Stability Criterion for a Wall-Following AUV

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***Abstract*—Wall-following with a torpedo style AUV is an enabling capability for mapping the submerged surfaces of icebergs or the walls of deep submarine canyons. While wall-following is conceptually similar to bottom-following, the lack of a reference heading comparable to "vertical" can be problematic. Specifically, unstable trajectories can result.**

This paper explains the instability and presents a method to determine the conditions under which it can occur. Also presented is a means of avoiding the instability by using a multibeam sonar instead of a simpler ranging device to measure the distance the the wall. Simulation as well as field results are presented.

***Index Terms*—AUV, Control, Mobile Robot, Underwater Vehicle, Sonar, Iceberg**

I. Introduction

Two AUV missions motivate this paper. The first is a NASA ASTEP mission (NNX11AR62G) to the Antarctic to explore and characterize the water column in the near field of free-drifting icebergs. One aspect of this mission is to generate a map (3-D reconstruction) of the submerged surface of an iceberg which will be used to log a suite of chemical, biological and physical data collected during the dives in a common iceberg-centric reference frame. It will also be used to enable return-to-site navigation of the AUV to monitor selected sites for change, or to collect additional data sets.

The second motivating mission is to map near-vertical walls in submarine canyons (e.g. the deep canyon in Monterey Bay). These maps will be used to augment existing bathymetric data sets collected using more conventional down-pointing instruments. Again, the goal is to enable return-to-site missions either to monitor for change or to collect new data.

To perform these missions, an AUV is required that can travel fast enough and far enough to circumnavigate an iceberg or transit past a long wall at multiple depths as it collects the multibeam sonar data. Also required is a control mode that enables the AUV to perform a wall-following maneuver, maintaining a constant standoff distance as it passes by the wall (e.g. at $\sim$ 3knots). That control logic is the focus of this paper.

Wall following is analogous to bottom-following, which is common practice in the industry. As examples, MBARI's Mapping AUV [1] and the Hugin vehicle are routinely used for seafloor mapping. The Autosub 6000 [2] and the Remus vehicle [3] also have bottom-following capabilities.

The altitude control laws used for bottom-following missions are typically based on a range measurement from a simple altimeter or from a range computed from DVL beams. Both of these measure a distance to the terrain perpendicular to the AUV's axis from which the vertical height (altitude perpendicular to the terrain) is computed knowing the AUV's pitch angle. That is, the distance perpendicular to a horizontal reference direction is used for feedback control.

Applying this control directly to wall-following can be problematic if the target wall has not been mapped previously or is moving (e.g. an iceberg). Specifically, computing a standoff distance requires a reference direction from which to project a perpendicular. Conceptually, this direction would be parallel to the wall, but that direction is not known a priori and it changes, for example during a 360 deg. circumnavigation of an iceberg.

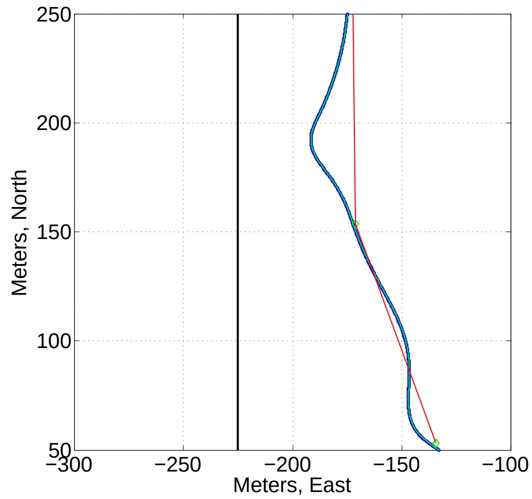

Fig. 1. Stable response for 20° approach angle. Wall is at -225m. Red line is desired trackline.

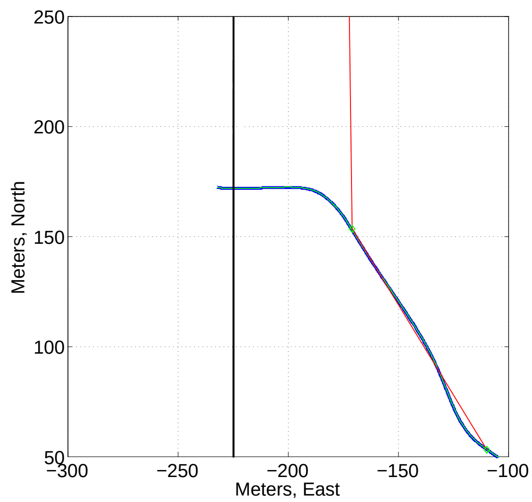

Fig. 2. Unstable response for 30° approach angle. Wall is at -225m. Red line is desired trackline.

