Moreover, we consider $\delta_{\text{ref}} = 7.45 \text{ mg/m}^3$, based on the available satellite data. While tracking the front, the AUV collects a measurement at $f = 1 \text{ Hz}$, considering a standard deviation of the measurement noise of $\sigma = 10^{-3} \text{ mg/m}^3$. The measurements are filtered using a weighted moving average filter of size 3. For this example, we chose the weights as $w = [0.2, 0.3, 0.5]$, with

$$\delta_{\text{filtered}}(t) = w_{-2}\delta(t-2) + w_{-1}\delta(t-1) + w_0\delta(t). \quad (11)$$

With the same sampling rate, the gradient is estimated as in (6), using data from the last $n = 200$ measurements. Then we apply a first-order low pass filter, with $\alpha = 0.97$,

$$\nabla \delta_{\text{filtered}}(t) = \alpha \nabla \delta(t-1) + (1-\alpha) \nabla \delta(t). \quad (12)$$

The parameters described are summarised in Table I.

TABLE I: Control algorithm parameters.

σ	α_{seek}	v	n	δ_{ref}	α
10^{-3} mg/m^3	20	1 m/s	200	7.45 mg/m^3	0.97

B. Numerical Results

We illustrate the complete AUV mission in Fig. 7 where the AUV is following the front while collecting chlorophyll *a* concentration measurements, estimating the chlorophyll *a* concentration field and its field gradient, and updating its direction. The complete mission has a duration of 13 hours, approximately. The starting position is far from the bloom and represented by the white star, while the final position is on the front and represented by the white square. In this figure, the AUV closely follows the algal bloom front. This

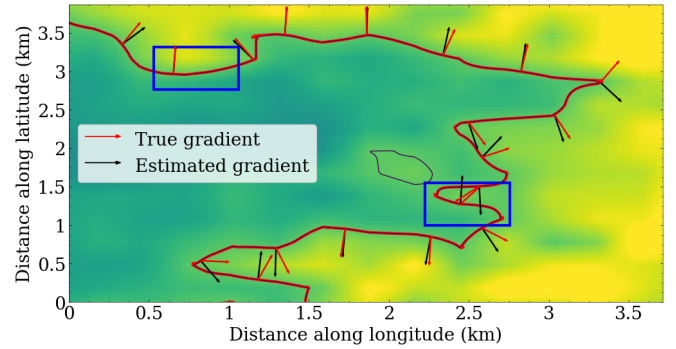


Fig. 8: Zoomed-in trajectory of the AUV (red) tracking the front (black), with arrows representing the true and estimated gradient. The two blue rectangles indicate the areas that will be further analyzed.

is further analyzed in Fig. 8, in which we focus and zoom in on the area inside of the blue square.

In Fig. 8, we zoom-in in on a region of the mission, previously defined by a blue square, to focus on the performance of the gradient estimation. This region corresponds to about 3.3 hours of mission time. Here we illustrate the gradient performance through arrows representing both the true and estimated gradients along the path. The true gradient refers to the gradient that the AUV would be able to compute if it had access to the global information of the field. We compute it by taking the spatial derivative of the chlorophyll *a* concentration field. The estimated gradient refers to the output of the gradient estimator, as in (7). The angle between the true and estimated gradient arrows indicates the gradient error. However, in this scenario, the chlorophyll *a* concentration field is non-convex and fast-changing even in small areas. Therefore, the gradient is an abstraction that gives an idea of direction rather than an exact measure of the gradient. If we analyze the straight portions

