Practical Feature-Based Navigation Using Forward Looking Sonar for ROV Positioning

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***Abstract* - Feature-based navigation methods using Forward Looking Sonar (FLS) have gained increased attention from academia over the past decade. The advent of lower-cost and smaller multibeam sonars and higher resolution scanning sonars have greatly contributed to the popularity of this topic for study. Yet, feature-based navigation methods for ROVs utilizing FLS data have not made it offshore in common practice because systems offering practical application are not currently available. Greensea has developed a new approach to feature-based navigation using FLS based on an open software architecture that is both practical and ready for offshore. This new technology can utilize either scanning or multibeam sonar data to provide a positioning and navigation solution for ROVs in structured and semi-structured environments. This capability is significant in that it can enable ROV positioning in very challenging environments where traditional methods would fail, as well as provide a positioning capability with minimal new equipment. A radical benefit of feature-based navigation is that it is inherently drift-free and can correct traditional INS navigation solutions, thus potentially enabling precise positioning and control with low cost navigation sensor suites. This paper provides an overview of Greensea's technology and presents field results.**

1 Introduction

Accurate and robust subsea navigation for Remotely Operated Vehicles (ROVs) is critical to meaningfully support and conduct even the most simple of operations. With greater operational demands on ROV operators and the ever-present demand for efficiency and cost savings offshore, navigation and positioning has never been more vital to ROV operations. The autonomy and advanced control modes such as station-keeping and dynamic positioning that are now required offshore are not possible without an accurate positioning solution.

While accurate navigation and localization for ROVs is now expected and arguably commonplace, the systems currently fielded as well as the supporting body of knowledge are based largely on traditional aided inertial technologies and acoustic positioning systems. Due to physics and manufacturing constraints however, the accuracy of traditional Inertial Navigation Systems (INSs) is proportional to their size, cost, and power consumption and their rate of drift or error growth is inversely proportional [1][2][3][4]. Traditional INS technology subsea is also highly dependent on a variety of aiding sensors such as Doppler Velocity Log (DVL) and Ultra-Short Baseline (USBL). The standard payloads required for accurate inertial navigation and the operational budgets of many projects preclude the use of high-grade aided INS packages on many jobs. Traditional INS technology has other significant shortcomings for ROV operations as well: it drifts, it is often overkill for the positioning requirements of most work-class ROVs, and it is highly dependent on the installation, calibration, and operation of a variety of sensors. Further, acoustic positioning methods are not suited for all ROV operations and cannot alone provide the positioning stability for the accurate closed-loop control and autonomy functions now greatly desired by operators. Acoustic positioning methods also fail easily in highly structured environments or complex operational areas. Because of these factors, for many operations accurate navigation on ROVs remains elusive. A new general-purpose navigation solution is required for ROV operations.

Greensea has developed a general-purpose feature-based navigation and positioning technology for ROVs that provides a significant reduction in size, weight, and power (SWaP) requirements over current navigation systems and methodologies while providing the accuracy and robustness needed for viable offshore operations. This system utilizes a flexible software framework that interfaces with many forward looking sonars currently on the market and provides a feature-based vehicle pose solution utilizing fused INS and Simultaneous Localization And Mapping (SLAM) methods. By detecting, extracting, and matching features from the sonar data, the system generates a vehicle pose estimate that is directly related to the environment and uses this pose estimate to correct the drift and error of the INS. As well, the system builds an online real-time map of the detected features to assist in wide-area localization.

While similar methods have been explored in academia for more than a decade, the system presented here overcomes several barriers to practical use present in most of the currently published solutions. Typical SLAM implementations based on the popular EKF-SLAM methods are very computationally expensive and have been shown to grow quadratically in computational time with each new feature added to the state vector [1]. Also, all of the solutions present in the body of knowledge are sensor-centric, focusing on specific perception sensors (scanning or multibeam sonar) and system configurations, versus being method-centric, or focusing on a generic and multi-purpose method and technology framework. The system presented here utilizes a very efficient algorithm and computational process to enable the use of light-weight embedded processors for feature-based system and is constructed on a highly flexible and scalable software architecture with native support for many sonars and sensor systems currently used in the subsea industry. These abilities to work efficiently in small embedded computers and to work with a wide variety of sonars, sensors, and vehicles make this technology practical for offshore use.

2 Relevance of Feature-Based Navigation to ROVs

Feature-based navigation and positioning has the potential to radically change the ROV industry by providing a simple, intuitive, and general-purpose positioning solution that is scalable to the ROV and well-suited to structured environments – environments where traditional navigation systems fail.

This technology provides several critical benefits to ROVs.

- **Simplicity.** Feature-based navigation offers a simple solution to vehicle navigation and positioning. Because it uses the same principles we use when we go for a hike in the woods — remembering landmarks — it makes sense to operators and is thus easy to diagnose, operate, and understand. Installation, alignment, and calibration takes nothing more than mounting the forward looking sonar on the ROV and mounting or interfacing an IMU.
- **Size, Weight, and Power (SWaP) reduction.** Due to the laws of physics and manufacturing constraints, the accuracy of traditional INS technology is defined by the size, weight, and power consumption of the total system. Big, heavy, and power hungry equals accurate. Feature-based navigation technology significantly shrinks the SWaP requirements for accurate navigation. Because feature-based navigation can correct INS drift using vehicle pose data derived from the direct observation of the environment, it enables the use of smaller and lower power INS technology such as MEMS-based components. In a well-structured environment, the vehicle pose

data derived from the forward looking sonar features eliminates the need for a DVL in many cases, further reducing the SWaP requirements for navigation.