One attractive option due to its simplicity for computing the standoff distance would be to use the measured range perpendicular to the AUV axis, but this approach can yield unstable behavior. This is demonstrated in Figures 1 and 2 using two different cases. In both, an AUV is commanded to approach the wall at an angle γ_o and then turn to follow the wall at a constant standoff distance of 50m. In the first case, the approach angle is 20°. In the second case, the approach angle is 30°. As seen in the figure, the AUV's response is well behaved for the 20° approach, executing a turn onto a trackline 50m from wall. The response is unstable, however, for the 30° approach angle. Instead of turning to track the wall, the AUV turns into the wall.

These figures were created using a high-fidelity simulation of MBARI's Mapping AUV. The simulation is written in C++ and runs concurrently on the embedded target alongside the flight code. The simulation includes a set of actuator and sensor drivers that substitute simulation inputs and outputs for the instruments. The simulation then runs entirely in software; it is not a hardware-in-the-loop simulation. It includes nonlinear effects such as rudder/elevator travel and rate limits, quadratic lift and drag, etc. The vehicle dynamics are modeled as a 6 DOF rigid body following Gertler's formulation [4], [1]. A standard 4th order Runga-Kutta fixed-step algorithm integrates the nonlinear ODEs.

Presented below is a description of this instability and a modification to the wall-following control law that will eliminate its occurrence. It is shown that the basic cause of the instability is a destabilizing feedback caused by an apparent increase in range generated when the AUV turns towards the wall as it attempts to decrease that range. Details are provided in Section IV where the extent of operating conditions under which the simple range measurement provides stable behavior is defined. Section V then describes how the instability can be eliminated by using a multibeam sonar which measures the wall profile along the direction of travel rather than a simple range measurement.

Preliminary results demonstrating successful wall-following in field-trials are presented in Section VI.

II. Vehicle Description

The AUV used for testing and development is a variant of MBARI's standard mapping vehicle. It is a Dorado/Bluefin 21" (54 cm) diameter type, which has a cylindrical midsection and a truncated hemispherical nose. See Figure 3. The aft section is a Gertler shape, Series 58 Model 4154, with a ring-wing propulsor providing movable control surfaces and vectored thrust [1], [4]. It is a torpedo-style flying vehicle design, and must maintain a minimum speed of around .8 m/s for control. It has a flooded-hull, so the batteries, main vehicle control computer, and various electronics are protected in individual pressure housings. The vehicle is 522 cm long, and weighs 1016 kg including entrained water.

Fig. 3. MBARI mapping vehicle used to test the wall-following control.

Two Imagenex 837 multibeam sonars provide sensing for wall following and obstacle avoidance. Each has a 120×10 degree field of view, with 120 fan beams. They operate at 220 kHz, and have a range approaching 200 meters. Although these are imaging sonars, the control and beam-forming software provides bottom-detects, with options for first-return and maximum amplitude. Both sonars scan along the direction of travel, in the vehicle x-y plane. The primary wall following sonar faces out the port side, with its center-line parallel to the -y vehicle axis. The second is mounted in the nose looking forward, but angled 30 degrees to starboard to prevent overlap. Taken together, both sonars have a combined field-of-view extending from -150 to 90 degrees in vehicle-relative azimuth. See Figure 4. The beam forming and control software runs on a separate computer that is not embedded in the sonar head.

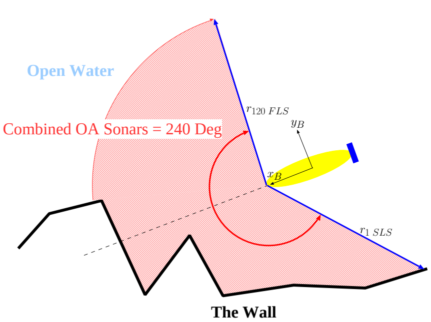

Fig. 4. Composite field-of-view of the side-looking and forward-looking multibeam sonars.

Navigation is provided by a vertically-mounted Kearfott Seadevil integrated INS/DVL/GPS, and is accurate to .05% DT, presuming the DVL has continuous bottom lock [5].

