Preliminary Field Trials of Autonomous Path Following

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Abstract—As part of the ongoing Responsive AUV Localization and Mapping project (REALM) Memorial University has been developing an autonomous path localization and following system. This Qualitative Navigation System (QNS) localizes an AUV to a predefined path and generates control inputs to maintain the AUV along that path without the need for an absolute position estimate. QNS processes sonar data into the two-dimensional image space and performs feature extraction and matching. The results of this matching are input into a filter which allows localization of the AUV on the path and determination of either a waypoint or heading to maintain the AUVs traversal along the path. This ability to autonomously follow a path will be of great use for long term environmental monitoring.

In May of 2013 QNS was deployed on Memorial’s Explorer AUV and field tested in Holyrood, Newfoundland. International Submarine Engineering, manufacturer of the Explorer AUV, provided an interface which allowed the QNS software to request control of the AUV, provide command inputs, and relinquish control. A test path consisting of two connected 755m and 470m line sections was defined and used for preliminary tests.

Although testing time was constrained, a series of successful tests were completed in which the AUV autonomously detected the path, localized itself and traversed the path to completion. The results of these tests validate the concept of QNS and the AUV control interface and will drive ongoing development and testing.

I. INTRODUCTION

The trials described in this paper mark an important milestone in the ongoing development of an autonomous path localization and following system. This system, referred to as the Qualitative Navigation System (QNS), is part of the Responsive AUV Localization and Mapping project (REALM), a multi-year project headed by Memorial University. The goal of QNS is to allow an AUV to follow a sequence of sonar images representing a path along the sea-floor.

Our system requires the initial collection of sonar data along a desired reference path. Later, when following this path autonomously, the AUV compares its most recent sonar image to the sequence of images collected along the reference path and determines the most likely corresponding position. This localization process does not require the full estimation of the vehicle’s pose. Instead, the result of localization is a single index corresponding to a stored sonar image captured on the reference path. The next step is to compute a waypoint further along the reference path that the AUV is then commanded to reach.

The development of this system required several core technology developments: a method to reliably process and match sonar data in real-time, an algorithm to localize to the path and determine required trajectory corrections, and an interface to allow the AUV to act upon control inputs outside of its normal mission plan.

A. Background

QNS represents the reference path as a sequence of nodes, each with an associated side scan sonar image collected during training. This strategy is based on the notion of topological navigation pioneered in mobile robotics [1] which is described as qualitative navigation [2], [3]. The approach of qualitative navigation is to represent the environment as a set of connected places with mechanisms for travelling between places. It is quite explicit that these places are not represented in the same global coordinate system. These ideas have led to considerable success in recent years in allowing an outdoor mobile robot to autonomously follow a trained route, despite changes in illumination and variable terrain [3], [4]. To our knowledge, our work represents the first attempt to apply the qualitative navigation approach to the underwater domain.

The entire path following system consists of a few key sub-systems. An overview of each is given in this section. Where available, references are provided to more complete works on each.

1) Image generation: Nodes along the path are represented by sonar images and our system requires the ability to autonomously generate new images in real-time as it collects sonar data. Our system is currently focussed on sidescan sonar—a popular acoustic sensor which produces intensity-based images suitable for the detection of distinctive patterns on the seabed. Sidescan sonar generates an acoustic ping and using two linear transducer arrays records return intensities at a fixed sample rate along a narrow beam orthogonal to the vehicle’s heading on the port and starboard sides. Each ping is recorded and indexed with the AUV’s current position estimate, heading, speed, and attitude.

When a set of pings have been collected the samples can be projected onto a 2-dimensional image grid
Fig. 1: Mapping of samples to image coordinates

Fig. 2: Generated sonar image. Area in centre represents the Nadir: an area not covered by the sonar.

Fig. 3: Extracted keypoints on sonar image. Circles indicate position and size of keypoint, lines indicate orientation.

Fig. 4: Images matched by keypoints. Lines indicate match pairs.

A more complete description of sonar image generation can be found in [5], including results on the robustness and efficiency. Figure 2 is a typical generated image.

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2) Image matching and Registration: When following the trained route, new sonar images are periodically generated and compared to the images of the reference path. This comparison process is known as image matching. Given two particular images with an assumed overlap, image registration is the process of determining the translation that maps one image onto the other (in our system the images are always North-aligned, hence there is no rotation component in image registration). For both image matching and registration we utilize distinctive keypoints and their associated descriptor vectors. The SURF keypoint extractor and descriptor [6] was chosen due to its promising results in offline tests. A brief description of image matching and registration will be given here, a more comprehensive treatment of our implementation is found in [5], as well as a comparison of keypoint extraction techniques in [7], [8].

