Lizhbeth: Toward Autonomous Toxic Algae Bloom Monitoring

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***Abstract*—With the recent increase of toxic algal blooms in lakes, biologists are looking for new sampling methods to analyze their spatiotemporal dynamics. In this paper, we present an Autonomous Surface Vessel (ASV) capable of achieving long-term sampling missions covering up to now a transect plane (1.5 km wide and 20 m deep). The ASV is equipped with a probe which can be lowered via a winch to measure critical environmental parameters allowing more sophisticated prediction models of toxic algal blooms. So far, 21 km of autonomous sampling confirmed the system stability and produced enough basin-wide biological data to gain biologists' interest. We intend to use this ASV as basis to further explore autonomous navigation on inland waterbodies.**

I. Introduction

A. Biological Background

The monitoring of water resources is of increasing importance as Earth's reservoirs of clean, potable water are drained by the growing human population, rapid economic growth, and environmental degradation [1]. One emerging threat to freshwater ecosystems is the growing incidence of mass proliferation (bloom) of toxic cyanobacteria (blue-green algae) [2] caused by rising rates of anthropogenic nutrient inputs [3]. The escalating occurrence of toxic blooms in freshwaters will likely be intensified due to the global increase of air temperatures [4].

For many lakes however, the basin-wide variability of these toxic algae at a given season and/or throughout the year are still poorly documented. Biologists are actively looking for solutions to increase the spatial and temporal data acquisition to improve the monitoring of those toxic algae, and to expand their understanding of lake ecosystems in general.

B. Automated Data Acquisition

Automated sensing technologies are developing into an increasingly important tool both for water quality monitoring and for research in aquatic microbial ecology [5]. So far, most systems for automated data acquisition in freshwaters are stationary buoys that do not allow for the investigation of horizontal heterogeneity in lakes. Academic institutions around the world are actively developing and deploying Autonomous Underwater Vehicles (AUV) and Autonomous Surface Vessels (ASV), but these are devoted to extended observation networks in coastal and marine environments [6]. So far, few studies have applied this technology for limnological work (i.e. the study of inland waters), and none of these deployments aimed for long-term missions on the order of months or years [7].

Even if oceanography has been leading researches in remote sensing for many years, new technical approaches must be developed to account for the specific needs of lake monitoring. In this article, we present our ongoing development of an ASV suited for limnological studies (see fig. 1), recent observations following field tests realized over the last year and, finally, future research orientations for our lake platform.

Fig. 1: Lizhbeth, our limnological ASV, during a sampling mission on Lake Zurich. The probe is in its parking position out of the water.

II. State of the Art

The domain of field robotics has recently gained more interest in AUV and ASV. The three most important uses of these platforms are military applications, structure inspections (particularly in the oil industry) and ecological studies. As a result, many universities around the world have developed or are developing their first prototypes. Whereas research in the field of AUVs is more concerned about localization and communication methods, surface vessels usually use GPS for localization. Military and defense applications deploy ASVs to patrol shorelines or harbors. Elkins et al. [8] have developed a ASV that operates on relatively large motor boats and feature a sophisticated set of sensors to detect obstacles or target boats, which can then be followed.

Applications for environment monitoring usually feature electrically driven ASVs, and aim for long-term autonomy because environmental dynamics occur on monthly to yearly time-scales. Some systems (e.g [9]) also employ solar panels

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to extend their maximal range. Caccia et al. developed an ASV called Sea Surface Autonomous Modular Unit (SESAMO) [10] to analyze the water quality of coastal marine waters in combination with atmospheric parameters. Other groups have also developed ASV for marine environment monitoring ([11], [7]), but the work by Dunbabin et al. [12] relates better to ours since it also uses sensors to measure physicochemical parameters of lakes. However, their equipment is designed for sampling at maximal depths of 5 m only. The maximal depth of 20 m can only be reached in stationary operation.

Given that toxic cyanobacteria can be found as deep as 25 m [13], new technical approaches are needed.

III. SPECIFICATIONS

A. Environment

Planktothrix spp. are among the most important producers of hepatotoxic microcystins in freshwaters [14], and *Planktothrix rubescens* are commonly observed in numerous lakes of the Northern Hemisphere [15]. For these reasons, our ASV is mainly employed to study the spatial and temporal variations of the toxic cyanobacterium *P. rubescens* populations in pre-alpine lakes. Our principal experimental field is Lake Zurich, which has an elongated shape of approximately 36 km long and has a maximal width of 4 km. This large (66.8 km^2) and deep lake (136 m, mean depth = 49.9 m) is subject to the typical seasonal dynamics seen in pre-alpine lakes, i.e. a summer thermal stratification followed by an autumnal mixis. Recurrent blooms of *P. rubescens* observed in Lake Zurich usually occur between late summer and winter. Surface water temperature varies from above 20 °C in summer to around 5 °C in winter. Lake Zurich is a very popular recreational area and is the major source of drinking water for the city of Zurich. The region of interest is a transect of 1.5 km close to the deepest point of the lake.