In addition to the downward-pointing DVL is a side-looking DVL. Both DVLs are 300 kHz RDI "Workhorse Navigators", and have an operating range of well over 100 meters. The primary purpose of the side-looking DVL is to log velocity of the AUV with respect to the wall. Additionally, it provides four out-of-plane range measurements, at ± 22 degrees above and below the vehicle x-y plane, which can be used for obstacle avoidance in addition to the in-plane multibeams.

The vehicle has a 200 kHz Reson 7125 multibeam mapping sonar also oriented sideways so it can scan the walls. However, its scan plane is aligned with the vehicle y-z plane, so it is perpendicular to the vehicle's direction of travel.

Power is provided by an Eagle-Pitcher Li-ion secondary battery pack contained in a 17" diameter glass sphere. It provides 2.5 kWh of energy, giving a maximum range of approximately 25-45 km at the design speed of 1.5 m/s, with the sonars running. In the normal mapping configuration the vehicle has two battery spheres, but for the wall-following tests one was removed to make room for the side-looking DVL.

The cells are arranged in an 8S-2P architecture, giving an operating voltage of 28.8 volts.

III. Description of Existing Control Loop

The control system consists of outer and inner loops. Figure 5 shows the heading/waypoint control. The depth control is separate and independent, and has a similar structure.

In the figure, r_C is the commanded standoff distance, or range, from the wall. r_M is the measured, or computed, range which is compared to the command to compute the range error. This range error then passes through a proportional gain, K_{wp}, to generate an offset $\Delta\psi_C$. If the measured range is too great, this outer loop computes a negative $\Delta\psi_C$ which turns the vehicle to the left of the nominal trackline towards the wall, and proceeds until the range error goes to zero.

The total ψ_c is computed by adding $\Delta\psi_C$ and any $\Delta\psi$ commands from a feedforward or obstacle

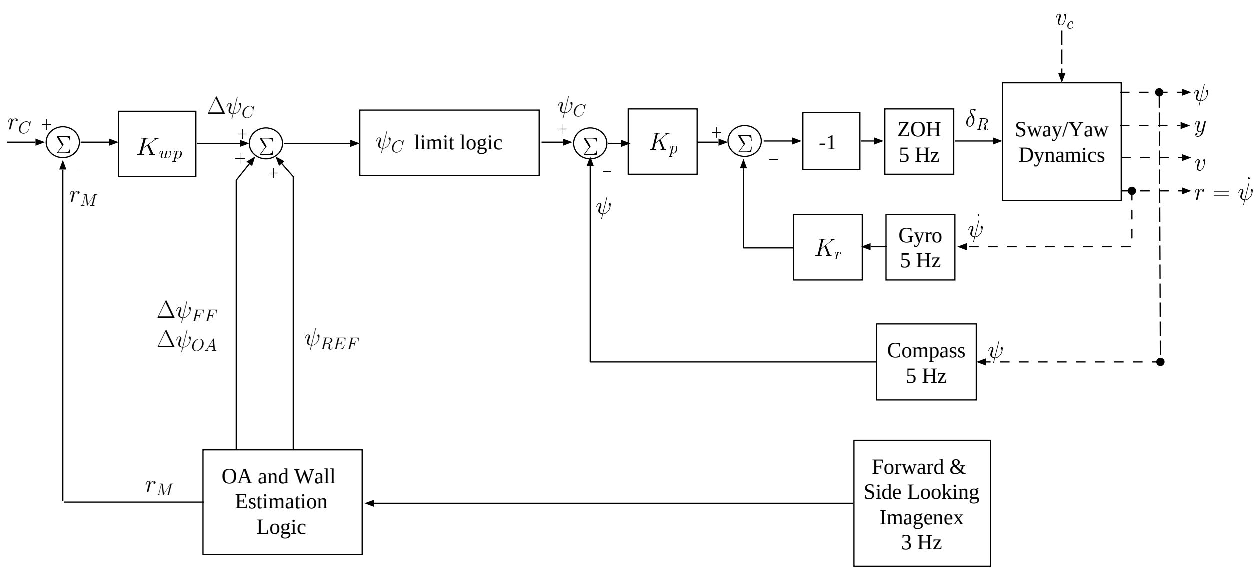

Fig. 5. Basic structure of the control, showing inner and outer loops.

avoidance logic to the reference heading ψ_{REF}. The inner loop then operates to cause the vehicle to follow the commanded heading, ψ_C. Feedback on both the measured heading, ψ, and heading rate, r, are provided. The result is a rudder position command δ_R.

