Aggressive Terrain Following for Motion-constrained AUVs

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***Abstract*—A motivating mission for AUVs is to collect a time series of images of a benthic site to monitor it for change. This mission includes performing a visual survey of an area of the seafloor and then returning to selected sites within that survey area on subsequent visits. To enable this capability for remote sites far from the launch point, an AUV designed for long-distance travel is required. Such AUVs are typically motion-constrained – they cannot hover and must maintain forward flight for controllability. In addition to a navigational system capable of returning the vehicle to the site, a terrain-following system is required to allow the motion-constrained AUV to fly safely within a few meters of the seafloor to collect images.**

Recent demonstrations using MBARI's Dorado-class AUVs combined with a Terrain-Relative Navigation system (TRN) have proven much of the navigational capability, demonstrating return-to-site within approximately 3 m. Imaging of the seafloor using these AUVs has also been demonstrated using a reactive obstacle avoidance control law. While successful, this reactive-only system is conservative, resulting in sections of the seafloor being missed during the imaging process.

This paper presents an approach for planning terrain-following trajectories for an AUV that will allow it to operate safely in close proximity to rugged terrain. The approach fuses reactive obstacle avoidance with anticipatory information from the TRN system. Specifically, by including knowledge of known terrain ahead, a more aggressive trajectory can be planned, resulting in improved mission performance without compromising vehicle safety. A reactive system is still incorporated, but only to handle any unmapped obstacles that are encountered.

The new terrain-following algorithm is described, and its feasibility is demonstrated through simulations using field data from AUV operations in Monterey Bay.

I. Introduction

Monitoring a benthic site for change by using images collected over time is one of the key motiving goals of achieving persistent presence in the deep ocean. Currently, most of these surveys are done using ship-based remotely operated vehicles. Being able to perform these mission with Autonomous Underwater Vehicles (AUVs) would allow for significant reductions in ship costs.

Fig. 1: Dorado-class AUV operated by MBARI. Photo courtesy Peter Kimball

There are two basic types of AUVs in use currently for underwater imaging missions. The first type is hover-capable. These vehicles have the advantage that they are able to perform precise surveys in complex terrain, however, they typically are limited in their ability to transit efficiently to remote locations.

The second type of AUV is optimized for transit surveys. An advantage of these vehicles for repeat survey missions is that they are able to reach remote sites. A limitation of these vehicles, however, is that they are typically restricted in their maneuvering capability. That is, they have large turning radii and must maintain forward flight for controllability.

The goal of the work presented here is to enable transit-style AUV missions to sites that are often far away from the vehicle launch point. Specifically, two challenges are addressed. The first is enabling these AUVs to navigate precisely to the site of interest without the need to surface for GPS position fixes. This is accomplished through the incorporation of Terrain-Relative Navigation techniques. The second is enabling the AUV to fly aggressively (e.g. at 3–4 m altitudes) yet safely over the site to be imaged. This is accomplished by modifying the AUV's control system to track pre-planned feasible trajectories that are calculated using existing bathymetry data.

This paper presents a framework for performing such missions. A modified control architecture is described, and a method for calculating aggressive yet safe and feasible trajectories is presented.

II. Test Platform

The target AUV for the work presented in this paper is shown in Figure 1. This vehicle has an 18 hour endurance and a typical speed of 2 knots. The vehicle can be equipped with a variety of instruments, including cameras and strobes for imaging missions. The primary navigation system on-board the vehicle is based on a Kearfott INS and an RDI 300kHz DVL. Actuation is provided by a single vectoring thruster at the rear which yields an approximate minimum turning radius of 15 m.

Several control modes are incorporated into the vehicle. Its primary mode is to navigate trajectories defined by (x,y,z) waypoints. However, it is also able to maintain a constant altitude above the seafloor using a reactive control system that couples into the depth control loop. Typical altitudes for this reactive system are ~20 m, however, it has been run at 3 m altitudes for imaging missions over relatively benign terrains.

Reactive obstacle avoidance has also been demonstrated on this vehicle using a forward-looking sonar to identify and avoid obstacles ahead of the vehicle using the approach described in Section III-B.

