BOTTOM-REFERENCED CONTROL OF AUTONOMOUS UNDERWATER VEHICLES

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Abstract - *Bottom-following of an unknown sea-floor will be a typical task to be carried out by future AUVs for survey and mapping missions. Controlling the vehicle will be done through a set of actuators, using information coming from a perception system with respect to the environment. The problems of choosing a suitable perception system, an efficient actuation architecture, and a suitable control strategy are strongly linked, in particular through controllability and observability of the overall system. This paper makes an overview of the points cited above that have been studied in the framework of the EEC MAST II CT92-0028 project.*

1 Introduction

In the future, autonomous underwater vehicles (AUVs) will be used in various application fields such as scientific (geology, geophysics), environmental (waste disposal and pollution monitoring) or commercial (oil and gas, submarine cables) activities.

To perform its mission, an AUV is planned to carry load sensors such as sidescan sonar, bathymetry equipment or sub-bottom profiler. Many of these sensors induce heavy constraints on the vehicle stability. During the mission, it is expected to follow a path such as making a detailed grid covering of a defined area while maintaining a constant altitude over the *a priori* unknown bottom profile. Consequently, the vehicle should be equipped with a perception system in order to have s sufficient knowledge of its environment. Furthermore, the shape and the propulsion system of the vehicle must be chosen in order to optimize energy consumption to reach efficient commercial range. Finally, a suitable control law must be designed in order to pilot the vehicle following the requirements of the payload. In fact, these problems are strongly linked through controllability and observability of the overall system.

*Work performed during a stay at Inria as an invited professor.

2 Altitude Sensors Configuration

The perception system of the vehicle is assumed to be made of a set of acoustic sensors, giving a more or less accurate measure of the distance between the sensor and the next obstacle. A first question is: according to the type of mission to be performed, how many sensors should be used and where should they be located on the vehicle ?

For synthesis purposes, it appears that the convenient altitude sensors architecture and number are function of :

- the *virtual linkages* we want to create between the environment and the vehicle through the involved sensors to achieve a desired task. An efficient and global enough approach including this notion is *the task-function approach* ([3]). Among the various missions that could be affected to an AUV using sensory data, we have considered the obstacle avoidance and the bottom following tasks. The linkages that should be considered are : the point/plane linkage for obstacle avoidance, the line/plane linkage for bottom following when the roll angle is left free, and the plane/plane linkage when we want to constrain at the same time the roll angle with respect to the seafloor slope. In the last two cases, a minimum of two and three distance measurements are required respectively.

- the *physical model* of the altitude sensors. Three of them have been studied: the simple unique ray model, the beam width angle sensor, and the acoustic Kuc's model. In general, we can consider that the distance measurement corresponds to the first received echo.

- the *location and orientation* of the sensors, that are assumed to be rigidly fixed on the vehicle, are function of (i) the physical characteristics of the transducer, (ii) the vehicle maneuverability, (iii) the level of desired redundancy, (iv) the required behavior during transient phases (for example in case of slope breaks when achieving a contour following).

It is worth noting that the methodology above is valid for what we call a "Relevant Information" (RI). This RI is intended to provide us with a distance between the virtual sensor location and the environment, whatever the real physical sensor -or required group of sensors- and fusion-filtering processes to obtain it are. By this way, we are not limited by the specific physical properties of the various sensors (or their models) that may be found on the market ([4]).

Tests have been thoroughly supported on our SIMPARC simulator ([1]) and confirm our theoretical results. Both sea-bottom following and obstacle avoidance tasks have been taken into account for these tests.

3 Actuators Configuration

Many types of actuators can be used on an underwater vehicle (screw propellers, mobile wings, Magnus cylinders...). The literature on underwater vehicles provides us with a huge variety of possible configurations. Our aim here is to give some basic principles of actuation when considering motion requirements and energy consumption. We have restricted our study to the simplest configurations induced from these considerations above.

To optimize energy consumption, long range AUVs have a preferred axis of motion and are generally torpedo-like shaped. Thus, the forward velocity is given through a main rear axial screw propeller. A mobile ballast is also needed to control the buoyancy and to keep a desired constant pitch angle for long ascents/descents for lower actuation/energy consumption.

For controlling motions along the vertical (z) axis of the vehicle and around the pitch axis, we have mainly studied (under the controllability point of vue) two configurations:

1. One with a "plan canard" configuration mobile wings as lateral actuators (see fig. 1);

2. The other with a front and a rear screw propellers as lateral actuators (see fig. 2),

The choice between these two configurations would mainly depend on the technical feasibility and the vehicle nominal axial velocity. It should be emphasized that using front and rear actuators allows to decouple the motions of the vehicle along the vertical and pitch axis (to a certain extent, lateral motion of a torpedo shaped vehicle induces a very high drag), and then leads to better expected accuracy of the bottom-following task. Simulation results confirm the fact that the drag due to the transversal velocity in the vertical plane is minimized thanks to the plan canard configuration. Moreover, required forces are better shared among the involved actuators ([5]).

