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First testing of an AUV mission planning and guidance system for water quality monitoring and fish behavior observation in net cage fish farming

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ABSTRACT

Recently, underwater vehicles have become low cost, reliable and affordable platforms for performing various underwater tasks. While many aquaculture systems are closed with no harmful output, open net cage fish farms and land-based fish farms can discharge significant amounts of wastewater containing nutrients, chemicals, and pharmaceuticals that impact on the surrounding environment. Although aquaculture development has often occurred outside a regulatory framework, government oversight is increasingly common at both the seafood quality control level, and at baseline initiatives addressing the basic problem of pollution generated by culture operations, e.g. the European marine and maritime directives. This requires regular, sustainable and cost-effective monitoring of the water quality. Such monitoring needs devices to detect the water quality in a large sea area at different depths in real time. This paper presents a concept for a guidance system for a carrier (an autonomous underwater vehicle) of such devices for the automated detection and analysis of water quality parameters.

1. Introduction

Fish farming in aquaculture is the world's fastest growing sector within the food industry, providing nearly 50 percent of fish consumed globally and creating more than 5 million jobs worldwide. Aquaculture is of growing importance to the European Community given the mere fact that the industry employs the local population in many areas of several countries in Europe. Especially the European fisheries and aquaculture must enhance their competitiveness while maintaining the sustainable production of aquaculture and marine resources. Therefore, the Marine Strategy Framework Directive (or Marine Directive) [10] was enforced and is the first encompassing piece of EU legislation specifically aimed at the protection of the marine environment and natural resources and creating a framework for the sustainable use

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of our marine waters. One possibility to follow this directive is to use highly advanced technologies for fish farm management; to create a competitive, sustainable aquaculture systems and to optimize the quality of products along with fish health and welfare.

The advance of climate change, leading to warmer water temperatures, will make the monitoring of the state of the water environment even more important. For cold-water species, such as Atlantic salmon, warmer water means that more energy is consumed for maintaining basic life functions; hence less energy is available for growth and coping with stress (i.e. farming operations, diseases, poor water environment etc.). A continuous and reliable system for monitoring the aquatic environment so that the farmer can make informed decisions is therefore essential for the future growth of the industry.

Very similar challenges arise in highly stocked ponds or raceways. Recirculation systems conditions are generally easier to control but their success is closely related to the reliable function of monitoring equipment. This underlines the need for continuous and precise monitoring of the aquatic environment, fish behavior and the functionality of technical equipment, particularly in highly stocked fish farming facilities. Intelligent monitoring and control systems for fish farming may enable a controlled and safe environment for production of fish in with a certification for high quality. With appropriate risk management these systems may generate labor, food savings, energy savings, limit disease and mortality, prevent catastrophic losses, increase yields, and provide favorable economic outcomes of the enterprises. Guaranteeing the cleanliness of oceans is of crucial importance, and efforts should be made to preserve it as a sustainable habitat. The Water Information System for Europe (WISE) demands, for example, detailed information about the status of the water quality of coastal ocean waters [1]. Such requirements are only accomplishable with a frequent logging of the water quality and their biological cause variables.

The current state of technology is to use specific research vessels to conduct such investigations. This requires an extremely high resource management on one hand, and a comparatively long preparation period for their use on the other. The "FerryBox" project shows one possible approach in the field of automatic water quality measurement [2]. The idea is to use existing platforms (ferry, containership, etc.) which are cost-oriented and without additional technical expenditure. However, this approach can be used only on the routes of the mentioned carrier vehicles and is therefore inflexible. Through the miniaturization of such a measurement system and its combination with the flexibility of an Autonomous Underwater Vehicle (AUV), the base for an automatic and closely meshed monitoring of inshore waters, fjords and inland waters will be created. One possibility is the usage of AUVs called gliders [3,4]. These gliders have a low cruising speed ($0.2–0.4\ \mathrm{m\,s^{-1}}$) for long operational periods up to 30 days with low energy consumption achieved by the passive drive concept. Since the payload capacity is limited, there are restrictions in sensor weight and volume as well as in energy consumption. Alternatively, the measurement system could be deployed on buoys, as described in [5]. This system is limited however, since measurement data can only be collected from one single position.

This paper presents a solution using a mission proven AUV as a carrier platform to implement a miniaturized measurement system to analyze water quality and focuses mainly on a concept for the mission (re)planning and guidance system of such an AUV to use for the task of water quality monitoring. The presented system leans on the research project SALMON (Sea Water Quality Monitoring and Management) [11]. In this project, German (Ilmenau University of Technology, Fraunhofer IOSB-AST, 4H-JENA engineering GmbH), Norwegian (Havforskningsinstituttet, Institute of Marine Research) and Danish (Mads Clausen Institute) companies and research institutions work on a systematic solution for automatic water monitoring. One goal is to show, by example, the import of nutritive substances in Norwegian aqua farms located in fjords. These fjords can be monitored with this system and can be refined in order to reduce outside influences on nature.

The remaining part of the paper is organized as follows. The current development and trends in underwater vehicles will be discussed in Section 2. In Section 3 potential application of underwater vehicles in net cages will be shown. In Section 4, the structure of the *mission (re)planning and guidance system* for water quality monitoring is introduced. In this the behavior (tasks) of the guidance system are also described. Section 5 describes the underlying controller for realizing the required behavior. The fish behavior observation and the in-situ water quality monitoring system will be described in Section 6. In Section 7 the first test results of the prototype vehicle will be shown. Finally the conclusions and future work are given in Section 8.

