SIMULATION AND GENETIC ALGORITHMS FOR CONTROL PLANNING OF UNDERWATER VEHICLE TRAJECTORIES

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ABSTRACT

The case of submarine rendezvous where a high-manoeuvrability AUV should meet a submarine platform for energy, samples and data service is considered. The AUV has a set of thrusters. It is difficult to know how to activate the thrusters for the rendezvous operation.

A simulation is developed to consider several scenarios, with submarine obstacles, and to solve the control problem. Genetic algorithms are used to determine the best AUV trajectory from surface to the final state, and to obtain the best control planning, using the thrusters, for path following along the trajectory. This paper describes the problem and the solution in simulation. Several scenarios are considered, and the solutions are presented. The simulation system will be used for programming a real AUV before diving.

KEY WORDS

AUV, simulation, genetic algorithms

INTRODUCTION

Autonomous underwater vehicles (AUVs) are gaining importance for several submarine applications and tasks. Recently we had in Spain an environmental catastrophe due to the sinking of a tanker near the northern coast. For all the country it became clear how useful is to have robotic submarine devices to handle such cases, avoiding as much as possible oil spill over.

Another example has its roots in the initiative, some years ago, about installing submarine observatories for monitoring several variables of environmental importance. Suddenly, due to the very unfortunate tsunami centered in Sumatra, the need of such observatories for safety reasons has taken first order interest. In this paper the case of submarine rendezvous operation is considered. A high manoeuvrability AUV is used for servicing a submarine observatory. The AUV starts from just beneath the surface, and dives to reach with zero speed and horizontal attitude a certain docking device of the observatory. It is important to follow a cheap trajectory, requiring not much AUV energy spent, and to reach the target in a reasonably short time. Not any trajectory can be easily followed by the AUV.

The AUV has neither rudder nor fins, only thrusters. The marine craft motions are coupled, so there is a problem of control planning, to activate the thrusters in the proper way. In the whole, there is a combined multiobjective optimization problem, involving trajectory and control optimization.

What is needed is a simple way of telling the AUV what to do, before a diving. Consequently, a simulation environment has been developed, in Matlab-SIMULINK, to state there the particular problem, with initial and final states and possible obstacles, to solve the optimization problem in the environment, to get a table of control actions, and to inject the table into the AUV computer to start the diving and rendezvous operation.

The nature of the multiobjective optimization problem makes advisable to use Genetic Algorithm, since they represent a direct and simple way to handle such problems. The EVOCOM Matlab Toolbox was used. This is a Toolbox developed by our group some years ago [1]. It drives efficiently to satisfactory solutions.

An important aspect of this paper is how the optimization problem has been stated in terms of chromosomes and fitting function.
The mathematical model of the AUV motions is inspired in the background given by [2]. Our main difficulty here is that most of the papers and textbooks consider submersible vehicles with fins and rudders, which is not our case.

Respect with Genetic Algorithms and AUVs, there are contributions about trajectory planning, such in [3]; in a recent article [4], the problem included sea currents and underwater mountains. Notice that these contributions deal only with trajectories; in this paper the control planning for using thrusters is considered.

Our research belongs to a topic of great interest in the robotic field. It is related to social and cooperative robotics, with homogeneous or heterogeneous robot teams. Our purpose is to carry this study perspective to the marine context. There are some recent contributions reflecting the same spirit. For instance [5] on ship rendezvous operations, [6] with platoons of AUVs, or [7] with the coordinated control of marine robots.

The paper begins delineating a basic rendezvous scenario. The mathematical modeling aspects of the case are stated. Then, our Genetic control planning method is presented.

The paper continues with two sections devoted to applications of the method. The first of these sections considers the basic scenario, with some alternatives. The second puts several types of obstacles, and shows the solutions obtained by the method. The paper ends with conclusions and comments on future activities.

A BASIC SUBMARINE RENDEZ-VOUS SCENARIO

Figure 1 shows a lateral view of the basic scenario. The AUV departs from an initial point near the surface, and must arrive to a submerged platform. The final state of the AUV, for docking with the platform, must be zero speed and horizontal attitude.