When wall-following in known terrain, latitude-longitude waypoints can be defined that can be used both to define the reference heading, ψ_{REF}, as well as a safe corridor in which the AUV can operate. This was used for the field tests described in Section VI, where ψ_{REF} was set to the commanded AUV bearing-to-the-next waypoint, ψ_B, and the corridor was implemented as part of the ψ_c Limit Logic.

For the simulation results presented in Figures 1 and 2, the measured range, r_M, was the single sonar beam perpendicular to the AUV's axis.

Additional description of this control, without wall-following, is in [1].

IV. Explanation of Instability

As demonstrated in Figures 1 and 2, using a beam fixed in the AUV body axis to compute the range to the wall can yield an instability. The explanation of this can be seen with the aid of Figure 6.

Two effects can be seen with this figure. First, if the AUV were to fly forward without rotating,

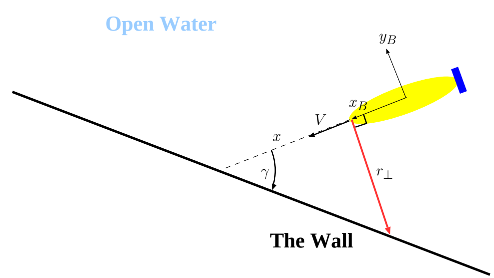

Fig. 6. Wall following using range perpendicular to vehicle centerline.

it is clear that the measured beam length would decrease (as desired). However, if the AUV were to rotate in place (i.e. turn towards the wall to increase the rate at which it approaches the wall), the beam would increase.

Using $r_\perp = x\ tan\gamma$, $\dot{x} = -V$, and $\gamma = \psi_{wall} - \psi_{auv}$ yields

$$\dot{r_\perp} = -V tan\gamma - \dot{\psi}_{auv}\frac{x}{cos^2\gamma}$$

where $\dot{(\cdot)}$ indicates a time derivative, and ψ_{wall} and ψ_{auv} are the heading of the wall and the AUV respectively. Note that turning towards the wall requires $\dot{\psi}_{auv} < 0$, and hence the relative signs of these two terms are opposite. In particular, the effect caused by the rotation is destabilizing.

The relative magnitude of these effects and hence the overall stability of the system is determined by the control logic defined in Figure 5. Specifically, a domain-of-attraction around a stable wall-following condition exists.

A graphic showing the predicted regions of stable and unstable operation for the MBARI's Mapping AUV is presented in Figure 7. Plotted are AUV trajectories for different initial conditions on AUV heading and position offset, $r_C - r_M$ (Δy in the figure). The axes are position offset vs heading error. A trajectory in the figure generally moves from the right to the left as time progresses. A stable trajectory converges to the origin. That is, it ends with $\Delta\psi = 0$ and $\Delta y = 0$.

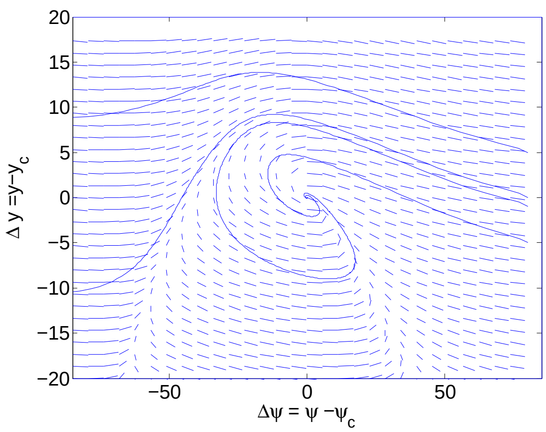

Fig. 7. Trajectories for an AUV starting at different initial conditions.

The figure is presented as a phase-plane, but care is required in its interpretation. Specifically, the AUV dynamics used to calculate the trajectories are fourth order, but the figure only allows the display of two dimensions. Also, the "flow field" indicated in the background was calculated using a simplified model of the AUV, so it is only approximate. For this plot, $r_C = 50m$, and the trajectories are for initial conditions of $r_C - r_M = \Delta y = -5, -1, +1, +5$. That is, $r_{M_{ic}} = 45, 49, 51, 55$. All trajectories start at $\psi_{ic} = 80$deg. The initial condition on angular rate and position rate are both zero.