2. Developments and challenges in underwater vehicles

Mainly, there are two types of unmanned underwater vehicles. The first category forms the Remotely Operated Vehicle (ROV) and the second category is the Autonomous Underwater Vehicle (AUV). ROVs are manually operated while AUV has to be either preprogrammed to perform a mission, or has to have some sort of intelligence to readjust the mission during its execution.

AUV mission is programmed upfront, before the mission starts, and is executed without human intervention. Hence, the AUV does not have umbilical. One challenge of AUVs is that when under water, they cannot rely on GPS for positioning so it has to be equipped with either good dead-reckoning navigation or have some means of acoustic localization. Their advantage is that they can survey larger areas of sea. Side scan sonar is used to scan the bottom and subsequent analysis of gathered acoustic images reveals potential objects of interest. Accurate geo-referencing of the identified targets depends on accuracy of navigation which ranges, depending on situation and mission strategy, from few meters all the way up to several tenths of meters. Recently AUVs have been used in cooperation.

Typically AUVs comprises a ROV a control console and a power supply, a camera with adequate lights and some navigational equipment.

3. Perspectives of using underwater vehicles in fish farming

Recently, underwater vehicles have been developed to become low-cost, reliable and affordable platforms to perform various underwater tasks such as manipulation all the way to data acquisition of the marine environment. Such tasks include:

(1) The use of ultrasound for net cage cleaning substituting the existing large, heavy and expensive systems.
(2) The determination of the environmental impact of bottom trawling. Deployment of the AUV instead of the diver can both reduce the risk for the diver and can improve amount and quality of collected data per unit time. The use of AUV to follow the trawling net by hovering relative to the moving net is a promising strategy for getting a more detailed picture of the impact of trawling net to the seabed and fish population.
(3) The monitoring of fish habitats. Regular and frequent monitoring of marine environment results in accurate estimate of the changes in water conditions. Frequent monitoring yields better understanding and consequently more efficient management of the net cages.

4. Vehicle guidance system architecture

Before we derive a strategy for the mission planning and guidance system for an AUV for water quality monitoring, let us have a look at a scenario for water quality monitoring using an AUV as illustrated in Fig 1. We can see an AUV following a mission plan, avoiding obstacles if necessary, sampling and analyzing data and replanning for securing data.

Thus, the following capabilities of the AUV are required for the mission planning and guidance: (1) *Mission (re)planning and controlling*; (2) *Navigation* around the water body according to a given *mission plan* collecting data; (3) Automatically analyzing the quality data – use this data if necessary to *re-plan the mission* if there is something which needs close inspection; (4) After a given time the AUV need to *secure the data*, therefore it should *seek the closest station* to upload acquired data; (5)While navigating through the sea it should be able to *detect obstacles and avoid* them. Therefore, the solution to the mission planning and guidance system is behavior-based, in-mission-planning and is illustrated in Fig. 2. The behavior controller starts with the go-to-monitoring-area behavior using the geodetic coordinates of the monitoring area. On completion, the behavior switches to the mission task behavior (follow a given mission plan). Within this state, the monitoring module is started. If a given time for securing data has elapse the AUV switches to the find-object behavior. The find-object behavior performs a complete revision of the surroundings, which finishes successfully if the target data upload station is found. On success, the behavior controller goes to the rendezvous-object behavior, in which the rendezvous controller is started and the AUV is positioned in the starting point of the inspection where the target was found, at the height and with the lateral offset defined in the mission settings. Consequently, the behavior controller switches to the uploading behavior. After a successful upload, the AUV goes back to mission task behavior and continues with water quality monitoring. In the following sections, the different behaviors will be explained in detail.

4.1. *Go to monitoring area behavior*

The go-to-monitoring-area behavior issues heading commands that will direct the vehicle from its current location to a target monitoring area location. For example, during mission start-up, the vehicle is dispatched from its home location to an area of interest before starting the mission task. Also, the vehicle returns to its home after it declares the end of mission. The go-to-monitoring-area behavior uses the following formula to calculate the commanded heading ψ_r and velocity v:

$$\psi_r = \arctan\left(\frac{y_g - y_{auv}}{x_g - x_{auv}}\right) \quad (1)$$

where (x_g, y_g) are coordinates of the target location, (x_c, y_c) are the coordinates of the current vehicle location, and v is a constant speed command set as a mission parameter.

4.2. *Mission task behavior*

To detect the distribution of pollution around aqua farms, a mission plan is created, that is based horizontally on a meander with saw tooth shaped dive profiles. Thus, it is possible to measure the pollute concentration at several depths and to support navigation of the AUV with actual GPS positions during the surface phases.