B. Goals and Objectives

The seasonal dynamics of *P. rubescens* in Lake Zurich have been widely documented over the last decades [13], but measurements have only been taken from vertical profiles at a single point in this large lake. Even though this provides a fair amount of information to describe dynamics with respect to depth and time, it does not allow for conclusions about the horizontal dynamics. Furthermore, the use of such single-point sampling strategy implies that the cyanobacterial population is evenly distributed over the entire lake. Our preliminary observations of Lake Zurich physical parameters suggest that this assumption might not hold.

The main objective of our work is to be able to collect physicochemical data over the transect of interest from the surface to at least 20 m deep. To gather relevant temporal information, especially during period of rapid biological changes such as in the springtime, sampling transects need to be executed once a week over a timespan in the order of months. While sampling, the platform must sail safely in this busy recreational lake that is also used for public transportation via ferries.

C. The platform - LIZHBETH

The construction of a surface vehicle that is able to lower a probe at different depths while navigating has been mainly motivated by the simplification of the localization problem. This solution also ensures the visibility of the platform at all time during a mission. The vessel (Fig. 1) has been designed especially for this project and has been optimized with respect to efficiency in forward direction, as well as for pitch and roll stability in the presence of waves. It was manufactured according to these optimized design specifications using a foam core layer strategy. The layers covering the foam core were made from fiberglass to ensure mechanical stability while keeping the weight of the boat as low as possible (130 kg in total, including 40 kg of batteries and 14 kg of motors). Lizhbeth has a catamaran configuration and is 2.5 m long and 1.8 m wide. Each hull is 0.6 m wide and hosts a commercial electrical boat motor (Yamaha M12) at its center. This special setup gives the ASV a differential drive configuration, which allows for rotations on the spot. This is very convenient during maneuvers in narrow passages mainly close to the shore. The hulls contain the necessary electronic equipment and a lead acid battery (12V, 70Ah) each. The option of solar panels has been considered, however, it was calculated that the area that could be used on the boat is not big enough to significantly improve the range of the boat.

A GPS module (UBlox Development Kit) and a digital compass device (HRM3200 from Honeywell) provide position and heading information. The GPS module also provides speed readings, which have proven to be reliable above approximately 0.3 m/s. Differential GPS is not required, as standard GPS readings are precise enough for limnological purposes. The boat features two computers. The Helios Development Kit (by Diamond Systems) is deployed to run hardware drivers as it features 4 RS232 ports, 4 USB ports and also provides analog and digital input and output lines. A second board (pITX-SP 2.5" SBC) featuring an Atom Z510 processor is used for higher level computations. Both devices have low power consumption ($\sim$ 5 W each). Controlling the power levels of the motors is achieved by a commercial motor controller (AX1500 by RoboteQ), which provides an easy-to-use serial interface.

In between the two hulls we installed a custom-designed winch, which allows to lower the commercial limnological sensor (YSI-6600, referred to as probe in this article). The winch it mostly built from aluminum and is driven by an electrical motor (Maxon RE40), which provides maximal force of 15 Nm. The corresponding motor controller (Maxon EPOS 70/10) provides both position and velocity control. The cable drum of the winch is designed to carry 130 m of cable. A special probe cover (see Fig. 2) has been designed to diminish its drag force in water. The tip of the probe is filled with steel to shift the center of mass in front of the fixation point. This shift, in combination with the wings, ensures that the probe is aligned horizontally and thus minimizes the offset of the probe from is desired position vertically below the boat. The wings also stabilize the probe and prevent lateral movements during navigation. The probe works on its own power, therefore the cable is used only for data transmission. To prevent the probe from hitting the ground in shallow regions, a single beam sonar sensor (TMD-1 by CruzPro) is mounted on the boat and provides measurements of the water depth. The range of the sonar (0 - 140 m) covers the maximal length of the cable.

Additionally the boat features a positioning light and a electrical horn. Despite the extensive system monitoring tools from a laptop via the wireless connection, these tools proved to be very useful during field tests for simple feedback to the user. A series of short horn blows, for instance, is used to report the successful completion of a task.

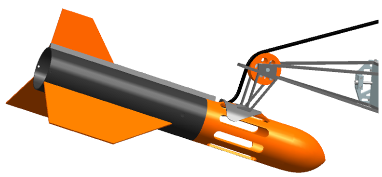

Fig. 2: CAD rendering of the probe supporting structure which reduces its drag.

