SAMPLE: SIMULATION AIDED MISSION PLANNING ENVIRONMENT

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Abstract: Autonomous Underwater Vehicles (AUVs) may be used in applications such as environmental monitoring, undersea structures inspection (offshore industry), area protection and security, and underwater archaeology. The mission planning phase of an expedition is very important because it can lead to an accurate prediction of vehicle dynamic behaviour in the expedition. During the planning phase, factors such as the type of survey, the different vehicles and payloads available, the environmental conditions, and the vehicle characteristics should be considered. The more accurate the mission plan, the higher is the probability of mission success. This paper presents a tool to simulate a desired mission, choosing between two different AUV classes (a small-sized and a mid-sized AUV). The resulting vehicle trajectory and the dynamic behaviour can be analyzed to eventually reshape the input parameters, and plan a path that best fit with the vehicle used and with the working area.

Keywords: Autonomous vehicles, Mission planning, Modelling, Simulation.

1. INTRODUCTION

Todays Autonomous Underwater Vehicles technology is mature enough to be used in many applications in a variety of areas, such as environmental monitoring (Cipollini *et al.*, 2001), undersea structures inspection (as oil and sewage pipelines), area protection and security, underwater archaeology (Vettori *et al.*, 2004; Caiti *et al.*, 2004) and so on. Usage of the vehicle could be different in various applications, the desired manoeuvres and the required dynamic behaviour could change on a case by case basis.

Mission planning is very important because it can lead to an accurate prediction of vehicle dynamic behaviour in an expedition. In some cases, the AUV user is not an AUV expert. Providing a software tool that is able to simulate the planned mission, using all the information available can contribute to the success of the mission. SAMPLE is one such tool that is being developed by the NATO Undersea Research Centre.

The paper will briefly review the mission planning problem, followed by a general description of SAMPLE. The simulation phase is shown in Section 4 while Section 5 describes the analysis of the data produced by simulation. Finally, the last section summarizes the work and proposes further developments.

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2. THE MISSION PLANNING PROBLEM

An AUV mission begins before the launching of the vehicle itself, with the planning phase. Mission planning operations have to foresee the mission evolution as accurate as possible. Many mission parameters have to be investigated in order to design a successful survey, among others:

- survey type
- available vehicle and payloads
- available information about seafloor
- presence of sea current
- area to inspect and vehicle desired path
- longitudinal plane navigation (constant altitude or constant depth)
- safety.

In the following, various aspects of mission planning are briefly introduced.
Let us assume that more than one vehicle is used, with different payloads, dynamic parameters and sizes. The first decision needed to be made is the vehicle type and the payload to use: this depends on the required survey type. Smaller AUVs are best suited for shallow and very shallow water applications and are easily deployable. Larger vehicles can be used in deep water applications and in circumstances where more sensors are needed to collect data simultaneously.
The next factor to consider is the survey area. Data useful in the mission planning process are bathymetry, seafloor type, the presence of strong sea currents and large salinity variations. Seafloor type may be sandy, muddy, rocky, covered with *Poseidonia Oceanica* (a seaweed), flat, smooth or irregular. Vehicle behaviour may be affected by the seafloor when navigating at constant altitude. When an AUV flies at constant altitude over an irregular bottom, or in presence of *Poseidonia Oceanica*, undesirable oscillations disturbing the payloads sensors have be observed. A survey using side scan sonar requires high vehicle stability along path legs, and preferable, constant altitude navigation, so that the surveyed area could be properly planned. Flying over a flat regular seafloor is the best condition for this type of navigation, but otherwise, it is possible that the AUV may experience pitch angle variations that are too large for acquiring a high quality sonar image. The alternative is to run the mission navigating at constant depth instead of constant altitude. Running such simulations in mission planning is useful in helping to choose a appropriate value for the desired depth. In general, the mission designer has to define the proper vehicle depth for each leg, evaluating the bathymetry in the working area and the performances of navigation and control systems.
In surveys where high navigation accuracy is not required (i.e. water sampling surveys), simpler and cheaper vehicles can be used (with simple navigation and control systems).

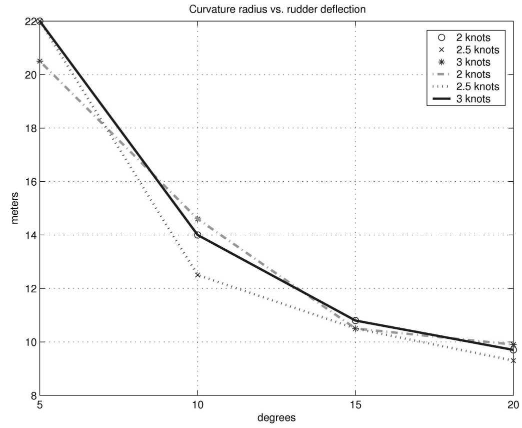

Figure 1. Ocean Explorer C curvature radius vs. rudder deflection.

