Dynamics and Control of Underwater Gliding

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LONG-TERM GOALS

My long-term goal is to help improve versatility of underwater gliders as platforms for ocean sampling and other applications by contributing to the development of a methodology for designing and analyzing high-performance, cost-effective underwater glider controllers.

OBJECTIVES

I am interested in establishing a framework for studying dynamics and control of underwater gliders. I am focussing on dedicated gliding vehicles that have the ability to change mass (or volume) for buoyancy control and to redistribute mass for attitude control. Later on it is of interest to consider vehicles that use glide maneuvers to complement more traditional methods of control actuation. The framework will consist of a dynamical systems model of underwater gliding vehicles together with techniques for generating and controlling glide maneuvers in the presence of uncertainty. The first objective is to develop a model that is representative of a general class of underwater gliders. Then, dynamics and stability should be studied followed by the development of control laws for stabilizing individual glide motions, e.g., straight-line or spiral glide paths. Next, it is intended to develop techniques for concatenating stabilized glide motions to perform maneuvers, follow waypoints and track trajectories. A further objective is to develop methodology for assigning performance measures and then to optimize vehicle control design with respect to these measures. Additionally, it is of interest to address problems in coordinating control for a network of underwater gliders.

APPROACH

We are using theory, analysis, simulation and laboratory-scale experimentation in this project. Modeling is based on rigid body dynamics of the glider with a dynamic model of varying mass

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(or volume) and mass distribution, potential flow models of the fluid to capture buoyancy effects and semi-empirical modeling of lift and drag. Methods from mechanics and dynamical systems theory for checking stability and for analyzing dynamics are being applied. Both linear control theory and nonlinear control theory are considered to first stabilize individual glide maneuvers and then to join them together for path following. The control design will be made to exploit the results and insights from the dynamic systems analysis. Physical limits on how much (and how fast) mass can be added or subtracted and how far (and how fast) the center of gravity can be moved from the center of the vehicle will be accommodated by using methods that deal with saturation. Optimal control theory is being used to come up with paths and control laws that are energy and time efficient. Simulation tools include MATLAB, Mathematica, as well as a 3-D interactive graphics simulation platform that we are developing on our Silicon Graphics workstations. The latter provides an effective means for off-line demonstration and study of underwater vehicle dynamics and control. We are also making use of a small (laboratory-scale), experimental underwater gliding vehicle that we have built and are continuing to develop in our laboratory. Key individuals who are working with me at Princeton include a graduate student (J. Graver) working on the gliding control laws, another graduate student (C. Woolsey) who is working primarily on a related problem of controlling and underwater vehicle using internal rotors, a post-doc (M. Chyba) who works on optimal control and a technician (R. Sorenson) who is working on upgrading the vehicle.

WORK COMPLETED

We have completed a first cut at a dynamic model for an underwater glider that can change mass and can move a point mass around inside to change mass distribution. The glider is assumed to be equipped with wings and vertical and horizontal stabilizers. We have specialized this model to the vertical plane and have studied stability of straight-line glides as a function of location of the moveable point mass. We have also studied controllability and are in the process of extending this analysis to cases where the extent of control over mass redistribution is limited (e.g., to one degree-of-freedom). We have designed linear controllers to stabilize a given glide using LQR design methods so that limits on mass change and redistribution can be incorporated. We have begun to complement these feedback control law with feedforward terms to drive the point mass in an appropriate way. We are currently studying regions of attraction for these control laws for the nonlinear dynamics in order to determine how we can concatenate controlled glides for path or waypoint following. We have also made progress on some preliminary investigation of time-optimal solutions. Simulations have been prepared using MATLAB and we are continuing to improve actuators, sensors, and aspects of vehicle design for our laboratory-scale underwater glider. Some very preliminary testing of this vehicle was done in Princeton's Olympic-size swimming pool and more of these tests are planned for the future.

RESULTS

We have a working model of the dynamics of a generic underwater glider with which we can study the fundamentals of glider stability, dynamics and control. In particular, we are learning how the effect of mass redistribution (both as it changes the gravity-buoyancy moment as well as the total vehicle inertia) can be used to change the dynamics of the vehicle. We now have control laws to stabilize in the presences of disturbances a straight-line glide path for a glider confined to the vertical plane. We have seen promising evidence that the regions of attraction for these control laws are relatively large and this should make it easier to get the vehicle to stably switch between different glide paths. We are beginning to have tools available so that we can sort out optimal paths for the glider and we have a laboratory-scale vehicle that is becoming more useful for testing of our ideas and results.

IMPACT/APPLICATIONS

Because our glider vehicle model is somewhat generic, we can consider a range of existing or potential gliding vehicle designs (although some simplifications in our modeling may have to be accommodated). This we hope will allow us to apply our results both to full-scale gliders under development and to provide design guidelines for future underwater gliders. We also hope that even our preliminary results might be useful for designers seeking to include a mass-redistribution module in a more traditionally designed vehicle and exploit gliding motions in their vehicle's operation. The deeper understanding of the consequences and opportunities afforded by using internal actuation, in particular using mass distribution but also using rotating masses (i.e., internal rotors) may have implications in a wide variety of vehicle applications.

TRANSITIONS

The results are new and are not yet being used by others. However, we hope that soon we may coordinate with the investigators who have built and recently tested full-scale gliders and try out some of our methods.

RELATED PROJECTS

I have just begun a new NSF/KDI funded project joint with A.S. Morse (Yale), P. Belhumeur (Yale), R. Brockett (Harvard), D. Grunbaum (U. Washington) and J. Parrish (U. Washington) on coordination of natural and man-made groups. We are studying schooling of fish and "schooling" of autonomous underwater vehicles. This project is related to the problem of coordination of groups of underwater gliders.

I am working on controlling autonomous underwater vehicles with internal actuation, namely internal rotors, as part of a project on stabilization of mechanical systems using controlled Lagrangians. This is a joint project with A.M. Bloch (U. Michigan) and J.E. Marsden (Caltech).

PUBLICATIONS

Bloch, A.M., N.E. Leonard and J.E. Marsden [1998] Matching and stabilization by the method of controlled Lagrangians, *Proc CDC* **37**, 1446–1451.

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