Towards Online Terrain Aided Navigation of Underwater Gliders

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***Abstract*—A terrain aided navigation algorithm has been developed through off-line trials which is suited for operations on an underwater glider. This method has been developed to enable persistent measurements using underwater gliders in regions where surface access is difficult or not possible. The algorithm is based on a jittered bootstrap particle filter. During two sets of off-line trials composed of a 10 km straight line segment and a 90 km survey segment the method was limited to RMS errors of 25 m and 50 m respectively. Integration of the algorithm into an underwater glider was achieved through the addition of a separate single board computer which is interfaced to the payload computer to retrieve the vehicle's dead-reckoning solution, attitude, depth and attitude. Navigation updates and a status flag are sent back to the vehicle which logs the estimates in open-loop trials or incorporates them for closed loop trials.**

I. Introduction

Autonomous Underwater Gliders have emerged as robust tools for gathering data remotely in challenging environments [1]. Navigation of these vehicles most often relies on a fusion of measurements from the attitude and pressure sensors to produce a dead reckoned location estimate. This navigation solution is subject to drift over time which for short duration missions or segments is often not a debilitating issue as the vehicle may surface and acquire a new GPS location. However, in the presence of seasonal sea ice the ability of the vehicle to surface for GPS updates is limited. Providing a surface vehicle for tending of the underwater glider with an acoustic location update is also challenging due to the ice cover. Low frequency acoustic infrastructure has been proposed as a method for providing acoustic location updates on the order of 100s of km [2], [3], however, deployment, maintenance and operational costs of such a system have been limiting factors.

The Autonomous Ocean Systems Lab at Memorial University has been pursing methods suitable for online navigation of underwater gliders in GPS denied regions. A particular focus has been on methods suitable for year round measurements on the Grand Banks and the Labrador Shelf which experience seasonal sea ice [4]. These regions are of particular scientific interest due to the significant mixing which occurs on the Grand Banks due to the interactions between the Labrador Current and the Gulf Stream.

Relative navigation techniques which compare onboard measurements of geophysical parameters to digital elevation models of the same parameters have shown promise in providing bounded error navigation solutions that are independent of surface access [5], [6], [7], [8]. These geophysical parameters include water depth, magnetic fields and gravity fields. While previous efforts in this area have required either a high accuracy inertial navigation system or a rich set of geophysical measurements, the authors have shown recently that bounded error estimates are possible with low accuracy dead reckoning coupled with simple geophysical sensors such as would be found on a standard underwater glider [9]. In that work navigation solutions were post-processed to evaluate the efficacy of the approach. The authors found that RMS errors were limited to 50 m over a 90 km survey pattern segment and 25 m over a 10 km transit segment when using a digital elevation model (DEM) with a 2 meter grid generated from a multi-beam survey.

This work outlines the integration of the terrain aided navigation algorithm into an underwater glider and presents preliminary field trials of the method. The algorithm runs on a separate single board computer which is interfaced to the payload computer to retrieve the vehicle dead-reckoning solution, altitude, depth and attitude. Navigation updates are sent back to the vehicle once computed. During open loop trials the vehicle stores these updates to be verified by an operator after the deployment to build confidence in the method while closed loop trials add the navigation update to the gliders dead-reckoning solution.

II. Glider Terrain Aided Navigation

Terrain aided navigation (TAN) methods on underwater vehicles often make use of statistical estimation techniques to compare the physical measurements with a digital elevation model (DEM). Due to the highly non-linear nature of the probability density function between the measurements and the DEM, particle filters have found success in underwater TAN schemes. State of the art TAN methods typically achieve bounded errors of less than 10 meters RMS. This accuracy is achieved through coupling a low drift inertial navigation system with a multitude of water depth estimates from a doppler velocity log or multi-beam SONAR sensor. The TAN method employed by an underwater glider has neither a high accuracy dead-reckoning estimate nor SONAR system capable of multiple simultaneous measurements. Instead the glider TAN method makes use of the standard glider model based dead-reckoning estimates produced by the combination of the attitude and pressure sensor. Additionally, the glider uses its single beam altimeter combined with its pressure sensor and uses a simple ray tracing scheme to produce and correct the water depth estimate. This TAN implementation in spite of the degradation of the dead-reckoning accuracy and the use of a single beam SONAR is possible on an underwater glider by relaxing the navigational accuracy requirements and careful design of the particle filter parameters.