Another important factor in the mission planning phase is the coverage of the survey area, especially when collecting side scan sonar data. When defining the vehicle's path, the space between legs should be chosen to maximize payload efficiency, therefore minimizing the overlap factor in the area inspection (redundant data), and to run the vehicle within its manoeuvrability characteristics. The objective is to find a trade–off between amount of data acquired and mission duration.
A useful feature in a mission planning tool is a compatibility check between vehicle characteristics and the planned trajectory. By comparing the simulation results with the vehicle dynamic performance, a preliminary compatibility evaluation could be obtained. The turning radius and the maximum yaw rate should be considered when analyzing the steering plane behaviour, while the longitudinal plane dynamic behavior is more relevant when navigating at constant altitude. As an example, figures 1 and 2 show the curvature radius and the maximum yaw rate with respect to rudder deflection, for the Ocean Explorer C AUV (available at NURC). Data reported in figure 1 suggests that, for this particular AUV, performing a lawnmower path with long legs spaced 20 meters is probably an impossible task (without accepting large trackline error during turns). Data are shown for different vehicle speed. Figure 3 presents the AUV altitude and depth together with the bathymetry when the vehicle is flying at constant altitude over an irregular sea bottom. It is clearly evident that the AUV dynamic is not fast enough to compensate all the bathymetry variations.
The safety problem is taken into account provided that the AUV flies not too close to the bottom, nor to the surface, in order to avoid collisions with the seafloor or with boats.
The evaluation of similar data during mission planning could help to define the AUV trajectory,

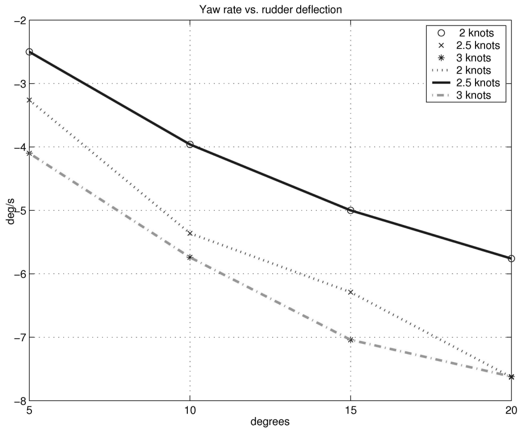

Figure 2. Ocean Explorer C yaw rate vs. rudder deflection.

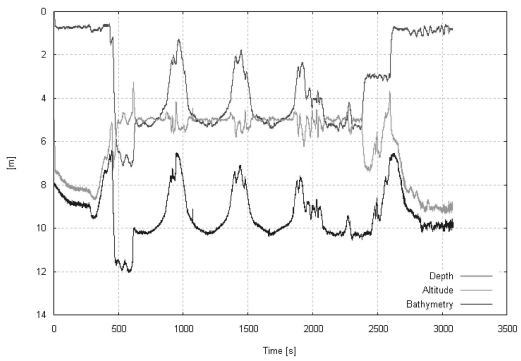

Figure 3. Ocean Explorer C depth and altitude flying over irregular seafloor.

choosing the guidance system and the navigation type in the longitudinal plane, thus reducing the risk of mission failure or unsatisfactory results.

3. SAMPLE

SAMPLE (Simulation Aided Mission Planning Environment) is a Matlab based tool designed to assist the AUV user in planning a mission. The basic idea is to run simulations with the largest set of known information on the vehicle and the environment. The analysis of the produced data is then used to generate a text file reporting detected problems. The work on SAMPLE is still under development, improvements and new features are planned for the future.