These results can be called into question by operational constraints like the maximum width of the vehicle. Indeed, many vehicles are planned to be controlled by a single rear mobile wing due to operational constraints. Not only it is no longer possible to decouple the two motions, but this configuration leads to nonminimum phase vehicles for which several difficult control problems arise.

These results can be easily extended to the horizontal plane, however taking into account the horizontal asymmetric plane problem. It is worth noting that hydrodynamic interactions between the (not well known) vehicle components were not taken into account in this study.

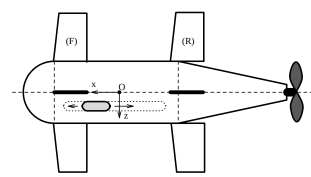

Figure 1: Configuration of actuators with mobile wings as lateral actuators

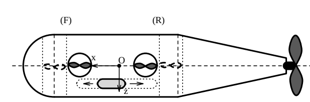

Figure 2: Configuration of actuators with screw propellers as lateral actuators

4 Control Methods

The goal of the controller is the regulation of the underwater vehicles with respect to its *a priori* unknown environment (e.g. following the sea-bottom profile at a desired altitude) using sensory data from exteroceptive sensors (e.g. range-device altitude sensors).

Two main classes of underwater vehicles may be distinguished : the *holonomic* and *non holonomic* (or generally speaking under-actuated) vehicles.

4.1 The case of holonomic underwater vehicles

The motions of the underwater vehicle are governed by the equations of the dynamics of rigid bodies and of hydrodynamics. It is said to be holonomic[1] when the desired force and torque screw achieving the control law can be fully applied through the set of actuators. The vehicle is not only controllable, but can be driven along any trajectory of its configuration space. This is for example the case of ROV-like vehicles where the set of screw propellers actuators allows to apply forces and moments on any vehicle axis.

Controlling such underwater vehicles that have to integrate sensory data from the environment requires two levels of study :

The high level control study dealing with the integration of sensory data in the closed loop control. The most global and appealing approach is the *task-function* one ([3]).

From this approach, the control problem is reduced to a simple problem of the regulation to zero of a task-function . An extension of this approach allows us to achieve in a same global task a combination of several sub-tasks such as the obstacle avoidance, bottom following and path following, which are the tasks to be achieved by AUVs. Of course, the problem is to define a good weighting among them. Two ways of dealing with such tasks merging have been studied: i) combining the different primary tasks in a single task function, leading to appropriate repulsion and attraction areas around the vehicle ([12], [6], [7]). ii) smoothly switching from a primary task function to another primary one when required ([9]). This is the kind of processes the ORCCAD approach ([11]) is willing to manage.

The low level control study dealing with the application of the control vector (forces, moments), from the precedent item, to the vehicle actuators.

Several robust control approaches exist for this class of mechanical systems that are more or less well-known. Among them, we have reviewed the following ones : Feedback Linearization, Nonlinear Feedback, Sliding Control, Adaptive Control. Their application mainly depends on the vehicle characteristics (parameters noise, dynamics modelling ...) and on their desired behavior. We use for the simulation results shown figure 3 the Feedback Linearization. The other approaches are expected to be tested on the Ifremer ROV testbed vehicle, VORTEX ([2]), during spring 1995.

[1] according to [10], a mechanical system is said to be holonomic when all the kinematic constraints are fully integrable. All other systems are, obviously, nonholonomic

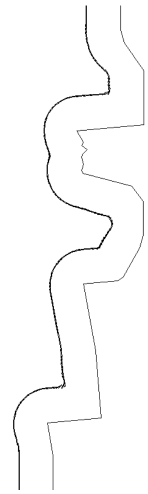

Figure 3: (landscape figure) Following the sea bottom at $U_o = 3m/s$ with a 3-sensor configuration . Sensors are submitted to gaussian white noise with a 3-meter standard deviation. Their range is limited to 1200m. A task function application is done with minimization of a cost function.

As shown on simulation result, this methodology gives satisfactory enough results.

In the case where it doesn't exist such a control set that makes the vehicle differential system equation fully integrable (*nonholonomic* vehicle), or even when the vehicles are such that their *fuselage is optimized on given axes* leading to preferred axes of displacement for better energy consumption, this method is no more usable. That is the case of vehicles controlled by mobile wings where: i) they are not controllable at null speed, ii) there are limitations on the possible trajectories (for example, the vehicle depicted by figure 1 cannot perform pure motion along the y and z axis).

The chart on figure 4 summarizes the task function approach and application to underwater vehicles.

4.2 The case of non holonomic underwater vehicles

Two cases must be distinguished, depending on the actuators configuration :

1. the lateral and rotational velocity components can be easily decoupled, which is the case when the configuration for the lateral actuators is the *plan canard* one.

2. the lateral and rotational velocity components are coupled, which is the case when for example there are only rear mobile wings.