Specifically, the glider TAN algorithm utilizes a jittered bootstrap particle filter with 1000 particles and a jittering variance of 15 m^2 [9]. In this method the particle locations are updated using the glider's dead-reckoning estimate and the water depth estimate is formed from the ray traced altitude from the single beam SONAR, vehicle attitude and depth. The water depth estimate is then compared to the DEM water depth at each particle location to compute the particle's weight. The particles are then re-sampled such that particles with low weights are discarded and particles with high weights are divided. The TAN location estimate is then formed from the weighted average of the particle locations. Prior to the next iteration the particle locations are jittered by adding normally distributed noise with a variance of 15 m^2.

The DEM is formatted as a list of double precision water depths with the extents and grid spacing as meta-data for indexing. The DEM coordinates are in latitude and longitude while the particle filter coordinate frame is in meters from an initial location and referenced to true north. The dead-reckoned locations from the glider are in meters from an initial location as well but are referenced to magnetic north. The DEM water depths at each particle's location are computed using bilinear interpolation. The interpolation function returns a shore line flag if the location is not in the water and a map bounds flag if the location is at the edge of the DEM.

III. Off-line Trials

The glider TAN algorithm was evaluated through two sets of field trials which overlapped the region of the DEM in Holyrood Arm of Conception Bay, Newfoundland. These experiments took place in October 2010 and October 2012 using a 200 meter electric Slocum underwater glider. In the 2010 trials the glider flew straight out of Holyrood Arm and past the boundary of the DEM for a total distance of approximately 12 km and in the 2012 trials the vehicle flew in overlapping rectangles up Holyrood Arm for a total distance of approximately 91 km as illustrated in Fig. 1.

In both experiments the glider recorded its navigation data to allow for the glider TAN algorithm to be evaluated off-line through post-processing. As no independent localization method, such as an ultra-short baseline system, was available the glider was programmed to surface approximately every hour and correct for the drift in its position estimate. The

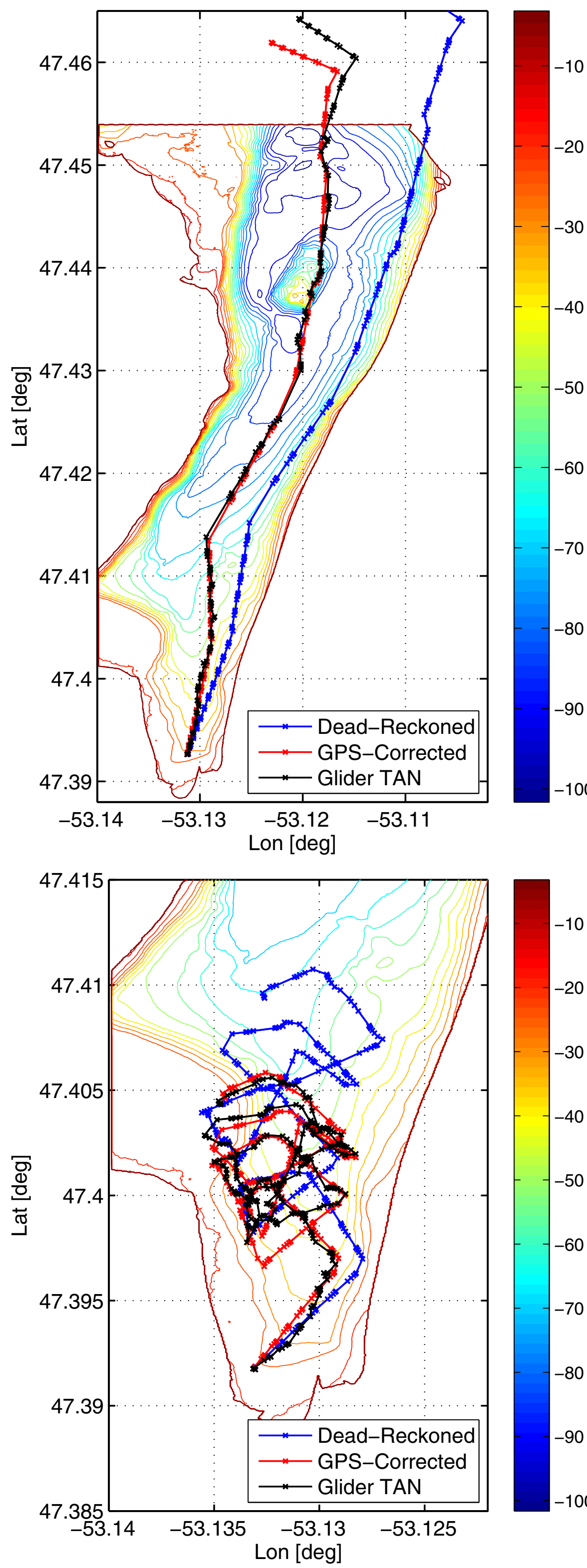

Fig. 1. Location estimates from the glider TAN algorithm (black) against the GPS corrected dead-reckoned locations (red) and the dead-reckoned locations (blue) from the 2010 trials (top) and from the first 10 km 2012 trials (bottom)