To create a mission plan a menu-guided planning system will be used. The user will be presented step by step with information and dialogs, which are necessary to solve the actual planning task. The typical planning sequence includes three stages: (1) defining the sea chart/area of interest; (2) selection of the vehicle; and (3) building a plan using defined mission elements. The mission plan is made out of base elements, which include an initial and a final element (to define the start and goal position of the mission), the three base maneuver elements, (waypoint, line and arc) and the complex mission element meander. The configuration of several elements can be started by choosing the respective element in the lower half of the window. The meander is specified by the following parameters: start position $x_{meander}$, $y_{meander}$, depth z_{max}, rotation $\theta_{meander}$, leg length l_{leg}, distance between two legs d_{leg} and the number of legs n_{legs} (see Fig. 3).

The control of the vehicle is realized by a state-based tracking controller [6]. This controller requires waypoints to create a reference trajectory using a cubic spline interpolation. In order for the reference trajectory to correspond as closely as possible with the defined meander which consists of lines and arcs, characteristic waypoints have to be defined. The requirements for such waypoints are: (1) smoothness conditions on the reference trajectory, needed within the controller design, (2) good reproduction of the saw tooth shaped dive profiles and (3) a minimum number of waypoints.

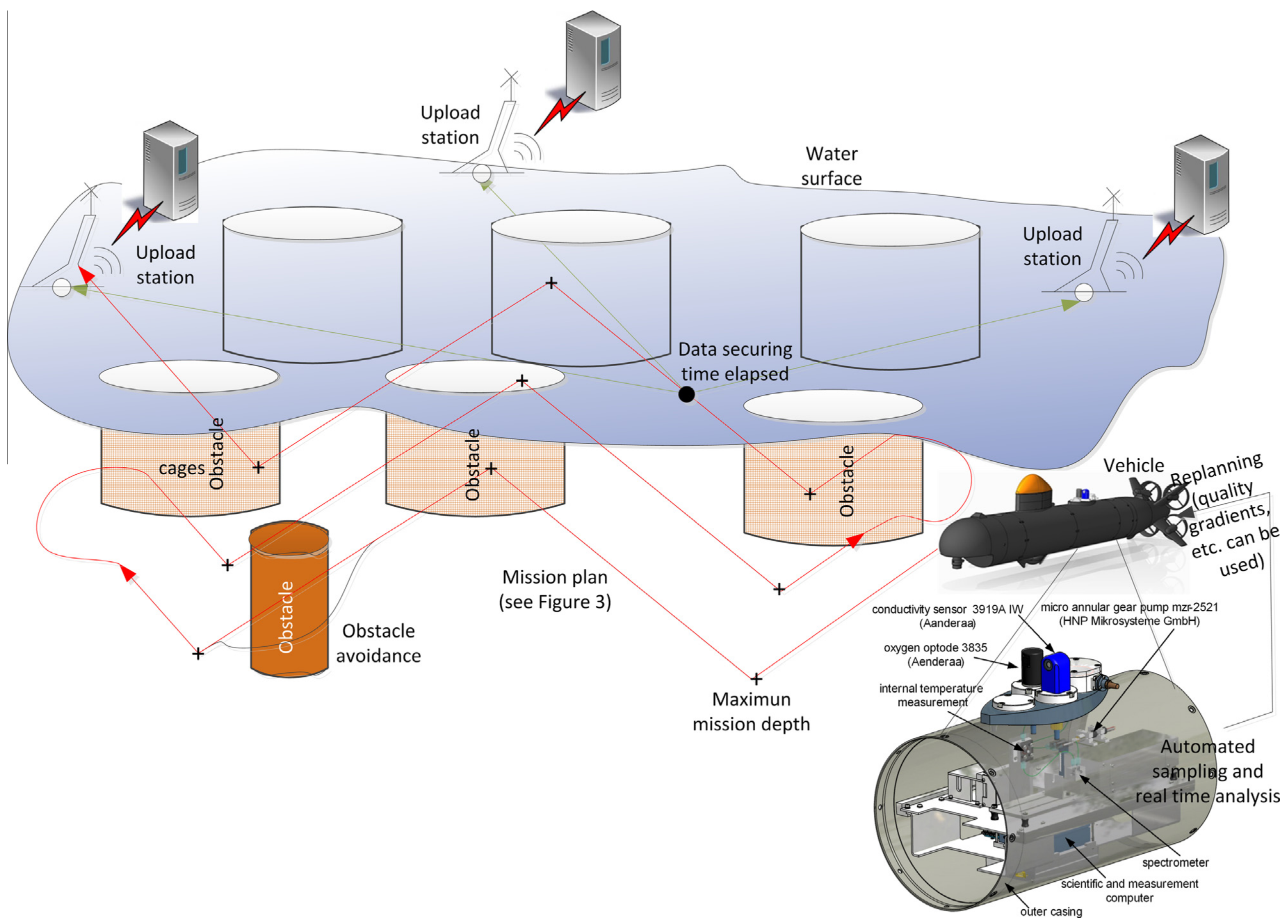

Fig. 1 – A scenario for water quality monitoring using an AUV.