An adequate trajectory (not much energy invested, not much time) must be determined, together with the action of the thrusters causing the AUV trajectory.

Figures 2 and 3 show two views of the AUV. The AUV has four thrusters. Each thrusters can be reversed.

The general motion of the AUV is expressed with the following vectors:

\[ \eta_1 = [x, y, z]^T; \quad \eta_2 = [\phi, \theta, \psi]^T; \]
\[ \upsilon_1 = [u, v, w]^T; \quad \upsilon_2 = [\rho, \varphi, \tau]^T; \]
\[ \tau_1 = [X, Y, Z]^T; \quad \tau_2 = [K, M, N]^T \]

Where \( \eta_1 \) and \( \eta_2 \) are the position and attitude of the AUV respect to earth-fixed coordinates; \( \upsilon_1 \) and \( \upsilon_2 \) the speed in the same reference, and \( \tau_1 \) and \( \tau_2 \) the forces and moments being applied to the AUV.

Textbooks on ship control offer six DOF models, with added masses, hydrodynamic forces, etc. For instance [2] uses this general equation for each of the marine craft six motions:

\[ M \cdot \dot{\omega} + C(\omega) \cdot \omega + D(\omega) \cdot \omega + g(\eta) = \tau + \omega \]

(2)
Considering our two-dimensional scenario, with only three relevant control actions (surge and heave forces, pitch moment), and taking into account only linear damping terms, the following equations of motions are obtained:

\[
\begin{bmatrix}
-m\ddot{x} - m\dot{y} - m z_g - Xq_y' w + Xu - Xw - Xq\frac{u}{w} \\
-m\ddot{y} + m\dot{x} - m z_g - Xq_x' q + Xw - Xz - Xq\frac{w}{q} \\
-m z_g - Xq_x' - m z_g - Xq_y' l y y - Mq' q
\end{bmatrix}
= \begin{bmatrix}
F_1 \\
F_2 \\
F_3
\end{bmatrix}
\]

For the SIMULINK model, the accelerations in each degree of freedom can be expressed as:

\[
\begin{align*}
\dot{u} &= \left( F_1 + Xw - Xu + Xw \cdot w + Xq - (m \cdot z_g - Xq') \frac{q' + Xw \cdot w}{m} \right) \\
\dot{w} &= \left( F_2 + (m - Xu') \frac{u \cdot q + Zw \cdot w + Zu \cdot u + (m \cdot Xq + Xq') \cdot q' + Xw' \cdot w}{m \cdot Zw'} \right) \\
\dot{q} &= \left( F_3 - w Zw' \cdot \sin (m Xq + Mq' \cdot q - (Zw' - Xu') \cdot u - Mw') \right) + \\
&\left( Mw \cdot u + (m Xq + Nq') \cdot w - (m z_g - Xq') \cdot u \right) \frac{1}{Mq'}
\end{align*}
\]

For the SIMULINK model, the accelerations in each degree of freedom can be expressed as:

\[
\begin{align*}
\dot{u} &= \left( F_1 + Xw - Xu + Xw \cdot w + Xq - (m \cdot z_g - Xq') \frac{q' + Xw \cdot w}{m - Xu} \right) \\
\dot{w} &= \left( F_2 + (m - Xu') \frac{u \cdot q + Zw \cdot w + Zu \cdot u + (m \cdot Xq + Xq') \cdot q' + Xw' \cdot w}{m - Xu} \right) \\
\dot{q} &= \left( F_3 - w Zw' \cdot \sin (m Xq + Mq' \cdot q - (Zw' - Xu') \cdot u - Mw') \right) + \\
&\left( Mw \cdot u + (m Xq + Nq') \cdot w - (m z_g - Xq') \cdot u \right) \frac{1}{Mq'}
\end{align*}
\]

Notice how these accelerations are mutually coupled. This is a source of difficulty for the control. Table 1 gives the numerical values of the constants used in the AUV model.