glider's recorded dead-reckoned locations were then able to

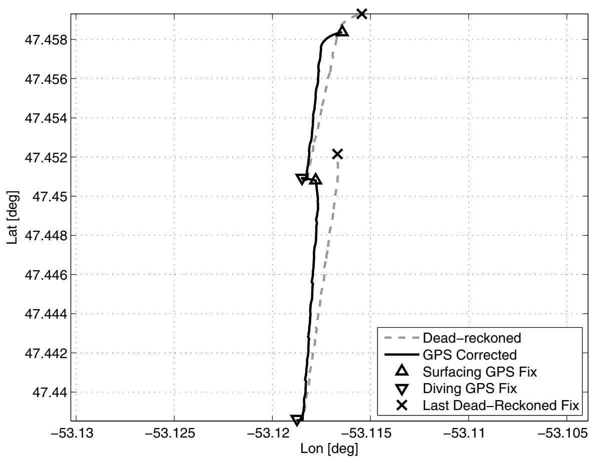

Fig. 2. GPS corrected dead-reckoned location estimates computed from the dead-reckoned estimates using the difference between the last dead-reckoned estimate and the GPS fix upon surfacing applied as a constant disturbance from the diving GPS fix to the last dead-reckoned estimate

be post-processed using these GPS updates as illustrated in Fig. 2.

The GPS corrected glider locations are used as the baseline locations for comparison of the performance of the glider TAN algorithm. This method of baseline comparison is most accurate at the locations of the GPS updates during surfacing events with the uncertainty increasing to a maximum halfway between updates. It should also be noted that because the glider does not record data, in particular attitude and altitude, during surfacing events the surface drift, that is the surfacing GPS location minus the diving GPS location, is removed from the glider TAN re-navigation. Otherwise, the glider TAN algorithm uses the GPS information only for initialization of the algorithm prior to the first dive during the off-line computations.

Moreover, since the altimeter is oriented at a 26 degree angle from the vertical, altitude measurements are only acquired on the downward glide due to the shallow grazing angle on the upward glide. During the downward glide, the period between altitude measurements is not constant, generally being around 30 seconds, decreasing when it approaches the sea-floor to about 10 seconds. This behavior is due to the vehicle's altimeter filter, which attempts to reject bad values and limit the power use of the device.

The large gaps in measurements when the glider is climbing are dependent on the depth of the profiles the glider is performing. For the field trials in Holyrood arm the maximum profile depth was around 100 meters limiting the maximum time between measurement updates to around 20 minutes. The non-constant frequency of the altitude measurements during the downward glide followed by the large amount of time during the upward glide with no altitude measurements creates a unique challenge for a TAN algorithm. The structure of the bootstrap algorithm with jittering is well suited to this problem as it makes no assumptions about the frequency of the measurements. Additionally, because jittering and re-sampling are performed at every time step, the particle distribution rapidly adjusts to an accurate representation of the prior density function. This behavior is particularly helpful in maintaining convergence during large measurement update gaps due to a climbing section and in re-convergence after the vehicle leaves the bounds of the map.

IV. Integration

The Teledyne Webb Research Slocum Electric glider has two embedded processors on-board, one for navigation and control termed the glider computer and one for the integration of payloads and sensors termed the science computer. These processors run a version of DOS on a 14 MHz Motorolla MC68CK338 which is packaged into the Persistor CF1 embedded computer. The Persistor has 1 Mb of flash memory and a standard suite of embedded interfaces including a hardware interface to Compact Flash memory storage. While these devices provide a low power, reliable platform for the operation and control of the vehicle the memory and processing requirements of the particle filter algorithm exceeds their ability. An additional single board computer or embedded processor was deemed necessary for the integration of the algorithm into the glider.

Initial tests were performed with low power ARM M0 processors which have similar memory capacities as the CF1 but run at frequencies of 40 MHz. The memory limitations required approximating the particle filter to avoid storing the prior particle states and placed a limit on the number of particles. While these processors are capable of running the algorithm in real-time, the approximated method was found to insufficiently represent the underlying probability density function resulting in unsatisfactory performance.