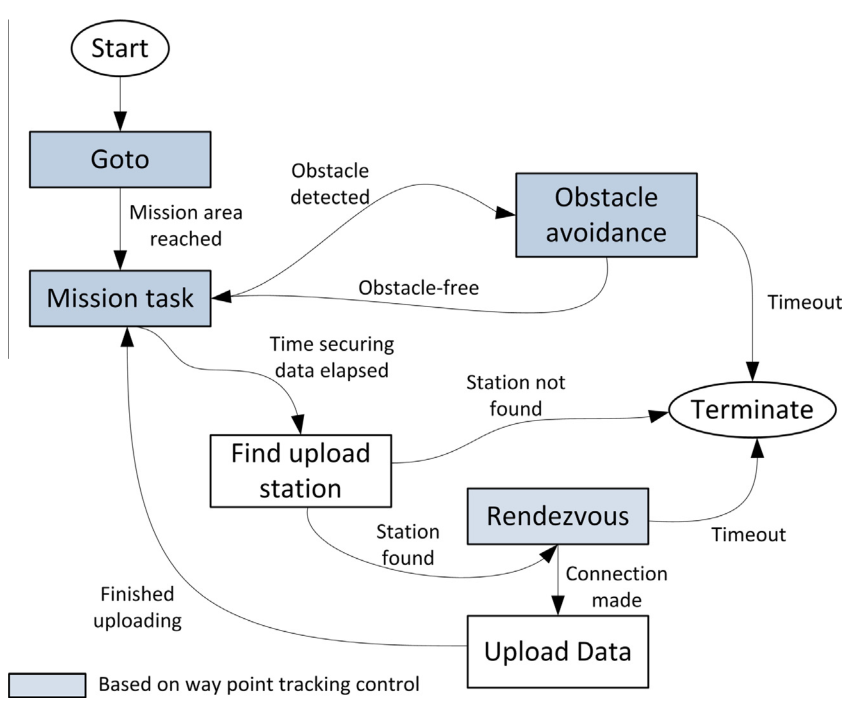

Fig. 2 – Structure of the guidance system.

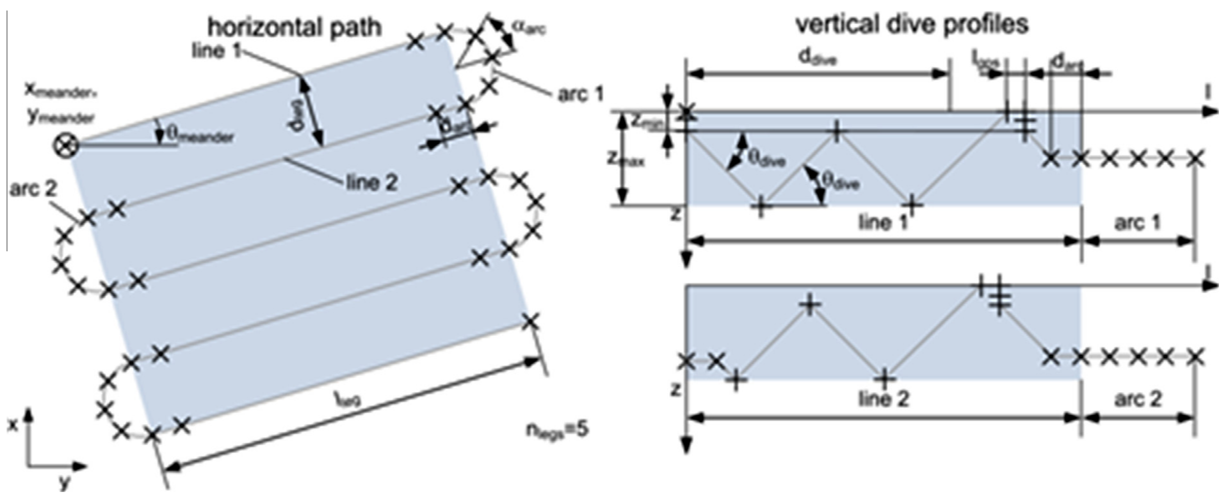

Fig. 3 – Parameters used to define the waypoint list.

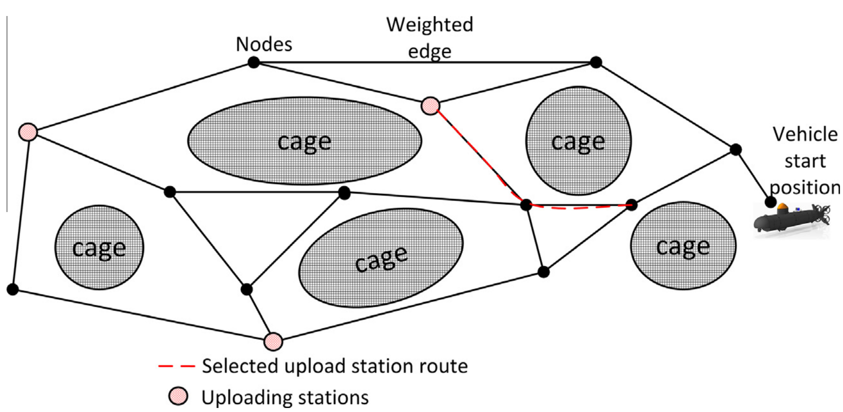

Fig. 4 – Maneuver plan generation.