<table>
<thead>
<tr>
<th>Constant</th>
<th>Numerical value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xu'</td>
<td>-7.61*10^(-3)</td>
</tr>
<tr>
<td>Xw'</td>
<td>1.7*10^(-1)</td>
</tr>
<tr>
<td>Xq'</td>
<td>2.6*10^(-2)</td>
</tr>
<tr>
<td>Xu</td>
<td>5.0*10^(-3)</td>
</tr>
<tr>
<td>Xw</td>
<td>2.0*10^(-1)</td>
</tr>
<tr>
<td>Xg</td>
<td>7.0*10^(-2)</td>
</tr>
<tr>
<td>Zw'</td>
<td>-2.4*10^(-1)</td>
</tr>
<tr>
<td>Zq'</td>
<td>-6.8*10^(-3)</td>
</tr>
<tr>
<td>Zu</td>
<td>-6.5*10^(-2)</td>
</tr>
<tr>
<td>Zw</td>
<td>-3.0*10^(-1)</td>
</tr>
<tr>
<td>Zu'</td>
<td>-1.4*10^(-2)</td>
</tr>
<tr>
<td>Mu</td>
<td>-1.7*10^(-1)</td>
</tr>
<tr>
<td>Mw</td>
<td>-5.5*10^(-2)</td>
</tr>
<tr>
<td>Mq'</td>
<td>-1.7*10^(-1)</td>
</tr>
</tbody>
</table>

Table 1. Numerical values of the AUV model.

The mass is 40 kg, and it can be assumed that

\[ W = B = 400 \text{ N} \]

The center of mass and the center of buoyancy are not coincident \((x_g = 0.1 \text{ m}, y_g = 0 \text{ m}, z_g = 0.02 \text{ m})\).

The problem is to specify along time the three forces in equation (3), so the AUV follows an optimal trajectory and stops at the docking point with zero speed and horizontal attitude.

### THE GENETIC CONTROL PLANNING METHOD

The successful application of Genetic Algorithms to an optimization problem is based on two factors: a good codification in terms of chromosomes, and an adequate definition of the fitting function. It is important to take advantage of the open opportunities offered by GA to include “a priori” knowledge about the problem (in the case of this research, this knowledge leads to a specific semantics of the chromosomes and to define constraints and criteria to be optimized).

Our fitting function is composed by several criteria to be optimized (multi-objective function):

- Trajectories avoiding obstacles.
- AUV trajectories without points over the sea surface or under the sea bottom.
- Good arrival at the submarine platform, zero final speed and zero final pitch angle.
- Short trajectory length, with not much time involved.
- Low energy requirements.

The objectives are grouped into two sets. The first set includes primary objectives; the second set includes secondary objectives. A Pareto front is determined for the first set but the second set is preferred: between two individuals with equal fitting function value, the individual with better value in the second set is preferred.

When the Pareto front has been determined for the first set, another Pareto front is determined for the second set considering values in the first set. This is repeated, till results converge.

For the chromosomes, the codification has been devised in the following way:

- The trajectory time is divided into intervals: \( t_1, t_2, t_3, \ldots t_N \). During the first \( t_1 \) seconds, the \( F_{1,1} \) surge force, the \( F_{1,3} \) heave force and the \( F_{1,5} \) pitch moment is applied. During the second interval, along \( t_2 \) seconds, increments \( \Delta F_{2,3}, \Delta F_{2,5} \) and \( \Delta F_{2,5} \) are added to the surge force, the heave force and the pitch moment. This is repeated in the rest of intervals (with increments \( \Delta F_{3,1}, \Delta F_{3,3} \) and \( \Delta F_{3,5} \)).
- Each chromosome has the following structure:

\[
\begin{align*}
\Delta F_{1,1} & \Delta F_{1,3} & \Delta F_{1,5} \\
\Delta F_{2,1} & \Delta F_{2,3} & \Delta F_{2,5} \\
\cdots & & \\
\Delta F_{N,1} & \Delta F_{N,3} & \Delta F_{N,5}
\end{align*}
\]

\( t_1, t_2, \ldots t_N \)

The characteristics of the Genetic Algorithm correspond to the standard described in [8], with the specifications of the EVOCOM toolbox [1].
The population includes 40 individuals, the selection is elitist, three points are used for crossing (probability 0.8), and the mutation probability is 0.008.

An important specification is that stepwise form of the control actions is desired, to get initial simple alternatives for the control planning.