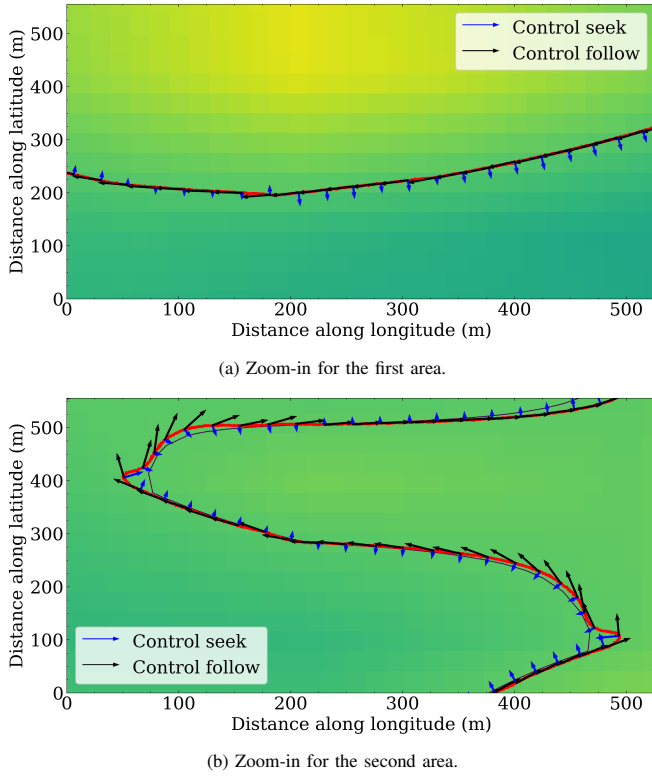
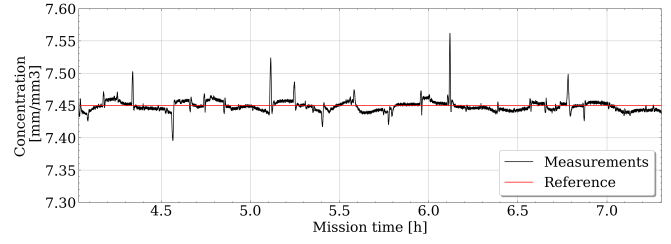


Fig. 9: Zoom-in trajectory of the AUV (red) tracking the front (black), with arrows representing seek and follow components of the control law.

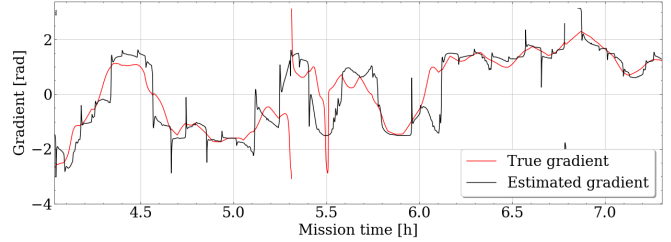
of the path, we would say that the error is very close to zero, while by analyzing the portions of the path with higher curvature, we could say that the error is larger while the gradient looks ambiguous and sensitive to small changes in position. As for the control performance, this figure doesn't allow for such analysis, so we zoom-in in on the two areas inside the blue squares.

Let us now analyze the performance of the control and its control components in Fig. 9. These figures correspond to the two zoom-in locations of the previous figure, the front is represented by the thin black line, and the AUV path is represented by a thicker red line. We also plot the seek and follow components of the control law using arrows along the AUV path. The control law is constructed as in eq.10, and it is a sum of the seek component, which has the same direction as the estimated gradient, and the follow component, which has a perpendicular direction with respect to the estimated gradient. This sum constitutes the control law corresponding to the AUV's direction of movement. In the first zoom-in, in Fig. 9a, the AUV always follows the front closely and with minimal error. Here, the follow component is always dominant, compared to the seek component of the control law. This is expected as the front is smooth in curvature, and the AUV remains on top of the front. The control seek component accounts for small adjustments in the trajectory, to drive the AUV towards the front.

In the second zoom-in, in Fig. 9b, the AUV remains on top of the front most of the time, and thus the control follow component dominates the control law. On the other hand, once the curvature changes at a faster pace, the control



(a) Concentration of chlorophyll a : measurements from the AUV, and reference value.



(b) Gradient of the of chlorophyll a field: Estimated from GP model and ground truth.