Fig. 4 shows several parameters to define a waypoint list according to the route of the horizontal path and the associated vertical dive profiles. The angle α_{arc} is used for the reproduction of the arc element. This also defines the angle differences between adjacent waypoints on the arc. To generate a smooth transition between a line segment and an arc, a way-point will be positioned before the start and behind the end position of the arc at a distance of d_{arc}. In the figure above these waypoints are signed by an "x" mark. The depth information for the defined waypoints will be generated from the required dive profile. The chosen dive profile has a saw tooth shape similar to a Slocum Glider dive profile [9]. This allows the recording of measurement data at every depth in the least amount of time using a minimal number on course changes. Therefore, the area of interest can be recorded in a minimal duration with small energy consumption by the AUV. To support the navigation with actual GPS positions, a surface drive is required when the distance of the underwater drive covered reaches d_{dive}. In the figure above this occurs on each leg element. It is also possible that the surface maneuver takes place after n legs. This is dependent on the leg length l_{leg} and the submerge and emerge angle α_{dive}. The track length of the surface drive is defined by the parameter l_{gps}. Due to the construction properties of the AUV a diagonal submerge maneuver is impossible. At the beginning of the submerge maneuver the AUV uses the thruster. In a depth of z_{min} the vehicle uses the propellers and starts with the diagonal maneuver. This depth will also be used for the initiation of a submerge maneuver after an emerge maneuver. Thus, the defined waypoints have a "+" mark in the figure.

4.3. *Find-object behavior*

This behavior simply uses the database information to locate the position of the nearest uploading station.

Here, we look at the AUV as a point in 3D plane for example (x_0, y_0, z_0) and we got a set of n points $(x_1, y_1, z_1)\ldots(x_n, y_n, z_n)$ and we want to find the nearest feasible point to (x_0, y_0, z_0) in a way better than trying all points (see Fig. 4).

This is a problem of path planning. The method which can be used for this problem is described in our previous paper [8]. In path planning, the entire information about the current area of operation is used to generate a route plan to the target upload station. These are in addition to the current information from the sonar, the "collected" obstacle data of the previous Missions and the data of a digital nautical chart. Such a route plan is determined on the basis of a graph. Here, points (nodes) are defined in the operational area, which are accessible by the vehicle. The navigable links between these points are entered as edges in the graph. Each edge has a rating (cost, weight), which L is the length of the connection, which can be the costs for following the connection or the time of travel along the connection. After generating the graph, a path (route) from the initial node (starting point) to the leaf node (destination) with the lowest total cost is determined by a search algorithm (Dijkstra, A*, D*, etc.). The algorithm browses through the graph to determine a combination of edges which connects the start and end nodes with the lowest total cost. After that a maneuver plan is generated from base elements under consideration of the vehicle dynamics. After locating the target position the vehicle enters into rendezvous mode, where it uses its onboard sensors to locate the exact position of the station.

4.4. *Rendezvous-object behavior*

The challenge in docking the AUV to the uploading station, when the target station is found is the ability of the AUV to navigate and orient itself in alignment with the target station desired position accurately as it approaches the object (see Fig. 5a). The trajectory for guiding the AUV to the start point found and in alignment with the target station is designed using waypoints navigation building on top of existing cross track error and LOS controller [7]. The number of waypoints and their location are then automatically determined based on the actual point of the AUV and the target station position as illustrated in Fig. 5b. These waypoints are designed to be fixed throughout the docking rendezvous based on fix target station heading. After determination of the way points, Waypoint guidance is used to achieve rendezvous with the target station. To design the waypoints, two important parameters, number of waypoints required and position of waypoints would need to be defined. Correct placement and number of waypoints is important as it will determine the path towards the underwater target station with sufficient settling time for the controller to track the path. This is especially important when the vehicle is very close to the target station where path tracking accuracy is crucial. The challenge in the design of waypoints is the capability in handling different vehicle's starting position and heading in respect to the underwater target station position and orientation. To achieve this, a parameter ψ_{diff} is defined as the difference between $\psi_{station}$ and the line of sight angle between the AUV starting point in the sequence and the point where the underwater target station was found where ψ_{diff} ranges from 0 to ±180 and is further divided equally into twelve segments. Depending on which segment ψ_{diff} is in, the number of waypoints will vary from 1 to 6. In our approach, the waypoints are placed at a length of vehicle's starting distance-to-go along the centerlines of each segments and the underwater target station. Thus, the AUV would travel along the track paths on these waypoints. For trajectory that has very sharp change in direction, as can be seen from Fig. 5a, a large watch radius for the waypoints is preferred.

4.5. *Obstacle avoidance behavior*

The goal of the obstacle avoidance (OA) algorithms is to avoid collisions and is based on local map acquired by forward looking sonars (FLS). It is assumed that the vehicle has horizontal and vertical forward looking sonars. The OA behavior is able to handle every possible obstacle situation in an optimal way based on some predefined criteria. Hence, a primary goal for the collision avoidance system is to try to stay on the desired track during collision avoidance maneuvers and simultaneously try to minimize the deviation in altitude from the specified operational altitude. Especially in aquaculture environment, the OA algorithm should be able to follow nets cages when detected and then resume mission if the way is free again. Suitable algorithms for this purpose include the Bug-2 algorithm, which commands the vehicle to head towards the goal on the mission line; if an obstacle is encountered, the AUV is commanded to follow it at a predefined distance D_f until the vehicle hit the mission line again; in this case the vehicle leaves the obstacle and continue towards the goal on the mission line.