The software for the boat is based on ROS [16] and features different control modes, such as staying at a given position or following line segments [17] at constant speed. Furthermore, the boat can be controlled remotely or can be asked to follow predefined waypoints. The two main actuators (the propulsion system and the winch) can be commanded to perform tasks either independently or in a synchronized manner. Synchronization is required to achieve the zigzag sampling trajectory of the probe, which will be described in detail below. In order to plan missions that define a sequence of actions, we have developed a mission scripting environment in Python, which enables to use convenient programming techniques. Trajectories for mission paths can be generated in Google Earth by simply drawing lines in order to be accessible to biologists in a near future. Furthermore the boat provides easy access to system monitoring information via a web server, which can also be used to upload mission files. A mission management system detects newly uploaded mission files and executes them. During the execution of a mission the user can pause it and use the remote control to override actuator commands.

D. Sampling missions

The first sampling missions have been chosen to be carried out along predefined straight lines (or transect) for reasons of simplicity and repeatability. While the boat is traveling along such a line with constant speed of 0.7 m/s the probe is being lowered and pulled up between two predefined depth levels. This generates a zigzag trajectory of the probe along which measurements are taken at a constant frequency of 0.5 Hz. The probe measures the following parameters: pressure, temperature, relative fluorescence unit (RFU) of phycoerythrin (a pigment of *P. rubescens*), dissolved oxygen, conductivity, photosynthetic available radiation and chlorophyll fluorescence. Fig. 3 depicts such a trajectory. In a post-processing step, a 2-D interpolation procedure can be applied to the data, as all measurements can be assumed to lie within a vertical transect plane. To account for the different scales in vertical and horizontal directions, an anisotropic distance kernel function has been applied.

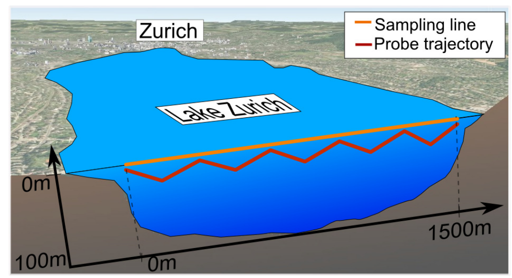

Fig. 3: Schematic representation of the resulting trajectory of the probe during a sampling mission. The total length of the path in horizontal direction is approximately 1.5 km. The map was taken from Google Earth.

IV. Results

A. System dynamics and control

The ASV possesses essential characteristics, as it has proven to be very stable in the presence of waves. It also generates very little drag in forward direction. Nonetheless, only very small rotational speeds can be achieved, due to the fact that the boat has two hulls. When rotating on the spot, the maximal angular velocity has been measured at 4.2 °/s. The line following controller has been applied in multiple test runs and has shown to be reliable, even in the presence of currents and strong winds. Over a distance of 1.5 km a lateral deviation from the target line of 0.67 m in average with a standard deviation of 0.66 m has been measured. Up to now the system has been running in autonomous waypoint navigation mode for more than 21 km in total and also a large total distance in remote controlled mode. Its endurance was found to be around 3 hours of continuous motion. This corresponds to sampling at 0.7 m/s over a distance of approximately 6 km.

B. Data collection

The interpolated plots in fig. 4 show the temperature distribution and the distribution of *P. rubescens* (assessed from the RFU measurements) along the sampling line across Lake Zurich. The horizontal axis indicates the traveled distance along the sampling line, whereas the vertical axis depicts depth. Besides the obvious and expected vertical temperature gradient, these measurements also show that the temperature is not equally distributed over the entire width of the lake. While the lake is warmer on the north-eastern side (right-hand side of the plot), the RFU values indicate that the density of *P. rubescens* is higher on the opposing side (i.e. the colder side) of the lake. To date, a total 21 km of measurements has been recorded to test the stability of the hardware, software and electronic components. To verify assumptions on the spatiotemporal behavior of *P. rubescens*, measurements at higher frequency have to be obtained over a fixed period. Nonetheless, these preliminary results confirm the capabilities of the ASV, and raise the biologists interest for more measurements to solve this intriguing spatial heterogeneity in *P. rubescens* distribution.