Finally, this vehicle has been used to demonstrate Terrain-Relative Navigation (TRN) within the Monterey Bay yielding return-to-site accuracies of ~3 m [1], [2]. TRN has been demonstrated by numerous researchers as an on-board navigational system that will allow a vehicle to localize itself with respect to a map of the terrain [2], [3]. This provides a realtime, drift-free estimate of position and orientation, along with confidence bounds on that estimate. Significantly, it provides navigation with respect to the map rather than with respect to inertial coordinates. This eliminates the effects of geo-referencing errors in the map.

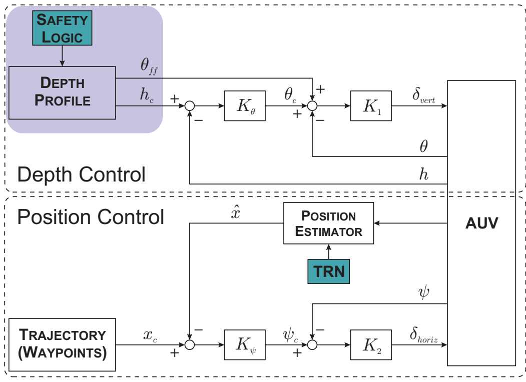


Fig. 2: The terrain following system is comprised of two main loops, controlling depth and position respectively. The new work presented in this paper primarily fits into the blue box.

III. Aggressive Terrain Following System

A schematic of the modified control system for the AUV is presented in Figure 2. It consists of two primary loops. One loop controls depth (or altitude). The other provides trajectory navigation. All the basic components in this loop are currently installed and are operational on the AUV, however, details within each of the functional blocks are being modified in this current effort. The Safety Logic and Depth Profile blocks (highlighted in blue) are the where most of the modifications for aggressive terrain following are incorporated.

A. Position Control

In the existing system, the goal of the Position Control block is to control the North and East position of the vehicle. An INS provides information to the position estimator from gyros, compass, accelerometers, etc., and the position estimator then combines these measurements with any updates from an external source (e.g. GPS) to arrive at an estimate of the vehicle position in North and East. Any error between the estimated and desired position is driven to zero by issuing heading commands which in turn are achieved by modulating the rudder.

One change that has been made to this logic to enable aggressive terrain following is to include a TRN update capability to the system in addition to the current GPS update. This addition makes it possible for the AUV to determine its position with respect to a map of the terrain instead of with respect to latitude and longitude. More detail on TRN is presented below in Section IV.

B. Depth Control

The goal of the Depth Control loop is to maintain a specified depth (or altitude) of the AUV. In the current system, the desired depth can be commanded as a function of vehicle position, or it can be commanded as a minimum altitude above the terrain. Depth is controlled by commanding changes in the AUV pitch, which is controlled by modulating the elevator.

Also in the current system is an obstacle avoidance capability that overrides the current depth command with a value that drives the vehicle to a safe altitude. This logic uses a forward-looking scanning sonar to determine the highest point within the look-ahead distance and and uses that point to set the new depth command. This is similar to the approach presented by McPhail in Reference [4].

One change that has been made to this system for aggressive terrain following is to modify the obstacle avoidance logic. Specifically, if the look-ahead sonar observes obstacles that are expected (i.e. exist in the map that was used to plan the trajectory), it does not override the depth or altitude command. If an unanticipated obstacle is seen, however, the system reverts to the safe mode of operation.

To keep the vehicle safe in uncertain terrain, a switching logic has been made to transition between three modes, as shown in Figure 3. The mode of operation dictates the source of the vehicle depth command, h_c, in Figure 2.

This safety logic makes decisions based on the look-ahead sonar and the Terrain-Relative Navigation system. The look-ahead sonar compares measurements to the map to check for unexpected obstacles. TRN provides both an estimate of the vehicle's position in the map (x) and a measure of the uncertainty of that estimate (Σ).

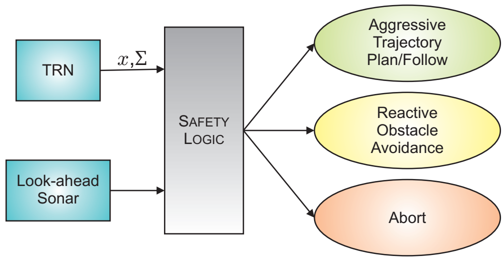


Fig. 3: Switching logic for obstacle avoidance. Based on the confidence of the TRN algorithm and the measurements coming from the look-ahead sonar, the vehicle switches between three control modes: aggressive trajectory following when confident, reactive obstacle avoidance when uncertain, and an abort mode that stops the mission.