As seen in the figure, for $\psi_{ic} = 80$deg, the field divides into two regions. If the initial position offset is less than 0 (i.e. $y_{ic} < y_c = 50$m), the AUV succeeds in converging to the origin. The time histories of Δy, Δy_m, and $\Delta\psi$ for the stable trajectory beginning at $\Delta\psi = 80$deg and $\Delta y = -0.1$m ($y_{ic} = 49.9$m) are shown in Figures 8 and 9. In Figure 8 the blue line, y, is the perpendicular range to the wall, and the green line, y_m, is the range measured perpendicular to the AUV axis. Due to the steep initial angle, y_m has a large initial value ($\approx 200m$), but quickly reduces as the AUV rotates to move from the initial 80deg relative heading to -20deg. Note that around $t = 50$sec, there is a short period where the vehicle's rotation and translation result in an $\dot{r}_\perp \approx 0$. The time history of heading $\Delta\psi$ is shown in Figure 9.

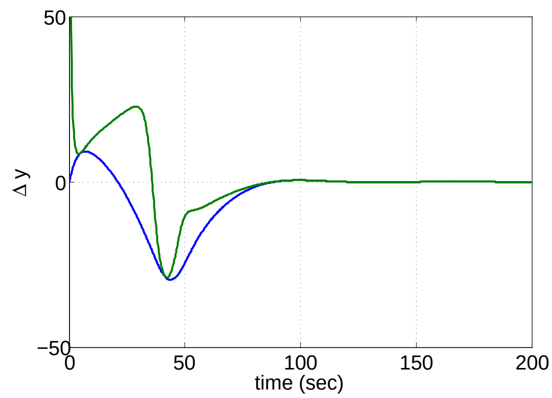

Fig. 8. Range to the wall for initial conditions $\Delta\psi = 80$deg and $\Delta y = -0.1$m. Blue is range perpendicular to the wall; green is range perpendicular to the AUV centerline, $r_\perp$.

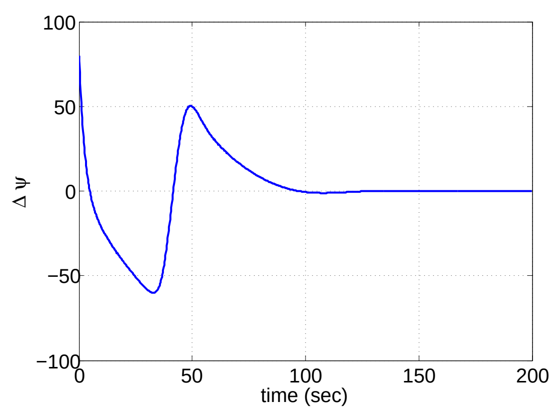

Fig. 9. Heading Error $\Delta\psi$ for the simulation in Figure 8.

V. Mitigation Stategies

As described earlier, to avoid this instability, it is necessary to compute a standoff range from a defined reference heading, which is nominally parallel to the wall. Given this reference direction and the AUV's heading, the perpendicular distance is just the projected length.

One effective method of computing both the reference heading and the perpendicular distance is to perform a least squares fit using the multi-beam sonar data. However, a simpler method of computing both the reference heading and the perpendicular distance is to make the assumption that the wall is flat, and hence that the beam of minimum length is perpendicular to the wall. This is shown in Figure 10. For this situation, the reference direction is simply perpendicular to the minimum beam's direction, and the range is that beam's length.

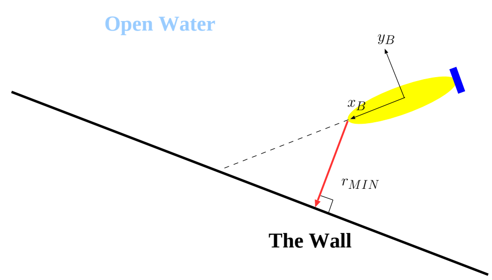

Fig. 10. Wall following using minimum distance.

The effectiveness of this simpler approach (in simulation) is shown in Figure 11. This result was obtained with the same simulation used for Figures 1 and 2. The only change was using the minimum beam length as r_M.

VI. Field Data

The site chosen for field testing the wall-following control strategies described above is at the junction of the Monterey Canyon and Soquel Canyon in Monterey Bay, CA. This test area is a bowl with a flat bottom, about 500 meters across, with near vertical walls on both the north and south sides. Figure 12 shows a bathymetry map, with a vehicle track overlaid of a typical wall-following test. In a typical test, the AUV starts on the shelf above the canyon where it can acquire both Gps and DVL bottom lock simultaneously. It then follows the bottom down into the test site while maintaining DVL lock.