When navigating in aqua farms under cages, the AUV should be able to avoid obstacles in the vertical plane while minimizing horizontal cross track error from the mission track. The cage bottom follower seeks to maintain a constant distance under the cage by feedback from the vertical altimeter. Given the distance between the location of the vertical

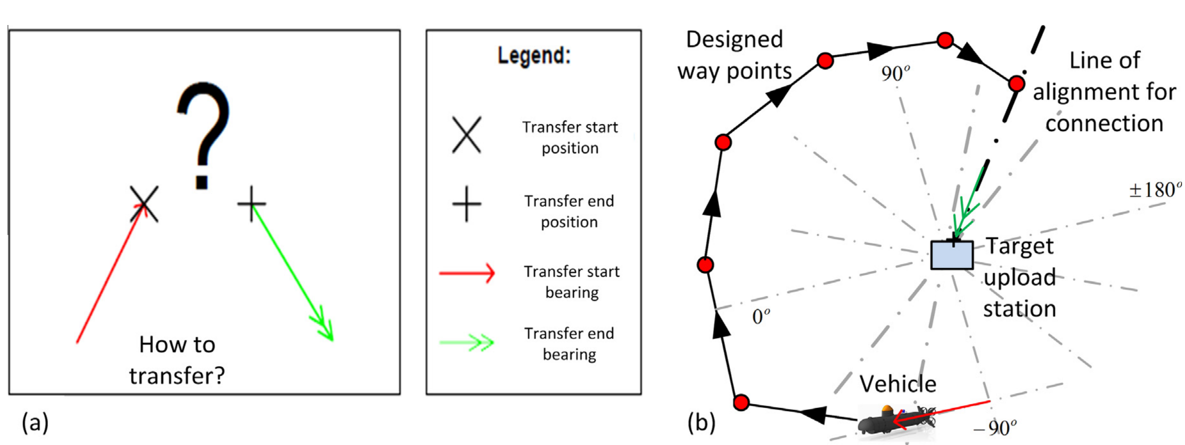

Fig. 5 – Waypoint allocation after confirmed search/reacquire.

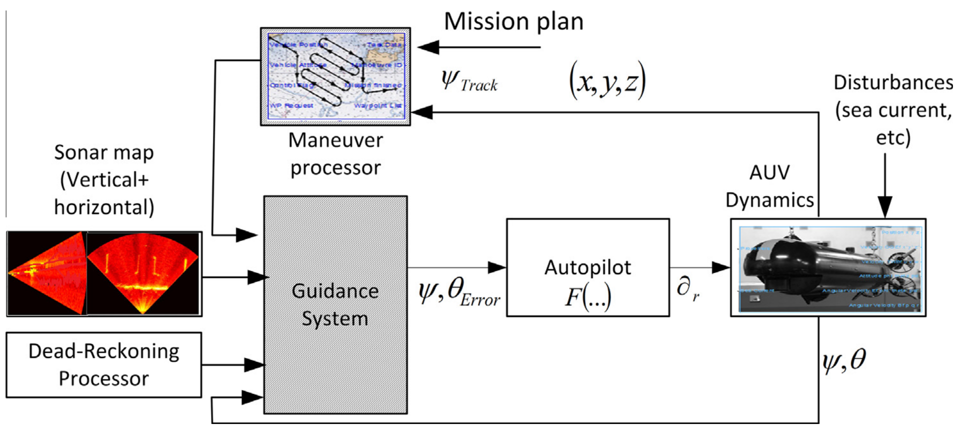

Fig. 6 – Guidance and control structure.

altimeter and the vehicle's center of gravity, ρ the actual pitch of the vehicle θ, a desired distance under the cage h_d and an estimation of the distance to the cage, h the set point depth z_d^* for the depth controller can be calculated as follows:

$$z_d^* = h_d - h + \rho * \sin(\theta) \tag{2}$$

Most of underwater vehicles have got technical depth limits; therefore it is necessary to bound the calculated set point depth. Other limits of the set point depth are imposed by the fact that sensors (in this case the altimeter) may give false reading and in order to prevent situations of possible trap or loss of the vehicle, we have also to consider the maximum allowed depths in the operational area z_{max}, which is defined by the user prior to mission. This value should be less than the technical value. Therefore, the resulting desired set point can be expressed as in Eq. (3).

$$Z_d = \begin{cases} Z_d^* & \text{if}(Z_d^* < Z_{max}) \\ Z_{max} & \text{otherwise} \end{cases} \tag{3}$$

For cage bottom following is also necessary to set the pitch, which can be done in two ways. Firstly, in cases where the FLS does not deliver measurements, a suitable set point pitch θ_d must be derived from the actual vehicle pitch θ and a feedback term θ_{fb} as in from the changing rate of the distance to the cage bottom, $\dot{h}$ and the surge velocity, u as in Eq. (4).

$$\theta_d = \theta + \text{atan}(\dot{h} * u) \tag{4}$$

In Eq. (4) we neglect the effect of water currents might have on the direction of the vehicle, and assume that u accurately describes the velocity of the vehicle in the forward direction. As $d_k u$ is a slope, or a ratio, therefore to get the equivalent angle it is enough to simply compute its arc tangent.

5. Guidance laws applied

Our approach uses three guidance laws which are combined to generate all the trajectories required to perform the AUV water quality monitoring mission. These are (1) Way point guidance law, (2) the Track guidance law, and (3) Feature following guidance law [7]. The guidance and control structure illustrated in Fig. 6 will be adopted.