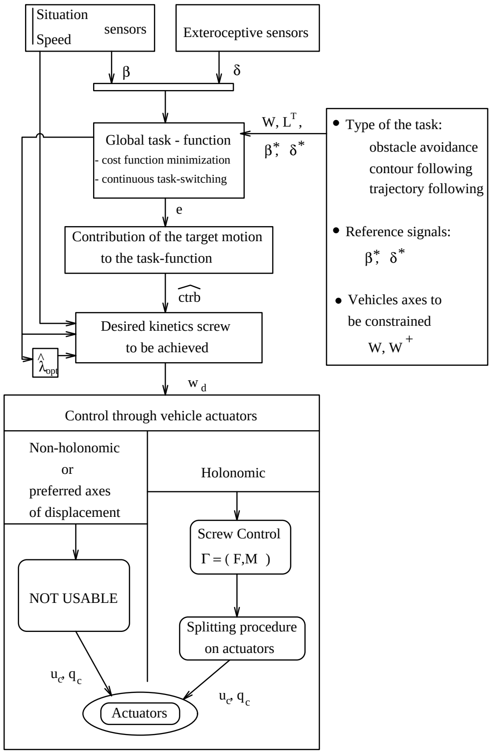

Figure 4: Scheme of the Sensor-based Control Algorithm using Task function Approach

For the first class cited above, a new control law has been developed. It is based on the conjunction of the parametrization with curvilinear abscissa and Lyapunov functions, already used for mobile robots.

It is shown that a typical nonholonomic vehicle, like any torpedo-shaped vehicle with mobile wings actuators, can be controlled through at least four actuations (u_x, w_x, w_y, w_z), which are respectively the translational velocity along Ox, the angular velocities around Ox, Oy, and Oz. Working in the vertical symmetry plane of AUVs, we can restrict the control actuations to (u_x, w_y).

Let us define :

- $\tilde{\theta} = \theta - \theta_d$, where θ is the vehicle pitch angle and θ_d is the bottom profile angle with respect to the reference horizontal plane.
- $\tilde{y} = y - y_d$, the difference between the altitude of a reference point on the vehicle with respect to the bottom and its desired altitude.
- $\delta_i, i = 1..p$, the distances obtained from altitude sensors $i, i = 1..p$

It is shown that $p = 2$ is a sufficient number to estimate $\tilde{\theta}$ and y. From the time derivative of y and $\tilde{\theta}$, and by use of a convenient Lyapunov function, a control law can be defined, which even allows us to constrain the transient phase of convergence (see fig. 5 where a desired relative maximum pitch angle $\tilde{\theta}_d$ is fixed). Another method, more depending on initial conditions and using the linearized tangent of the differential equation involving the time variations of a vector set of combinations of δ_i, has been also developed.

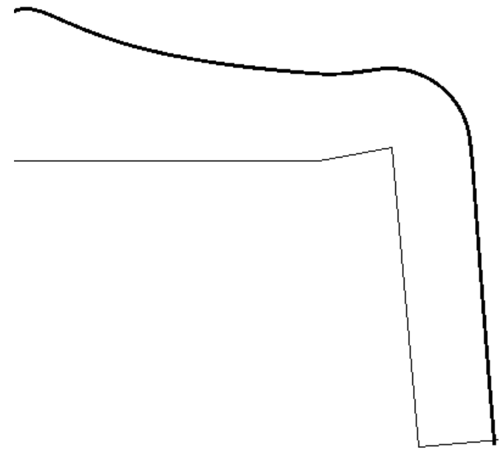

Figure 5: Following the sea bottom at $U_o = 3m/s$ with a 2-sensor configuration using Sensor-based Nonlinear Control for non holonomic vehicles. There is no noise on sensory data. Their range is limited to 1200m. With only 2 sensors, a problem exists with corners (on this example, collision).

Considering the problem of abrupt corners (e.g. vertical cliffs), a third sensor is required and a model break detection through Cumulative Sum test has been successfully tested to define a convenient and reliable method to deal with such a problem. This method can be completed by a virtual path following when the obstacle avoidance sensor orientation is smaller than the slope break in order to avoid some oscillations. A complete discussion of this method is done in [8].

Considering the second class of vehicles cited above in this subsection, a different approach is currently investigated. The approach is based on state-variable feedback and estimation in the nonlinear setting and uses many techniques from Linear Quadratic Gaussian methods which are able to preserve the design aspects of the formulation. By preserving the linear aspects as long as possible, we are able to formulate this problem as one of the classical *disturbance rejection* in which a priori information about the ocean floor may be easily included. The migration from linear to nonlinear control is then performed so as to preserve as many linear design features as is possible. Several theoretical points have been investigated, however some others remain to be developed. This last part is still under study.

5 Conclusion

Controlling an AUV to achieve a task like sensor-based bottom-following should not be reduced to only control law design, as the overall system performances strongly rely on the vehicle actuation and perception system architecture. Therefore, designing such a vehicle implies feedbacks between control scientists, naval architects and operators, with regular intermediate validations such as realistic simulations.

The task-function approach has proven to be a suitable framework to define the perception system and to specify the control objectives for holonomic vehicles as a high level methodology. Existing robust control schemes can be rather easily derived for such vehicles. For under-actuated vehicles, existing recent results in mobile land robots can be derived for plan canard actuated vehicles, while the single rear wing actuated vehicles open new areas of study as these vehicles are partly known nonlinear, nonholonomic, and nonminimum phase systems.

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