Figure 4 shows the appearance of the graphical user interface of SAMPLE. The user selects the desired vehicle model from the listbox on the left side. Following that, pressing the *Description* button from the *Mission panel* brings up a dialog box asking for files and data describing the desired mission, and the information on the environment. In particular, the user should enter the mission waypoints list, the desired values for constant altitude or constant depth navigation along each leg and the bathymetry of the working area. Details

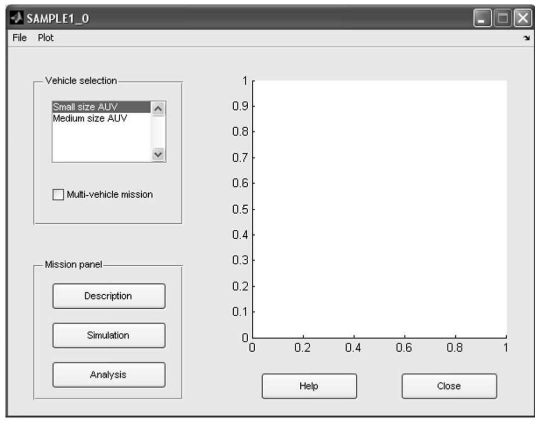

Figure 4. SAMPLE graphical user interface.

are given in section 4.1.

The *Simulation* button first produces an estimated value for the mission duration, then opens the selected vehicle model, runs the simulation and saves the results in a file (see section 4.2). At present it is possible to consider two AUVs operating in the same area at the same time, but simulations are performed separately. The resulting data are then analyzed, evaluating for possible collisions. This approach is reasonable based on the assumption that the mission is working with vehicles that do not communicate with each other and do not possess cooperative behaviour.

Pressing the *Analysis* button, the files generated in the previous simulations are analyzed to highlight possible problems that may be encountered in the AUV mission. In the plot area of the graphical user interface (on the right side), the AUV (simulated) and the planned trajectories are plotted together, projected in the steering plane. From the plot menu, the plots of the vehicle state variables and of the trajectories (included the 3D case) could be obtained (plots are shown in new figures). More details on the mission analysis are given in section 5. Figure 5 summarizes the data flow and the elaboration phases in the SAMPLE tool.

4. THE SIMULATION PHASE

The vehicle models used to perform simulations are based on the standard representation described by Fossen in (Fossen, 2002). The AUV type considered are torpedo shaped, with four perpendicular fins in the vehicle's tail section. In the present version simulations are performed with constant thrust, thus resulting in constant speed along straight long legs (without considering sea current).

The equations describing the vehicle dynamic, expressed in body fixed reference frame, are:

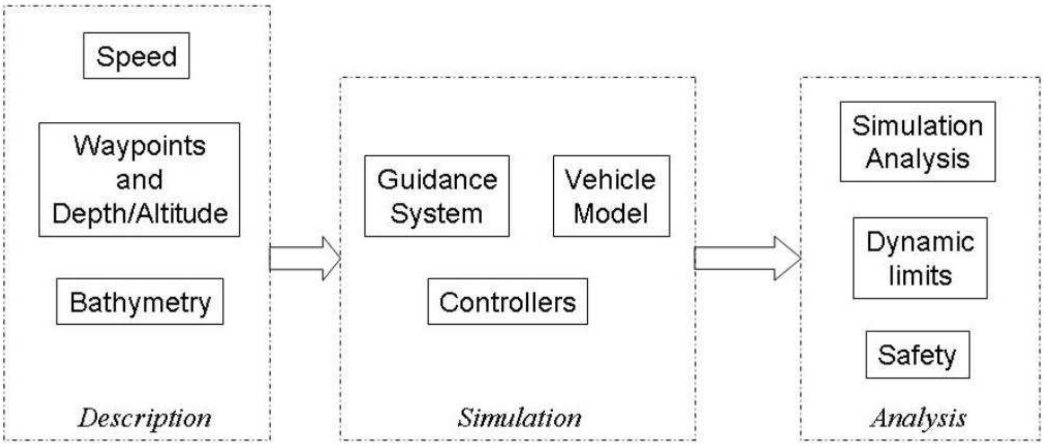

Figure 5. SAMPLE block diagram.

$$(m - X_{\dot{u}})\dot{u} + mz_g\dot{q} - my_g\dot{r} = X_{HS} + X_{u|u|}u|u| + \\ + (X_{wq} - m)wq + (X_{qq} + mx_g)q^2 + (X_{vr} + m)vr + \\ + (X_{rr} + mx_g)r^2 - my_gpq - mz_gpr + X_{prop} \tag{1}$$

$$(m - Y_{\dot{v}})\dot{v} - mz_g\dot{p} + (mx_g - Y_{\dot{r}})\dot{r} = Y_{HS} + \\ + Y_{v|v|}v|v| + Y_{r|r|}r|r| + (Y_{ur} - m)ur + \\ + (Y_{wp} + m)wp + (Y_{pq} - mx_g)pq + Y_{uv}uv + \\ + my_gr^2 + my_gp^2 - mz_gqr + Y_{uu\delta r}u^2\delta r \tag{2}$$