To facilitate image matching a keypoint extractor is used to isolate areas of interest on each image; selection of these areas vary by the particular algorithm used. For SURF a typical sonar image would yield keypoints as shown in figure 3. These keypoints are then assigned a descriptor which provides a compact vector describing the keypoint region and offers an efficient means for comparing keypoints from pairs of images to determine matches. Two images with a sufficient consensus of matched descriptors can be considered a possible match. Figure 4 shows two matched sonar images with lines joining matching keypoints. When there are a high proportion of matches which agree in their relative translation, there is a correspondingly high probability that these two images overlap and represent the same area. Different areas of the seabed will vary in appearance, and thus the presentation of the same set of keypoints for different areas is unlikely.

3) Localization: A sonar image will potentially match one or more images along the reference path. These matches fall into two categories: positive matches, in which the match is real and the two sonar images do indeed cover that same geographic area; and false positives, in which the keypoints are similar enough to indicate a match, but the two images do not overlap. To deal with the possibility of false positives a Bayesian filter is used to generate the actual estimate of location [9]. A Bayesian filter is a recursive estimator in
which a prediction of state is made based on the current state estimate, using a system model. This prediction is compared to a measurement of state and a resultant updated state estimate is computed. In the case of QNS, each iteration involves a motion prediction step and a measurement step which coincides with the arrival of a new sonar image. A more complete description of the localization algorithm is found in [10].

When a high-confidence estimate is achieved the registration information is used to determine the AUV’s position in relation to the path. A heading based on the current position and a position further along the path is calculated and communicated to the AUV’s vehicle control computer (VCC).

4) AUV Interface: Under normal operation control of the vehicle is handled by the vehicle control computer (VCC) running ISE’s Automated Control Engine (ACE). This real-time system typically relies on a set of pre-defined waypoints presented as a mission file. ACE provides mechanisms for: inter-waypoint line following; constant depth or altitude tracking; speed and attitude control; and monitoring and response to fault conditions defined in a fault-response lookup table. Payload control, data collection and the QNS application were run on an independent computer connected via Ethernet to the VCC, this is the payload control computer (PCC).

Transitioning from offline tests to field trials required a means of interfacing with the AUV to allow QNS to dictate the vehicle’s movements. For these trials an interface was developed by ISE which allowed the vehicle to deviate from its set mission plan and take control inputs from an outside entity. The interface is a simple, but flexible, series of command and response messages sent to/from ACE over Ethernet.

A general overview of the interface as it pertains to QNS will be given here, a detailed description of the proprietary details is omitted.

The basic structure of the interface consists of four message types:

**QNS command**
- QNS can request or relinguish control of the vehicle in either heading or waypoint mode

**QNS parameter**
- When in control QNS sends required parameters to ACE, such as speed, depth, and heading or waypoint setpoint

**ACE status**
- Periodic message from ACE with AUVs current state: position, speed, heading, depths, etc

**ACE acknowledge**
- sent in response to QNS command to acknowledge receipt and acceptance of command

A typical set of interactions would be as follows:

1) ACE in mission mode, processing pre-defined mission steps in order
2) QNS localizes and request control in heading mode
3) ACE acknowledges control request
4) ACE suspends current mission execution and stores current mission step
5) QNS begins periodic transmission of requested parameters (heading in this case)
6) ACE sends periodic status messages
7) QNS request to relinquish control
8) ACE acknowledges and retrieves stored mission step
9) ACE enters transit to return to point of mission suspension
10) ACE resumes mission

As one would expect, the interface includes several key safety checks. The interface provides bounds on AUV deviation from the mission location, as well as timeout limits between interface requests or parameter updates.

II. Field Trials

In May of 2013 a short series of field trials were performed to determine how QNS would perform in the real-world. The trials allowed all aspects of the system to be tested: collection and real-time processing of sonar data, matching of collected data to a priori path data, localization of the AUV to the path, determination of control inputs, and AUV action upon provided control inputs.

A. Constraints

This set of trials, though valuable, cannot be considered comprehensive and did not represent a complete validation of the QNS system or AUV interface. Due to time and range constraints these trials should be considered only a proof of concept that the QNS system will work in the field. These trials have been invaluable in helping to define areas for further study.

As QNS was not the only field objective on this particular deployment only a short amount of time could be allocated. This time would also include some unit testing of the AUV interface, which had not yet been tested in the field. In the end, QNS testing came down to a single day available for full path-following trials, May 3, 2013. A total of nine trials were executed on this day.