With staircase controls it is easy to elaborate a table of actions to be injected into the AUV before diving.

**CASES WITH NO SUBMARINE OBSTACLES**

Several cases have been defined to check the optimization procedure. Basically the cases consider several interesting situations corresponding to different final positions to be reached. Table 2 summarizes the cases.

<table>
<thead>
<tr>
<th>Final point (m)</th>
<th>Length(m)</th>
<th>Time (s)</th>
<th>Intervals</th>
</tr>
</thead>
<tbody>
<tr>
<td>X=1; Y=1.</td>
<td>1.44</td>
<td>33.3</td>
<td>8</td>
</tr>
<tr>
<td>X=1; Y=2.</td>
<td>2.28</td>
<td>39.8</td>
<td>10</td>
</tr>
<tr>
<td>X=2; Y=1.</td>
<td>5.11</td>
<td>68.8</td>
<td>20</td>
</tr>
<tr>
<td>X=2; Y=2</td>
<td>2.48</td>
<td>40.5</td>
<td>12</td>
</tr>
<tr>
<td>X=5; Y=1.</td>
<td>5.30</td>
<td>64.1</td>
<td>20</td>
</tr>
<tr>
<td>X=5; Y=2</td>
<td>5.57</td>
<td>70.1</td>
<td>20</td>
</tr>
<tr>
<td>X=5; Y=5</td>
<td>7.31</td>
<td>93.27</td>
<td>35</td>
</tr>
<tr>
<td>X=10; Y=5</td>
<td>12.00</td>
<td>134.7</td>
<td>50</td>
</tr>
<tr>
<td>X=10; Y=10</td>
<td>16.06</td>
<td>163.7</td>
<td>60</td>
</tr>
<tr>
<td>X=15; Y=5</td>
<td>17.53</td>
<td>128.3</td>
<td>58</td>
</tr>
<tr>
<td>X=15; Y=10</td>
<td>18.83</td>
<td>148.5</td>
<td>60</td>
</tr>
<tr>
<td>X=30; Y=20</td>
<td>36.7</td>
<td>209.6</td>
<td>88</td>
</tr>
<tr>
<td>X=40; Y=20</td>
<td>50.41</td>
<td>203.0</td>
<td>89</td>
</tr>
</tbody>
</table>

Table 2. Several rendezvous basic cases.

In all cases the GA procedure reaches successful solutions in less than 1200 generations (15 minutes in a Pentium IV at 512 Mhz).

Figure 4 shows an example of the cog trajectory for an optimal solution, reaching X=30, Y=20 in 209.6 seconds. Although control actions are stepwise, the cog trajectory is smooth because the marine craft inertia integrates the forces.

**CASES WITH SUBMARINE OBSTACLES**

There will be practical cases with submarine mountains, which represent obstacles to avoid by the AUV trajectory. Obstacles are easily included in the optimization procedure. Indeed, the time for the GA to obtain a solution increases, but not too much. Figure 5 shows the cog trajectory of the AUV for an optimal solution avoiding a submarine obstacle. Figure 6 shows the planning of control actions, which is part of the optimal solution, obtained with the GA procedure. Figure 7 shows the pitch evolution of the AUV along the trajectory.
To check the flexibility of the method, a combined case, with a floating obstacle and a submarine obstacle, has been studied. Figure 9 depicts this scenario.

A good solution has been attained in a reasonable time.

Figure 10 shows the AUV cog trajectory, and figure 11 shows the corresponding planning of control actions.
CONCLUSION

A genetic control planning and a simulation for high manoeuvrability AUVs has been presented. The simulation is done in SIMULINK, and the genetic method is implemented in Matlab, to interact with the simulation.

Both trajectory and control actions have been optimized. The control planning is expressed as a table that can be injected into the AUV before diving.

Several cases, into a general submarine rendezvous scenario, have been studied, reaching good results with moderate computational costs.

The system will be experimentally tested in the next months. Some other developments must be done before, since the ion-board control must accomplish the control plan and correct any deviations during course.

Further improvement of the described method is the possibility of smooth control actions, and to decompose the trajectory into curve segments according with the obstacle configurations.

REFERENCES