The Line of Sight guidance in 3D space can be defined by two angular variables as:

$$\psi_{ri} = \arctan\left(\frac{y_{i+1} - y_{auv}}{x_{i+1} - x_{auv}}\right) \tag{5}$$

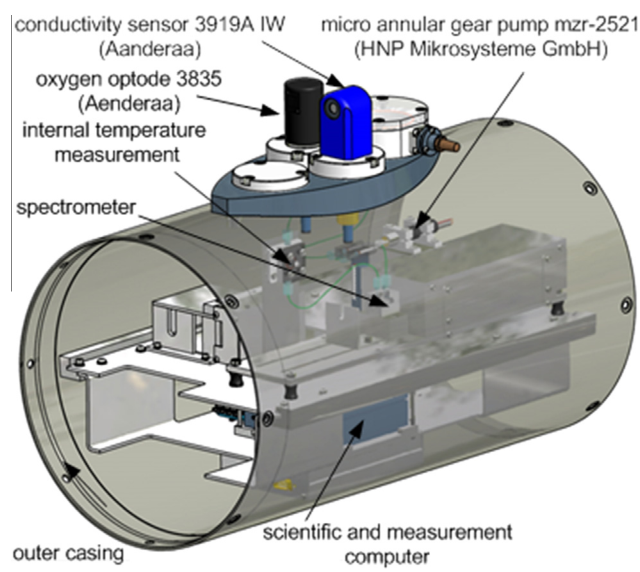

Fig. 7 – Water quality measuring system.

Table 1 – Technical details of the water quality measuring system.

Parameter	Measuring range/value
Sodium nitrate ($NaNO_3$)	0–1000 mg/l
Oxygen concentration (O_2)	0–500 mmol/l
Conductivity σ	0–75 mS/cm
Temperature T	−5–40 °C
Measurement cycle	1 s(O_2, σ)/5–10 s($NaNO_3$)
Power supply (Computer)	12 V
Power supply (Sensors)	19–25 V
Energy consumption	12 W(12 V)/10 W(22 V)

Fig. 8 – Test area, Austevoll, Norway.

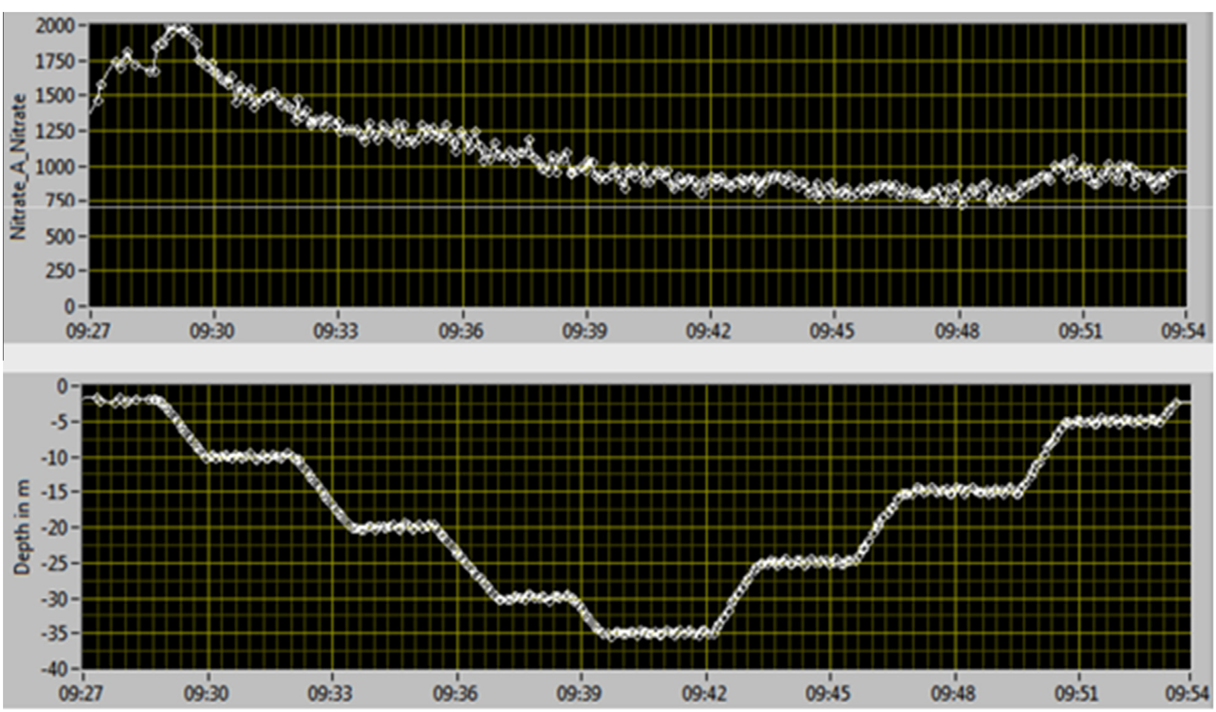

Fig. 9 – First results – Nitrate concetration.