The desired primary mode is planning and flying aggressive terrain-following trajectories. When confident that the world around the vehicle agrees with the map, it will fly the aggressive terrain-following trajectory that it has calculated as described in Section V. So long as the look-ahead sonar measurements agree with the map and the TRN uncertainty is low, the aggressive trajectory will be flown. Otherwise, it reverts to one of the more conservative modes. In this mode, the depth profile is accompanied by a feed-forward pitch command, further described in Section V-A. This feed-forward system has not previously been flown on the MBARI AUVs.

The second mode is reactive obstacle avoidance. Should the vehicle lose confidence either through TRN or the look-ahead sonar, it transitions to the reactive obstacle avoidance mode. This is the same as the current obstacle avoidance, described above, and has been tested on the MBARI Dorado-class AUV. In this mode, the imaging mission continues, although coverage will be reduced in areas where this conservative mode takes the vehicle safely over terrain that it sees ahead.

The final mode as a layer for safety is to stop the vehicle, giving up on the mission to protect the

AUV. This mode is triggered by the look-ahead sonar seeing an obstacle ahead that is too close to avoid.

IV. Terrain-Relative Navigation

Flying close to rough terrain is not feasible with a motion-constrained AUV unless the vehicle is able to anticipate approaching "obstacles" and plan appropriate control actions in advance.

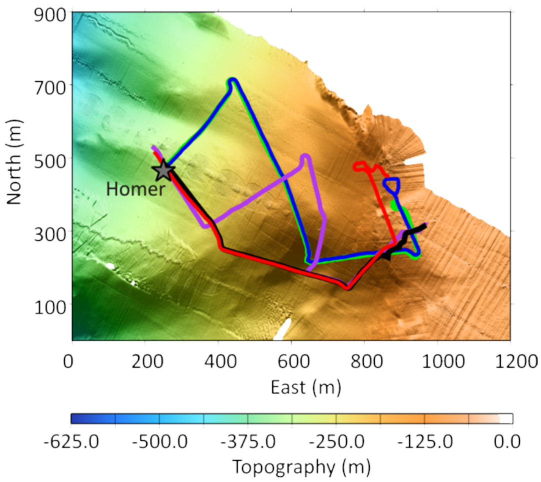
While the necessary information required to enable this capability may be contained in bathymetry data of the area, geo-referencing errors within those data require that navigation be done directly with respect to the map rather than with respect to latitude-longitude position estimates.

Terrain-Relative Navigation is an approach that has been demonstrated to enable this capability. For example, Figure (4a) presents results from field trials at Soquel Canyon in Monterey Bay performed by Meduna [5]. In these trials, the AUV was commanded to fly a path specified on a bathymetry map to a (known) homer location. The homer was not used as a navigation aid, but it was used to validate the AUV's position when it was near the site. Figure (4a) displays the multiple paths taken by the AUV to reach the site. Figure (4b) indicates that the accuracy in reaching the site was approximately 3 m.

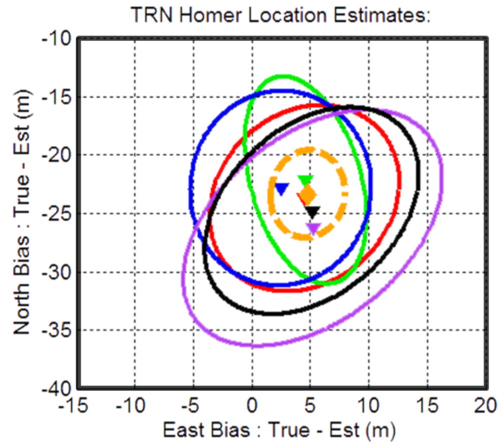
Also visible in Figure (4b) is that the site was not geo-referenced correctly. Based on the site's coordinates, it was thought to be at coordinates (0,0). In reality, it was roughly 30 m offset from that location. This ability to return to sites in a map, rather than latitude-longitude locations, is a key feature of the TRN approach.

Using the knowledge of location within the map gives the aggressive terrain following approach its ability to use data from the map when generating an aggressive trajectory. It also allows the safety logic to decide whether it is confident enough in its position to use the aggressive trajectory, as described in Section III-B.

For the purposes of the terrain following system, TRN has been implemented using a particle filter, with the measurement updates based on four DVL beam range measurements. The filter estimates North and East position, along with a depth bias to account for tides, using the same formulation as Meduna [1].