Fig. 10: Analysis for the zoom-in region of Fig. 8, consisting of concentration of chlorophyll a and gradient of the chlorophyll a field.

follow component reduces, and the control seek becomes the dominating component. In this scenario of fast-changing curvature, the AUV seems to have a delay in updating its direction. There are two leading causes for this behavior: the AUV's turning radius and the update function with the update rate on the gradient. The gradient's update function in (12) introduces a delay and a cut-off frequency. This cut-off frequency is inversely proportional to the update rate, so the algorithm's performance becomes a trade-off between the smoothness introduced by the update function with a smaller update rate and the delay introduced by it. For this scenario, we considered smoothness of movement a more important objective than the apparent delay in the tighter curvature of the front.

We further analyze the algorithm's behavior through time series plots in Fig. 10 corresponding to the zoomed-in area in Fig. 8. First, we consider the chlorophyll a concentration measurements taken along the path in Fig. 10a. The time series indicates that, as seen in the previous figures, the AUV is always on top of the front, oscillating around it and with a minimal error, in this case, lower than $\pm 0.1 \text{ mg/m}^3$. Second, we consider the gradient field estimation also taken along the mission, in Fig. 10b. This time series also confirms what we saw in the previous figures. Here we can see both the delay of the estimated gradient and its smoothness in comparison with the true gradient. Finally, let us further analyze the control law, considering the time series of the two control components in Fig. 11, for the region in Fig. 9. For the first zoom-in area, which considers an almost linear segment of the front, we get a small oscillation in Fig. 11a. This corresponds to the zig-zag around the curve that we see in the corresponding path figure. Whereas in the second zoom-in, in which we consider a segment with two tight curves, Fig. 11b, we see different patterns that represent oscillation around the front, followed by constant, almost linear tracking with the control follow component dominating. For both examples,

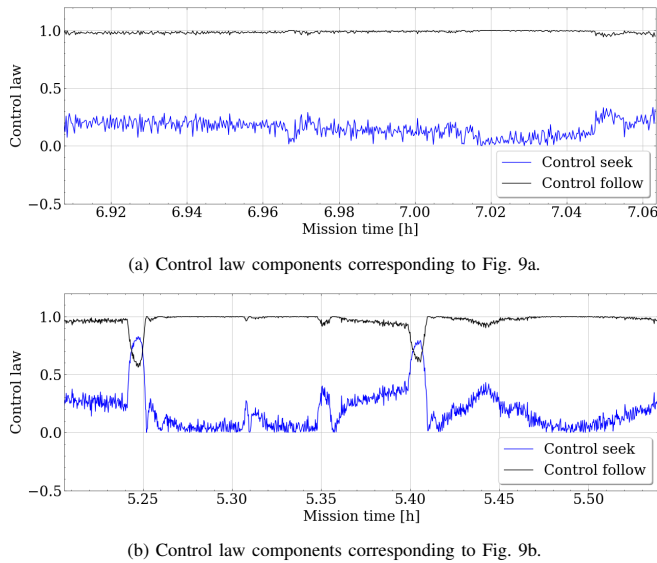


Fig. 11: Analysis of the control law components seek and follow, for the two regions of Fig. 9.

the follow component dominates the control law, and the seek component grows when the AUV is far from the front.

IV. CONCLUSIONS

We considered the problem of how to use satellite data to improve adaptive sampling missions of an AUV equipped with a chlorophyll *a* concentration sensor. Our solution used GPs to model a chlorophyll *a* concentration front, from which we derived the chlorophyll *a* concentration field gradient and integrated it into the front tracking algorithm. The front tracking algorithm was tested on a realistic simulated environment, including a detailed AUV model and sensor noise. The results indicated that the AUV could find and track the front closely and that both the control law and the gradient estimator result in convergence to the desired behavior with bounded errors.

Our future plan is to run experiments using this method. This will consist of testing and improving the method implemented in ROS, running more simulations on *Stonefish*, integrating the chlorophyll *a* sensor on the AUV, and, finally, running experiments on a local front in the summer of 2023 in the Stockholm archipelago.

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