$$(m - Z_{\dot{w}})\dot{w} + my_g\dot{p} - (mx_g + Z_{\dot{q}})\dot{q} = Z_{HS} + \\ + Z_{w|w|}w|w| + Z_{q|q|}q|q| + (Z_{uq} + m)uq + \\ + (Z_{vp} - m)vp + (Z_{rp} - mx_g)rp + Z_{uw}uw + \\ - my_grq + mz_gp^2 + mz_gq^2 + Z_{uu\delta s}u^2\delta s \tag{3}$$

$$- mz_g\dot{v} + my_g\dot{w} + (I_{xx} - K_{\dot{p}})\dot{p} = K_{HS} + \\ + K_{p|p|}p|p| - (I_{zz} - I_{yy})qr + my_guq + \\ - my_gvp - mz_gwp + mz_gur + K_{prop} \tag{4}$$

$$mz_g\dot{u} - (mx_g + M_{\dot{w}})\dot{w} + (I_{yy} - M_{\dot{q}})\dot{q} = M_{HS} + \\ + M_{w|w|}w|w| + M_{q|q|}q|q| + (M_{uq} - mx_g)uq + \\ + (M_{vp} + mx_g)vp + (M_{rp} + I_{zz} - I_{xx})rp + \\ + M_{uw}uw - mz_g(wq - vr) + M_{uu\delta s}u^2\delta s \tag{5}$$

$$- my_g\dot{u} + (mx_g - N_{\dot{v}})\dot{v} + (I_{zz} - N_{\dot{r}})\dot{r} = N_{HS} + \\ + N_{v|v|}v|v| + N_{r|r|}r|r| + (N_{ur} - mx_g)ur + \\ + (N_{wp} + mx_g)wp + (N_{pq} + I_{xx} - I_{yy})pq + \\ + N_{uv}uv + my_g(wq - vr) + N_{uu\delta r}u^2\delta r \tag{6}$$

On the left side of the equations there are the rigid body terms, on the right side there are the hydrostatics, the damping, the added mass, the thruster and control terms. The hydrodynamic coefficients and the added mass terms have been derived based on relations found in Prestero's work (Prestero, 2001).

The open loop nonlinear vehicle model has been completed with the controllers for the steering and longitudinal planes, and a guidance system. The steering plane controller is a heading autopilot system implemented with a simple proportional, integral and derivative (PID) controller. The control system in the longitudinal plane is made of two loops: the inner is a linear quadratic regulator (LQR) on the pitch angle; the outer is a PID controller for the AUV's depth/altitude. The gains of the pitch LQR are obtained using a reduced linear model for the longitudinal plane. The guidance system is based on the modified Line Of Sight (LOS) algorithm given in (Fossen, 2002), with additional improvements. The simulator has been implemented so that by changing the vehicle's geometrical parameters and the basic hydrodynamic coefficients, the updated dynamic equations are automatically generated.

4.1 The input data

The desired mission is described through the waypoints list, the desired depth or altitude in each leg and the requested vehicle speed. In addition, the bathymetry of the working area is needed to simulate the legs performed at constant altitude. The vehicle coordinates are expressed in a North-East-Down reference system having the origin in the first mission waypoint. The waypoints list is passed to the simulator in an array of nx4 elements, where n is the waypoints number. The first and second columns of the array are the waypoints coordinates. The third columns elements could assume only two values corresponding to constant altitude or constant depth navigation. The fourth column contains the desired altitude or depth value. The array considers that the *i-th* element of the third and fourth columns are relative to the leg joining the waypoints $i-1$ and i.

The bathymetry is inserted in a lookup table and it is used to calculate the vehicle depth, using its position. In a real AUV, the vehicle altitude is

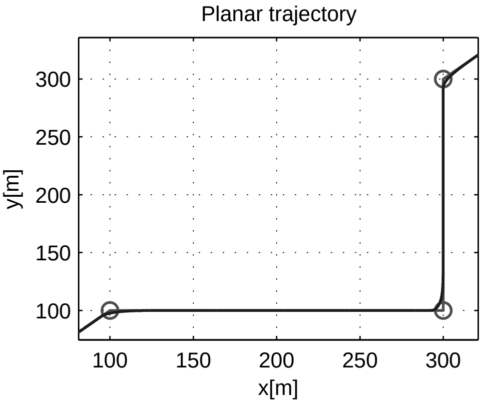

Figure 6. Desired and simulated AUV trajectory (projection in the steering plane).