(a) Soquel Canyon 1 m resolution map with estimated vehicle track overlaid from five TRN runs of the AUV. The location of the destination (a homing beacon) is shown as a grey star.



(b) Estimates of the homer location in the map above. The error in the geo-registration of the map can be clearly seen by the offset of nearly 30 m.

Fig. 4: TRN results from previous work by Meduna [5]

V. Planning and Following Trajectories

As described above, bathymetry data (i.e. *a priori* maps) provide a source of information that can be exploited to plan aggressive yet feasible paths for a motion-constrained AUV to fly through terrain. Further, TRN provides a means for the AUV to determine its position precisely within that terrain, making it safe to fly those trajectories.

Two key steps remain in the development of the control architecture presented in Figure 2. The first to modify the Depth Control loop to enable it to exploit the anticipatory information available in a precomputed trajectory. The second is to develop a method for calculating the feasible trajectories.

A. Trajectory following

A direct way to improve trajectory tracking is to include a feed-forward path in the control architecture. In a reactive depth-control system (i.e. no feed-forward), an AUV issues elevator commands only when an error in depth is detected. With feed-forward present, the AUV can control depth as well as depth-rate, making it possible to apply control in anticipation of a change.

This feed-forward is implemented in Figure 2 as a commanded pitch angle (pitch angle is directly related to depth rate). Note that this feed-forward pitch signal needs to be consistent with the commanded depth (or altitude) trajectory.

The performance benefits of this feed-forward signal are demonstrated in the results presented in Section VI.

B. Curvature-constrained trajectory planning

There are several methods that can be used to calculate feasible paths for an AUV flying over terrain. These include methods drawn from the mobile robotic community [6], the Nap-of-the-Earth flight control literature [7], as well as global path planning for motion-constrained AUVs [8].

The trajectory generation approach presented here is derived from Murthy's trajectory generation using curvature-constrained bi-variate spline surfaces [9]. This work extends his approach by simplifying to a uni-parametric spline for the trajectory. This allows for trajectories through any sequence of 3D points, while significantly reducing the required computation, allowing the approach to be implemented online. Another advantage of this approach is that it allows the minimum turning radius of the AUV to be captured as a single curvature constraint, enforced at points along the spline, during the optimization process.

A uni-parametric spline can be written as follows,

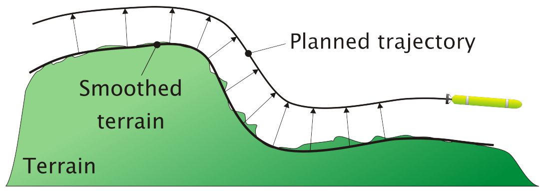


Fig. 5: Pictorial depiction of extracting points for trajectory. Points from the smoothed terrain are lifted out perpendicularly to the desired stand-off distance. Then a trajectory is fit to those points that satisfies curvature and minimum error constraints.

$$\begin{aligned} C &= NP \\ C^{(1)} &= AP \\ C^{(2)} &= BP, \end{aligned} \tag{1}$$

where C is the spline curve, $C^{(k)}$ its kth derivative, P are the control points, N are the basis functions, and A and B are the first and second derivatives of the basis functions respectively.

To calculate a trajectory, a set of data points, D, is generated through which the trajectory should pass. These points can be found in a variety of ways. The approach used here takes a smoothed version of the points on the terrain and moves them perpendicularly to the desired stand-off distance away, as shown in Figure 5. Maintaining a constant perpendicular stand-off distance to the terrain is desirable for maximizing the quality of images taken by the vehicle.

Thus, the goal of the optimization is to find the control points P for which the data points D are most closely matched while enforcing the constraint on the curvature, κ_{max}, and a maximum fitting error, E, for each data point d_k. This finds a spline that satisfies the curvature constraints and never gets too close to the terrain. Specifically, the goal is to

$$\begin{aligned} \underset{P}{\text{minimize}} \quad & \|NP - D\| \\ \text{subject to} \quad & \kappa \leq \kappa_{\text{max}} \\ & \|N(u_k)P - d_k\| \leq E \quad \forall d_k, \end{aligned} \tag{2}$$

where curvature is defined as

$$\kappa = \frac{\|C^{(1)} \times C^{(2)}\|}{\|C^{(1)}\|^3}. \tag{3}$$

Note that the curvature constraint is difficult to implement as written in Equation 2. However, by applying the following simplification, a more computationally convenient version of the optimization problem can be formulated. That is, by making the relaxation