For development and testing Memorial University uses the Holyrood Marine Base in Holyrood, Newfoundland. This sheltered harbour is an ideal safe-haven for testing. Operations are conducted from shore to reduce the burden of ship-based support. This does come at a price as there is no ability to shepherd the AUV. Tracking is done from the wharf at the south end of the harbour with an Ultra Short Baseline acoustic tracking system (USBL). In this environment we typically track the AUV to a maximum range of 1200m. As we were enabling a previously untested autonomous mode of operation it was decided not to perform operations in which the AUV would be out of acoustic communication range. With this constraint a test path limited to 1200m was selected.

B. Operational parameters

Trials were conducted using Memorial University’s Explorer AUV [11], manufactured by International Submarine Engineering (ISE) [12]. The Explorer is a 3000m depth rated survey class vehicle measuring 4.5m (at time of trials). The
TABLE I: Trial summary

<table>
<thead>
<tr>
<th>Attempt</th>
<th>Localized</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Y</td>
<td>System timeout. Parameter incorrectly set</td>
</tr>
<tr>
<td>2</td>
<td>Y</td>
<td>System timeout. Parameter incorrectly set</td>
</tr>
<tr>
<td>3</td>
<td>N</td>
<td>Vehicle Depth threshold reached before localization occured</td>
</tr>
<tr>
<td>4</td>
<td>Y</td>
<td>Series of successful localizations with heading corrections. Low altitude condition ended run</td>
</tr>
<tr>
<td>5</td>
<td>Y</td>
<td>Out of range condition. Parameter too conservative</td>
</tr>
<tr>
<td>6</td>
<td>N</td>
<td>Logging system failure, no sonar data presented to QNS</td>
</tr>
<tr>
<td>7</td>
<td>N</td>
<td>Logging system failure, no sonar data presented to QNS</td>
</tr>
<tr>
<td>8</td>
<td>Y</td>
<td>Localization and full traversal of path</td>
</tr>
<tr>
<td>9</td>
<td>Y</td>
<td>Localization and full traversal of path</td>
</tr>
</tbody>
</table>

payload consisted of an Edgetech 2200m combined sonar system, with a 100/400KHz chirp sidescan sonar. All data used in trials was from the 400kHz channel. Navigation information is provided by an IXBlue PHINS inertial navigation system with inputs from a surface DGPS, paroscientific depth sensor and RDI Workhorse Doppler Velocity Log (DVL).

Sonar data was logged into files consisting of 1001 pings. As each new file was created QNS was notified. This was the main triggering event for the QNS workflow. The selection of the number of pings is somewhat arbitrary, but worked well in offline tests. At the end of the QNS workflow, if localization was successful, QNS would request control of the AUV in Heading mode only, as this was the only mode fully supported by QNS at the time.

During trials the vehicle operated at a speed of 1m/s and a constant altitude of 7m from the bottom. These values were selected as they had been used in previous AUV based sonar data collection and had been shown to produce high quality sonar images.

All tests utilized the same reference path. The path was selected in an area which would be rich in bottom variation, with both rock outcroppings and sediment variations. Based on offline tests, this area was predicted to provide good performance in the keypoint extraction and matching phases. The path itself consisted of a straight section and a 30° turn to provide some feedback on the system’s ability to follow path variations. Figure 5 shows the reference path in Holyrood harbour. Divisions are included to show the distinct image breaks used for matching. The straight section is a 755m line at a heading of 180° followed by a turn to 150° for an additional 470m straight section.

III. Trial Summary

A total of nine attempts were made at following the test path. Of these three could be classified as successful operation of QNS, with the remaining six having failures due to systematic errors. Table I summarizes the attempts.

Attempts 1, 2 and 5 failed due to safety parameters in the AUV interface being set too conservatively. In all three cases a successful localization was achieved and QNS assumed control of the vehicle, but the trials were cut short. If nothing else these trials serve as validation of the safety checks. Attempt 3 failed before any successful localization occurred due to an over-depth condition, in which the AUVs depth exceeded a pre-defined limit. Upon review, the limit was deemed too conservative and relaxed. Attempts 6 and 7 failed due to a failure in the data logging system, in which it did not delivering new sonar images to QNS, thus no matching was possible.

