Aggressive Terrain Following for Motion-Constrained AUVs
Sarah E. Houts, Stephen M. Rock
Aerospace Robotics Lab

Motivation
A motivating mission for Autonomous Underwater Vehicle (AUVs) is to collect a series of images over time to monitor it for change. To perform such a mission with a boat becomes extremely costly, encouraging the use of autonomous vehicles, particularly for remote sites. Figure 1 shows such a site of interest off the coast of Monterey. There are two main challenges to navigating images – navigating back to the site of interest, and flying close enough to the terrain to gather images (~5 meters) while remaining safe.

Figure 1: Chemosynthetic clams at a remote site off the coast of Monterey. The mission that took this photo took 3 days with a fully-crewed boat, but could be done more easily with an AUV.

Terrain-Relative Navigation
Navigating over long distances underwater can be extremely challenging. GPS cannot penetrate the water, and using underwater beacons is prohibitively expensive when considering the long distances to remote sites. Terrain-Relative Navigation (TRN), is an approach that allows the vehicle to localize itself with respect to a map of the terrain by correlating sonar range measurements over time. The basic process of this correlation is shown in Figure 2, with the vehicle's sonar measurement being correlated against the map. This approach [1] has been extended to be more robust to map errors [2] and recover from "lost" situations, allowing it to consistently provide map-resolution level accuracy.

Figure 2: Correlation of sonar beams against a particular, Rob McEwen control system expertise has been invaluable. Aquarium Research Institute) for their hard work and support. The authors would like to thank the team at MBARI (Monterey Bay Aquarium Research Institute) for their hard work and support. Figure 3: A Dorado-class AUV at MBARI, August 2011.

Figure 3: A Dorado-class AUV at MBARI

Motion Constraints and Uncertainty
Flying close to the bottom to gather images once the vehicle has navigated back to the site of interest provides additional challenges. The approach presented here focuses on using the a priori map to plan a safe trajectory over the terrain. Many AUVs have been optimized for efficient long-distance travel, such as the MBARI AUV shown in Figure 3, and as a result are not very maneuverable. This leads to a very large turning radius on the vehicle, which can lead to areas of the terrain that do not get imaged, particularly with a purely reactive survey. This can be seen in Figure 4. This places a constraint on the curvature of the trajectories that the vehicle is able to fly.

In addition, there are a number of sources of uncertainty that must be accounted for to maintain safe operations for the vehicle. Some examples include the vehicle's ability to follow the commanded trajectory in the presence of disturbances and imperfections in the map itself. These types of uncertainty can be incorporated in the optimization by constraining the probability of an undesirable event occurring (such as getting too close to the terrain) to remaining below a given threshold.

Figure 4: The results of a purely reactive survey as compared to a survey done with a pre-planned trajectory. The vehicle may not be able to physically image the entire area, but with a pre-planned trajectory that takes motion constraints into account, it can do a much better job because it can anticipate the terrain.

Figure 5: The basic optimization performed to create the univariate spline trajectories. The points that are extracted from the map are fit as closely as possible while constraining the curvature of the spline and enforcing that the probability of getting closer than a minimum distance to the terrain is below a desired threshold.

Constrained Optimization
To generate a trajectory for the vehicle to follow, a constrained optimization was performed. The objective is to follow as closely as possible the terrain at the desired standoff distance, constrained by the turning radius of the vehicle and a requirement to not get dangerously close. The latter is enforced as a chance constraint – a constraint on the probability of getting too close to the terrain. The constraints are enforced at particular locations along the trajectory, which is defined as a univariate spline. This allows for uncertainty in the vehicle’s ability to follow the trajectory to be included as uncertainty on the control points of the spline and uncertainty on the location of the points extracted from the map. This is shown in Figure 5.

Implementation
The implementation of the optimized trajectories is straightforward, but required some care. One of our goals was to use the existing control system, both for ease of implementation as well as to retain the existing safety mechanisms. As a result, the information that is passed to the control system includes both the desired depth profile and feed-forward pitch profile. This gives the vehicle some anticipatory information to enable it to follow the trajectory more closely. A block diagram of the control system is shown in Figure 6.

Figure 6: A block diagram of the AUV's basic control system. The trajectory that is output to the vehicle from the optimization is highlighted in purple.

Conclusions
Using this optimization approach using motion and chance constraints to plan safe, feasible trajectories for the vehicle using a map of the terrain, the AUV is able to image a much larger amount of terrain without compromising the safety of the vehicle. This enables return-to-site imaging missions to monitor an area for change over time.

Further Information
Contact information: Sarah Houts – shouts@stanford.edu
Website: arl.stanford.edu

Bibliography

Acknowledgments
The authors would like to thank the team at MBARI (Monterey Bay Aquarium Research Institute) for their hard work and support. In particular, Rob McEwen control system expertise has been invaluable. The implementation of the optimized trajectories is straightforward, but required some care. One of our goals was to use the existing control system, both for ease of implementation as well as to retain the existing safety mechanisms. As a result, the information that is passed to the control system includes both the desired depth profile and feed-forward pitch profile. This gives the vehicle some anticipatory information to enable it to follow the trajectory more closely. A block diagram of the control system is shown in Figure 6.

Figure 6: A block diagram of the AUV's basic control system. The trajectory that is output to the vehicle from the optimization is highlighted in purple.