$$\kappa = \frac{\|AP \times BP\|}{\|AP\|^3} \leq \frac{\|BP\|}{\|AP\|^2}, \tag{4}$$

the optimization problem can be rewritten as

$$\begin{aligned} \underset{P}{\text{minimize}} \quad & \|NP - D\| \\ \text{subject to} \quad & \frac{\|B^{(i)}P\|}{\|A^{(i)}P\|^2} \leq \kappa_{\max} \quad \forall u_i \\ & \|N(u_k)P - d_k\| \leq E \quad \forall d_k. \end{aligned} \tag{5}$$

The u_i are selected parameter values that coincide with the second derivative maxima. These parameter values are independent of control point locations (P). The maxima of the curvature occur close to these points, resulting in the curvature constraint approximately being enforced everywhere along the trajectory.

If the maximum error bounds cannot be satisfied to get a feasible safe trajectory, this constraint can be relaxed and locations that do not meet the minimum altitude bound can be adjusted to satisfy the constraint.

Solving the optimization problem in Equation 5 can be done using SQP or interior-point methods. The constraints can be squared to allow the Hessian of the Lagrangian to be computed in closed form, enabling efficient solution. With a single curve spline, this is fast enough that it can be done onboard the AUV, allowing for online trajectory planning.

Once a curvature-constrained spline trajectory has been planned, it contains all the information that might be required to allow the vehicle to follow it closely, such as the feed-forward pitch command.

VI. Results

To demonstrate the approach for aggressive terrain following described above, simulations of the AUV were run using data from a field trial with the MBARI Mapping AUV, operating over a section of upper Monterey Canyon.

For the results shown here, the turning radius of the AUV was estimated to be 15 m, and the desired stand-off distance for imaging is assumed to be 4 m with an allowable range of 3 to 5 m.

Figure 6 shows simulations of the vehicle over the canyon. Each subfigure shows the path flown by the vehicle over the terrain on the left, and the altitude of the vehicle over the terrain on the right.

In Figure (6a), the reactive obstacle avoidance system is operating. When it sees the canyon wall ahead, the vehicle immediately pulls up to almost 40 m above the terrain. This results in its failing to image nearly 150 m of the terrain.

Figure (6b) shows the results of using a feasible trajectory (calculated with the methods outlined above) but not using any feedforward control. While it is successful at imaging the terrain when fairly flat, it cannot react fast enough when approaching the canyon wall, and contacts the bottom.

In the final figure, (6c), the feedforward pitch command was included. The result is the vehicle successfully flying safely at the desired imaging altitude over the whole terrain.

VII. Conclusions

To allow return-to-site imaging missions for an AUV, an effective system for aggressive terrain following is required. This work presents an approach that takes into account *a priori* map information to create a feasible trajectory for a motion-constrained vehicle, and uses TRN to localize the vehicle within that map.

VIII. Acknowledgements

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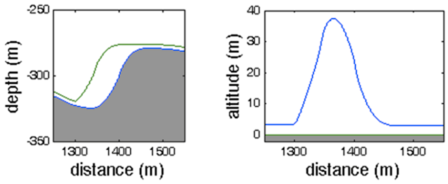
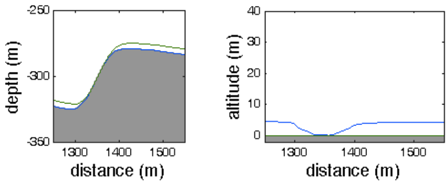
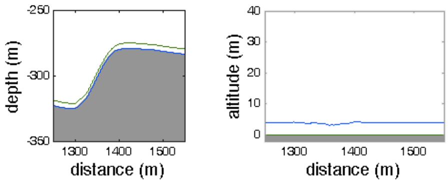


(a) Reactive obstacle avoidance with look-ahead sonar



(b) Constant altitude tracking



(c) Feasible trajectory with feed-forward pitch

Fig. 6: Simulation results over upper Monterey Canyon. (6a) the vehicle using reactive obstacle avoidance mode, which is safe but overflies a large section of the terrain at up to almost 40 m. (6b) the vehicle using the existing altitude tracking mode, which comes in contact with the terrain. (6c) the vehicle flies a planned feasible trajectory with feed-forward pitch commands.

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