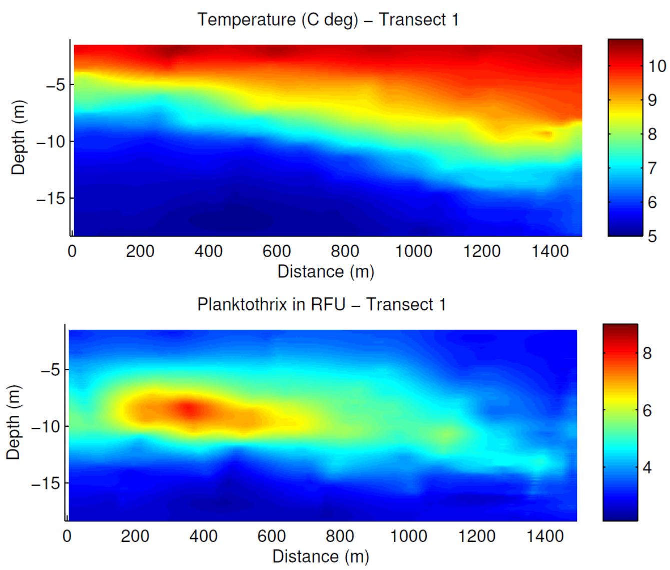

Fig. 4: Plots showing the results of a sampling mission after the application of 2-D interpolation methods. The graphs show the temperature distribution and the presence of *Plankthotrix* (in RFU) respectively.

V. Outlook

The platform that we presented in this paper is ready to be deployed and is capable of taking transect measurements autonomously. We intend to deploy it frequently during summer months in order to generate a large data set. However the system is still blind, i.e. it can not perceive its local environment and can only localize itself with the help of artificial landmarks (GPS references). Especially in summer, Lake Zurich is a popular recreational area and is used both by boats of different sizes and by swimmers. This justifies the need for an obstacle detection and avoidance system. Additionally, more sophisticated methods to collect data in the lake could be applied. Some ideas that will be pursued during the next month are presented in the following.

A. Obstacle detection

As our platform is designed for long-term sampling missions, an energy-efficient solution to detect obstacles should be preferred. A vision-system consisting of a single pan-tilt camera, multiple fixed cameras or an omni-directional camera should be able to operate at low power consumption and to cover a large field of view. This will allow to cover small, close objects (such as buoys or even swimmers) as well as larger boats at distances of several hundred meters. Detecting obstacles on a lake reliably is very difficult to achieve, because weather and lighting conditions can change fast and the water surface can act as a moving mirror. However, it is crucial to improve the ASV's autonomy on Lake Zurich, as it can be dangerous to swimmers.

B. Visual Homing

Preliminary tests have been conducted to test visual homing methods to home the boat into a boat house, where pure GPS localization is not precise enough. Reliably matching previously recorded features is difficult since a camera mounted on the boat is subject to pitch and roll motion. Furthermore, changes in lighting can significantly alter featured distributions and thus, have a negative effect on successful homing procedure. The idea to use normal cameras to apply visual servoing methods is similar.

C. Dynamic sampling

In the first phase of the project, only transect sampling missions will be conducted to gain basic knowledge on the dynamics of the different environmental parameters. Afterwards, dynamic sampling missions can significantly improve the information density of the data representation one mission. By analyzing the measured data in an on-line manner the boat could explore areas of high interest or search for local maxima or minima of certain parameters. The biologists could then be notified about such places of interest. This would allow them to also take water samples from these regions.

In another scenario, the boat could follow a isocline in the parameter space, i.e. try to control the position of the probe such that one parameter remains constant.

D. Bathymetry

Additionally to its primary purpose of sampling for biological research, we would like to deploy our ASV to record bathymetric information. To achieve this we plan to use a multi-beam sonar sensor. In order to fuse the scans of the sonar, we intend to use an IMU in order to retrieve roll and pitch information of the boat. Based on the quality of the scans, we would like to explore the possibility of applying Simultaneous Localization and Mapping Methods (SLAM), which could improve the boats navigation capabilities in narrow regions (such as harbors) where GPS might not provide the required precision. SLAM in combination with bathymetric measurements has been investigated in AUV applications [18] but could be of great support for ASV navigation also.

VI. Conclusion

In this paper we presented a new ASV system and the progress on deploying the platform to execute sampling mission for limnological monitoring tasks. The boat was designed and manufactured to the specifications of these algal bloom monitoring tasks and therefore it is mainly intended to be used on lakes. However, due to its relatively small size (2.5 m by 1.8 m) and its light weight, it is simple to transport it to different testing sites. Also marine environments are possible testing areas, the only limitation is imposed by the strength of external forces (wind and waves) which might exceed the maximal thrust force that the motors can provide. Apart from such hardware related limitations the system is very versatile and has proven to operate in a robust manner in autonomous waypoint navigation. The platform was deployed in several data collection missions during which it covered a total distance of 21 km in autonomous mode. With its ability to sample at a large range of depth in combination with precise GPS localization methods, the ASV provides methods to collect data sets that allow to analyze the horizontal variability of populations of *P. rubescens* in an unprecedented manner.

VII. Acknowledgment

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