Subsequently, the more powerful Beagle Bone Black (BBB), Fig. 3 single board computer was selected for use which has a 1 GHz ARM Cortex-A8 processor with 512 Mb of RAM, 4 Gb of on-board flash and standard set of embedded peripheral options. For this work the BBB was loaded with Ubuntu 13.04, allowing the particle filter to be programmed in C/C++.

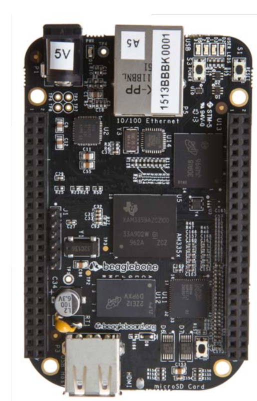

Fig. 3. The Beagle Bone Black 1 GHz Arm Cortex-A8 processor with 512 Mb of RAM and 4 Gb of onboard flash

The BBB has a frequency scaling module which adjusts the processor frequency depending on the demand. The voltage supply to the board is 5 Volts with a current draw of around 300 mA during boot (10 seconds) and while processing, dropping to 100 mA while idle. The BBB is powered through a separate switching regulator from the standard power pins in the payload module which supplies 10 to 15 Volts. The communication interface connects from the 5 Volt UART on the BBB through a logic level converter to the standard RS232 port on the science computer of the glider. In this way the BBB connects to the glider as any payload or science sensor would as illustrated in Fig. 4.

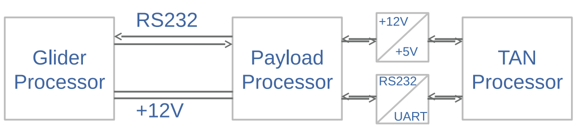

Fig. 4. Diagram of the glider Terrain Aided Navigation hardware integration showing the power and communication connections to the science computer

The particle filter program that runs on the BBB is configured to run as a background process once the operating system has booted. The UART and processor options are also configured at boot. The particle filter code accepts an initialization command and an update command from the vehicle. The initialization command sets reference location for the local mission coordinate frame and resets the particle locations to this initial location. The update command computes one iteration of the particle filter and sends back to the vehicle a location update as well as a status flag. The status flag indicates if the location update is nominal, near shore, or near the map bounds.

The particle filter program on the BBB is controlled by the science processor. The science processor runs a glider TAN "proglet" which requests the attitude; altitude; depth; dead-reckoned latitude and longitude; GPS latitude and longitude; and the local mission coordinate locations from the glider computer. The transmission of these variables from the glider processor to the science processor is triggered upon their being updated on the glider processor. Whenever the GPS latitude and longitude variables are updated on the science processor it sends the initialization command to the BBB. In this way the best navigation data is always used. Subsequent to the first initialization, any updates to the altitude variable triggers the transmission of the update command to the BBB. The BBB then computes a location based on the TAN particle filter and sends a location update and status flag back to the science computer. The science computer then sends the location update and status flag to the glider computer and logs the variables in the payload database. This flow of variables is illustrated in Fig. 5.

The glider computer computes the dead-reckoned navigation update without modification until the location update and status flag variables are changed from the science computer.

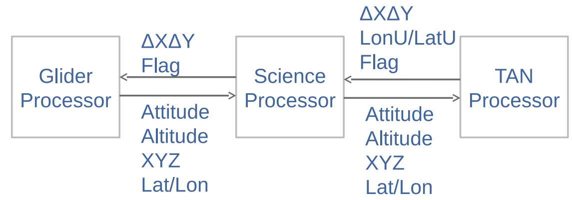

Fig. 5. Flow of variables for the glider TAN integration, showing the transmission of vehicle navigation data from the glider computer through the science computer to the TAN processor. The TAN processor then sends back location updates and a status flag to the science and glider computers.

Upon receiving these variables the glider computer checks the status flag to see if the location update should be integrated into the dead-reckoned location estimate. The location update includes an offset in meters which may be added to the vehicle local mission coordinate location asynchronously as well as the latitude and longitude of the TAN location for interpretation later. In this way the glider TAN method may be tested with minimal modification to the vehicle navigational code in open loop and closed loop modes.