Figure 13 is a top-down view of a portion of the south wall of the test site, as measured by the side-looking obstacle-avoidance sonar. It is near the bottom of the hooked vehicle track in Figure 12.

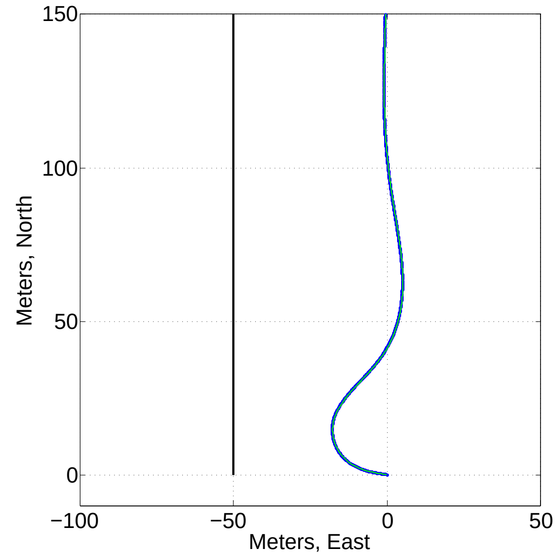

Fig. 11. Simulation showing stable response of the minimum-distance algorithm. The simulation started with the vehicle pointed head-on to the wall.

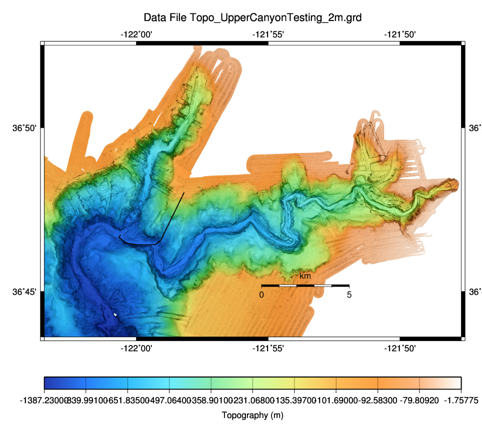

Fig. 12. Map of the Monterey Bay Canyon. Soquel Canyon is the arm to the north. The vehicle track is the black line that descends into the junction of the two canyons.

The vehicle trackline is to the north of the wall in Figure 13, bounded by two lines that represent the "saftey corridor". The third interior line is the path to the next waypoint at bearing ψ_B . On-board safemode logic prevents the vehicle from traveling outside of the corridor. The vehicle is following the inboard edge of the corridor to the east of -3550 meters because the wall was too far away. The wall-following control uses the side-looking sonar for the range measurement, but uses ψ_B as the heading reference direction as shown in Figure 5.

Successful wall following is visible in Figure 13 where the vehicle is seen to hold an approximate 50 meter stand-off. Also visible in the figure is that the safety corridor used for this test was too conservative, limiting the overall wall following performance.

Apparent in this figure is a significant amount of noise and multipath, which gives rise to various filtering algorithms. In this run, the vendor's beamforming algorithm computed bottom detects using first-return, and provided filtering before passing the ranges on to the vehicle control system.

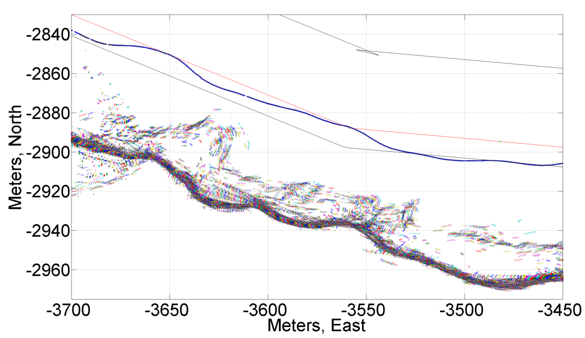

Fig. 13. Vehicle track while wall following.

VII. Conclusion

This paper has demonstrated and explained the existence of an instability that can result when performing a wall-following maneuver with a torpedo-style AUV and ranging sensors that measure a distance perpendicular to the AUV's centerline (e.g. altimeter). The issue is that, in some operating conditions, the change in measured range increases rather than decreases as the AUV changes heading in an attempt to close distance on the wall. This effect is destabilizing. To avoid this instability, the range perpendicular to the wall should be measured, but calculating this range requires knowledge of the heading of the wall. An alternate approach is to measure the range directly using a multibeam sonar aligned to measure the wall's profile. The effectiveness of this approach is demonstrated both in simulation and field trials.

VIII. Acknowledgements

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