$$\theta_{ri} = \arctan\left(\frac{z_{i+1} - z_{auv}}{\sqrt{(x_{i+1} - x_{auv})^2 + (y_{i+1} - y_{auv})^2}}\right) \tag{6}$$

where (x_i, y_i, z_i) are the coordinates of the given set of way-points ψ_r and θ_r are denoted as the vehicle's heading (azimuth) and path (elevation) angles. When the vehicle lies within the sphere of acceptance with a radius, ρ_0 around the waypoint, i.e. if the vehicle location (x_{auv}, y_{auv}, z_{auv}) satisfies Eq. (7), then the next waypoint can be selected.

$$dP_{ci} = \sqrt{((x_i - x_{auv})^2 + (y_i - y_{auv})^2 + (z_i - z_{auv})^2)} \leqslant \rho_0 \tag{7}$$

where dP_{ci} is the distance between the vehicle position and the current waypoint. Usually, the sphere of acceptance ρ_0 is taken as $2L$, where L is the length of the vehicle [12].

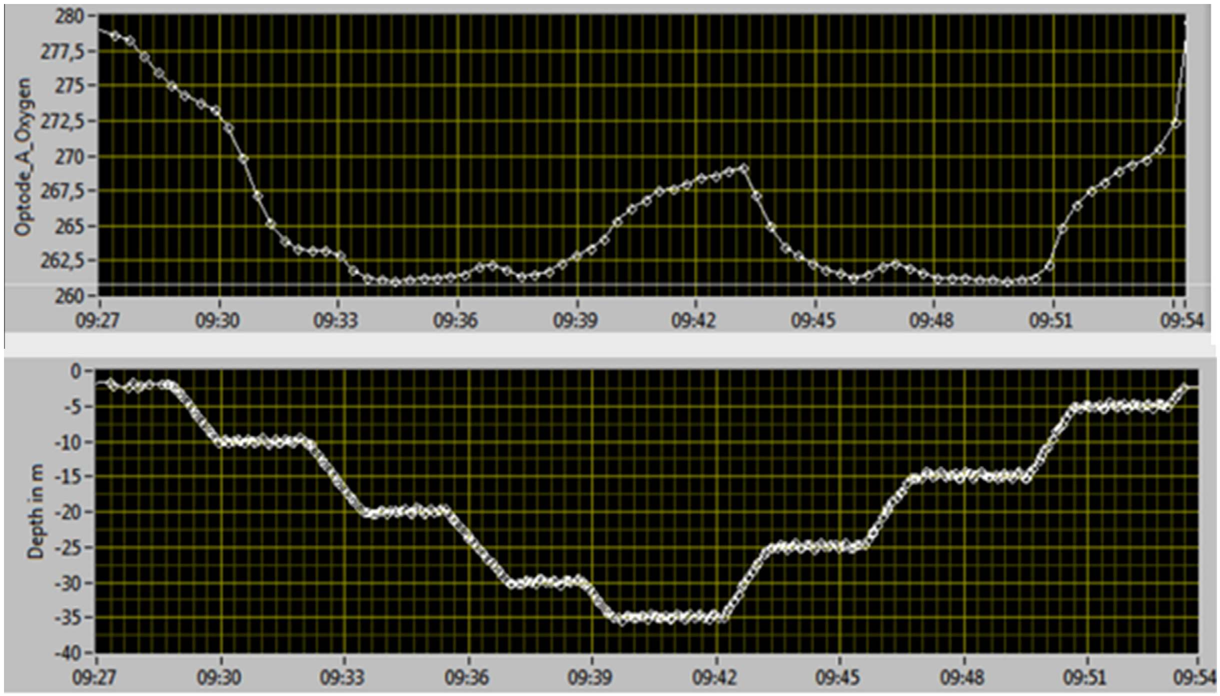

Fig. 10 – First results – Oxygen concetration.

6. Fish behavior observation and monitoring system

The system in Fig. 7 is used for in-situ quality monitoring. It is a miniaturized sensor system for water quality analysis with low energy consumption, automatic and intelligent measurement and logging. Several water qualities shown in Table 1 can be measured using spectroscopy analysis. The system uses UV absorption to measure Nitrates, Oxygen is measured optically and electrical conductivity by magnetic induction. As the system is modular a miniaturized, it can be easily adapted into other carrier platforms.

The underwater observation system is composed of cameras with high power LEDs. During the mission, images and videos of the environment around the net cages are collected and analyzed in a later stage. This information can be used to study the behavior of the fish, for example during feeding. The movement of the fish can also be used by ecologists to estimate the wellbeing of the fish.

7. Results of the first tests of the system

The prototype vehicle was tested in Austevoll at IMR, Norwegen (see Fig. 8) in September 2013. In the Scenario illustrated in Fig. 9 (bottom), the vehicle was sent stepwise to different depths while taking water quality measurements. Figs. 9 and 10 (top) show the water quality examplary at different levels with respect to Nitrate and Oxygen. The results are quite promising and further tests are planned.

8. Conclusions

A guidance system for an AUV for water quality monitoring navigation in large sea area was presented. It uses a behavior based controller coupled with waypoint tracking. Methods for realizing the necessary behaviors to be able to fulfill a mission for water quality monitoring have been discussed. Most of the methods have been demonstrated in our previous papers. The concept can be applied to other types of AUVs.

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