V. Online Trials

Preliminary online tests of the glider TAN method were performed in Holyrood Arm of Conception Bay, Newfoundland on June 10th and 11th, 2014. For these tests the glider was flown in straight line segments roughly one kilometer in length and the glider TAN processor allowed to compute open loop location estimates. These estimates were recorded on the Science computer for analysis later. Subsequent to these initial trials the glider outfitted with the glider TAN processor was refitted for a 3 month long deployment in the Labrador Sea and no further data collection was possible. A sample segment of this deployment is shown in Fig. 6

During these trials the TAN location updates were successfully recorded on the science computer. However, the local mission coordinate frame on the glider was in magnetic north and the coordinate frame on the TAN processor was in true north resulting in location updates which were rotated with respect to the glider coordinate frame by the magnetic declination. Additionally, the depth of the vehicle during the shallow inflection was set to be too shallow, allowing the glider to receive GPS fixes. These GPS locations reset the dead-reckoning locations on the glider and also re-initialize the TAN algorithm on the BBB. The data from these tests is therefore challenging to interpret and further tests are scheduled with a deeper upwards inflection and a properly rotated dead-reckoned location updates for early September.

VI. Conclusion

Navigation of persistent platforms in surface denied regions remains a significant challenge. One promising avenue for underwater gliders is the use of terrain aided navigation (TAN) techniques.

The TAN algorithm for this work is composed of a jittered bootstrap particle filter with 1000 particles and a jittering

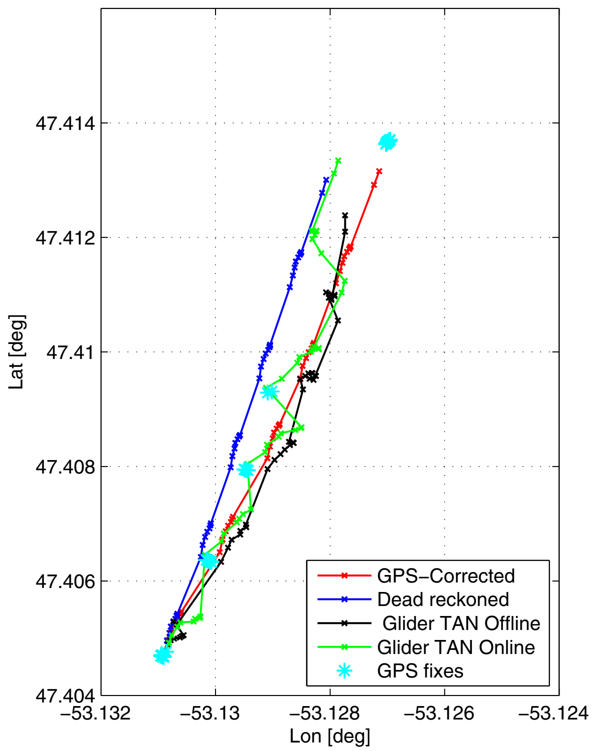

Fig. 6. Comparisons of the on-line location estimates with the glider dead-reckoned, GPS corrected dead-reckoned and off-line TAN location estimates. In these trials the vehicle was shallow enough to receive GPS locations mid-trial shown by the light blue markers which resets the on-line TAN algorithm. Also, during these trials the glider coordinate frame was in magnetic north while the TAN coordinate frame was in true north.

variance of 15 m^2. The inputs to the glider specific TAN method include the vehicles dead-reckoned navigation estimates computed from the vehicles attitude and depth sensor, a water depth estimate calculated from the gliders single beam altimeter and depth measurement and bathymetric digital elevation model of the operational region.

Two separate off-line trials were performed where the glider was flown first in a 10 km transit segment and second in a 90 km survey pattern segment. During these trials the RMS errors were found to be limited to 25 m and 50 m respectively.

To implement the glider TAN algorithm on an underwater glider a Beagle Bone Black (BBB) single board computer was integrated into the vehicles payload computer. The BBB consumes 1.5 W when processing or booting and 0.5 W while idle. The TAN algorithm is written in C/C++ and is run as a background process upon boot of the BBB's Ubuntu 13.04 operating system. The Payload computer on the glider acts as the controller for this process, requesting the input variables from the glider control computer, sending them to the BBB when appropriate and retrieving the TAN location updates to send back to the glider control computer. The TAN algorithm is initialized whenever a new GPS fix is received and it computes a location update whenever a new altitude measurement is taken.

During preliminary on-line trials of the glider TAN method the vehicle was flown in straight line segments of around 1 km. In these trials several issues were found during the analysis of the recorded location estimates. The vehicles shallow inflection was set too shallow resulting in intermediate GPS fixes which reset the TAN algorithm. Additionally, the TAN coordinate frame was set to true north while the location updates from the glider where in magnetic north. Future tests with these issues corrected are scheduled for September of 2014.

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