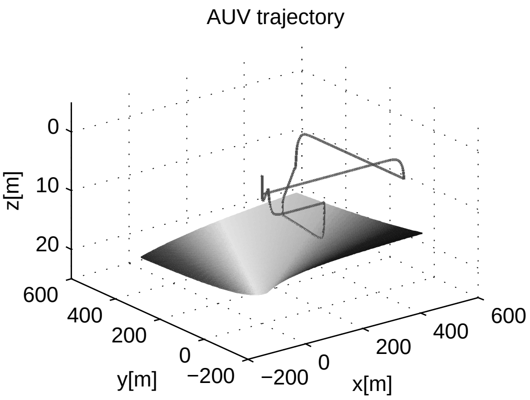

Figure 7. 3D view of the AUV trajectory.

measured by the DVL/ADCP sensor. A bathymetry map in a real vehicle could be useful in those cases where the DVL/ADCP is not able to calculate the altitude.

4.2 Simulation output

The simulator generates the time evolution of the vehicle's state variables. These vectors are saved in a file specified by the user, together with the time vector, the array describing the requested mission and the bathymetry. All the data are organized in a structure, to simplify further elaboration, in particular when two vehicles are considered.
Figure 6 shows a plot with a portion of the AUV trajectory projected in the steering plane of a sample mission. The desired and simulated path are quite coincident but with larger errors during turns. Figure 7 shows the 3D view of the same mission. In figure 8 are shown AUV's depth and altitude, together with the relative bathymetry. Legs run at constant altitude or at constant depth can be clearly identified in the plot. The plot of all others state variables are obtainable from the *Plot* menu.

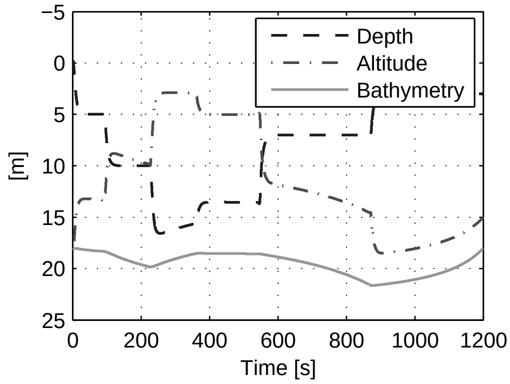

Figure 8. AUV depth, altitude and bathymetry during the mission.

5. MISSION ANALYSIS

The mission analysis should indicate to the AUV user, if the mission is properly planned. The analysis script reads the mission data from the user specified file looking at different aspects. The user should enter in a dialog box the maximum acceptable values for some AUV states: the yaw rate and the pitch rate, the minimum altitude and minimum depth. If the simulation shows turn rate values close to the limit, it is possible that the desired path include some manoeuvres and that the vehicle may not perform properly in presence of disturbances. High values of the pitch rate should be considered because they could affect the data collected by payload sensors. Reviewing the plots of all state variables is useful in order to check the presence of persistent unwanted oscillations, although limited in magnitude. The minimum altitude value is important to avoid collisions with the sea bottom due to rapid variations in the bathymetry. The minimum depth value is relevant for safety reasons, for example in case a boat enters in the working area. Defining a minimum value for the AUV depth is useful so that collisions with boats can be avoided.
The mission designer, using the analysis report together with the state variables plots, could reshape the desired path and the mission plan, increasing the success in obtaining the desired results thereby reducing the number of real missions needed to be run.

5.1 Multi-vehicles mission

When a multi-vehicle mission is selected through the *Multi-vehicle mission* checkbox, and the two simulations have been performed, a dialog box opens for the user to enter the data described in the previous section for both AUVs. In addition, three values, used in the estimation of possible collisions, are requested. The first value defines the width of a rectangular region build on the AUV position at a given time. The rectangle height is determined from the product between the vehicle speed and a time window specified by the user with the second parameter. The third parameter specifies the requested vertical separation between vehicles. SAMPLE considers first one vehicle, at each time step, builds the described rectangle with the height parallel to the instantaneous speed direction, and the width centered on the AUV position. Then it checks the second AUVs simulated positions in the time interval between the current time and time window parameter previously established. The time instants in which possible collisions are identified are reported in a file together with the vehicles coordinates.

6. CONCLUSIONS

This paper first briefly reviews the mission planning problem for autonomous underwater vehicles. The SAMPLE tool, a Matlab based aiding software for planning AUV missions, is introduced and explained. The software is still under development, and improvements are considered for the future. In particular, there is a plan to add more vehicle models, to simulate missions involving more than two AUVs, to consider, in the analysis phase, the presence of obstacles of known position and dimension, and to simulate the navigation in constrained environment.

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