Attempts 4, 8 and 9 represent trials in which the QNS system successfully localized, took control of the AUV, and tracked the path. However, attempt 4 ended prematurely due to a low altitude condition, most likely due to passing over a raised object. Both attempts 8 and 9 completed the full path and entered the transit stage to return to the mission suspension.
A. Detailed summary

Using the final attempt a more detailed exposition is provided for QNS operation in the field. Each phase is summarized with data from the QNS system logs.

1) Initial path discovery: After entering the initial mission mode QNS began receiving sonar tiles. A total of 6 tiles were received and processed before a match was determined. The first 3 did not overlap with the path and were (appropriately) not matched. The 4th and 5th image tiles did overlap the path, but at a point when the AUV was turning. The 6th tile was successful and a correct localization was determined. Figure 6 shows the first 6 tiles in relation to the reference path. As we can see, the early tiles are fragmented as the AUV is settling in to the dive and then turning toward the path. This could be a contributing factor to the lack of initial matches.

Figure 7 is the results of the first match and visually we can see it is indeed a positive match. In figure 9 we can see our initial belief is uniform across all path locations 9(a), when a positive match is made we develop a spike in our belief confidence at this point in the path 9(b). Now localized, the QNS determined a heading suggestion of $192.375^\circ$.

2) Path Following: Following initial localization to the path QNS requested and received control of the AUV, entering what is called override mode. QNS now sends out periodic messages with control parameters for the AUV to follow, in this case headings. As new localizations are made the heading target is adjusted. Over the course of the path a total of 27 matches were made with 21 successful localizations and heading updates. In these trials successful localizations were made to every tile in the reference path, once path following started. Figure 9 shows a sample set of plots for the prediction, measurement and location belief for each step along the path following.

In some cases a single match is made which falls within the prediction, this leads to a strong localization 9(e). In many cases a new sonar image matched to multiple path tiles - due to an overlap in coverage. As we see in 9(d) we match to two locations, but due to our prediction of moving along the path we localize to a single path node. In all cases the filter was able to determine a best estimate and generate a sensible heading correction. Figure 8 shows the complete path following mission.
We see that the AUV tracked the reference path fully, covering both straight sections and the connecting turn. There are some noticeable variations to the path as the vehicle attempts to track based on heading. As well we can see that there is a distinct offset, noticeable from the reference path not being in the center of the sonar data. Possible sources of this error include: navigation errors between collection of the reference path and the path following; offsets in the registration of sonar images as compared to actual image coordinates; errors in the heading calculation; and the inherent delay in the vehicle’s tracking of the heading setpoint. Field trials expose many such real-world effects that must be studied further as the technology progresses.

3) Path Completion and transit: Upon localizing to the final image in the reference path QNS request to relinquish control of the AUV. ACE acknowledges this request and enters a transit mode to return the AUV back to the mission point where control was initially acquired. We see this in Figure 8 at the south end of the path where there is a sudden turn back toward north. Once in transit mode QNS ends its execution.
IV. Summary

Though not a comprehensive validation of the QNS system, the field trials proved a worthy exercise in the overall development. Work leading up to these trials had used offline data and provided confidence in the system, but there is always some uncertainty as to how a system will operate in the real-world. Overall the trials allowed all facets of QNS to be run in the field with positive results. The issues experienced were mainly due to mis-tuning of parameters and in-experience with a new mode of operation on the vehicle.

Of most value was the ability to test a completely new AUV interface which allowed a separate software entity to take control of the AUV, putting it in a mode beyond simple mission step following. This was an important step toward true autonomous operation as actions were not pre-meditated, but derived from decisions on real-time data. The interface proved functional, robust, and adequately safe due to several layers of safety parameters to protect the vehicle from venturing outside of pre-defined boundaries.

From these trials some weak areas were discovered in the system. There is reduced ability to match tiles as the AUV is turning and diving, as was made apparent during the initial approach to the reference line. This may limit how robust the path discovery phase can be. For these tests only heading control was used, which has its limitations. Analysis of the AUV trajectory indicates the heading control may be fragile for long-term path following. Waypoint calculation should allow better Ace has robust waypoint logic, and would provide a smoother and more deterministic approach.

A. Future work

This milestone in the development of QNS has focused attention on some areas that will require more attention as we move ahead. Although image registration worked well in these tests, the area was specifically selected to be feature-rich, much more offline testing is needed to show that our system can be robust over a variety of sea bottom types - this is the current primary focus. Future trials will also need to include longer and more dynamic paths. For QNS to be useful as a tool it will need to operate over greater distance and be robust over more complex trajectories. Testing will also have to show performance in areas where there will be gaps in the matching, when not every path tile is localized.

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References