While advantageous for work-class vehicles, this is a game changer for observation class vehicles and small UUVs. Over the past decade, observation-class vehicles have become increasingly popular due in large part to both the miniaturization of critical payload components and pressure from operators due to the high costs of the support vessels required to handle large vehicles. Further, the shift in navies worldwide towards focusing on littoral region patrols and port security has driven the demand for small, lightweight, and man-portable UUVs drastically. While the commercial offshore industry continues to invest heavily in inspection-class and observation-class ROVs, these systems will not be truly viable until an accurate navigation system is available for small vehicles. Feature-based navigation, offering a tremendous reduction in SWaP requirements, has the potential to fill this requirement and unlock the potential of these systems in critical applications.

The following table provides a SWaP comparison of sensors commonly used for Inertial Navigation Systems as well as SWaP figures for a MEMS-based INS and two forward looking sonar sensors: a popular Multibeam Imaging Sonar (MBIS) and a micro mechanically scanned imaging sonar (µMSIS). In the following table, all independent sensors are housed in a 500m pressure housing.

Single Sensor Units	***Size (m^3)***	***Weight (kg)***	***Power (W)***
CDL MiniPos T16 IMU	0.007	9.8	20-35
CDL MiniPos T24IMU	0.013	21	20-35
RDI Explorer DVL 1200kHz Phased Array	0.010	4.3	2-12
Tritech Gemini 720i Multibeam Imaging Sonar	0.004	3.9	35
MEMS-based INS (Gladiator LandMark40 IMU, Keller pressure sensor, PCI TCMXB mag compass)	0.001	1.04	7
Tritech Micron Mechanically Scanning Sonar	0.0003	0.324	4
Aggregate Sensor Suites	***Size (m^3)***	***Weight (kg)***	***Power (W)***
CDL MiniPos T16 IMU + RDI Explorer DVL	0.017	14.1	22-47
CDL MiniPos T24IMU + RDI Explorer DVL	0.024	25.3	22-47
MEMS-based INS + Tritech Gemini MBIS	*0.005*	*4.94*	*42*
MEMS-based INS + Tritech uMSIS	*0.001*	*1.364*	*11*

Table 1: SWaP comparison table of common navigation systems components as well as aggregate sensor suites. Note significant reduction in SWaP using feature-based navigation suites.

- **Cost reduction.** As SWaP grows with INS accuracy, so does cost. Commonly used high-end INS installations aided with a DVL easily cost $100k to $200k depending on the options selected. Depending on the requirements of the operation, feature-based navigation methods can significantly reduce the cost associated with “accuracy”. Part of the cost reduction is certainly realized by utilizing the existing FLS on the ROV for navigation purposes instead of just visualization.

- **Positioning with respect to the work area.** For ROVs, perhaps the most compelling benefit of feature-based navigation is that it provides a navigation and positioning solution *relative* to the work area. As such, vehicle control can then be done relative to the work area as well. With many ROVs already coming stock with station keeping and dynamic positioning capabilities, feature-based navigation provides a much more meaningful positioning input as it references the work field around the vehicle versus interpolated absolute positions.

- **Superior performance in complex environments.** Traditional aided INS and acoustic navigation and positioning systems struggle in complex environments. Shallow, highly-structured environments and environments with significant acoustic activity corrupt acoustic positioning systems. Operating close to the bottom, high off of the bottom, on varied terrain, or near structures corrupts DVL quality. Ferrous environments corrupt heading data in lower-cost systems. Unfortunately, these are the environments in which ROVs are typically used.

  Feature-based navigation and positioning is unaffected by these factors that impair traditional ROV positioning systems, as long as there are features in the field. As such, feature-based positioning technology can make operating accurately within these environments not only efficient but viable.

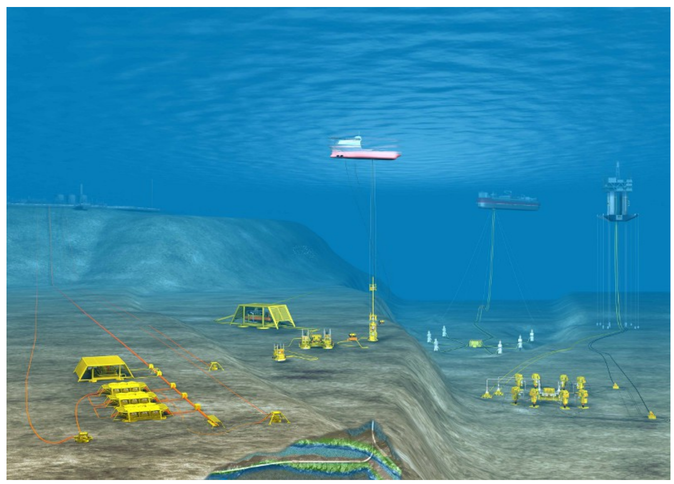

Illustration 1: A typical offshore work area for an ROV. Highly structured environments aid high-quality feature-based positioning.

- **Stable heading solution around ferrous structures.** Our feature-based ROV positioning technology uses the vehicle pose (position and attitude) to correct an on-board INS solution. Within this, the feature-based solution compensates for heading changes due to the presence of ferrous structures, thereby enabling conventional auto-pilot functions, such as auto-heading, around ferrous subsea equipment.

- **Automation with respect to the work area.** With a positioning solution relative to the work area, accurate and reliable automation is possible. A critical factor preventing practical ROV automation in structured environments is the quality of navigation. As previously stated, traditional aided INS and acoustic navigation and positioning methods do not provide the reliability or accuracy in highly-structured environments to permit true automation. Further, the positions, orientations, and geometries of the subsea structures are typically not modeled accurately enough to enable true intervention autonomy. With the ROV being able to position itself with respect to the subsea environment by "seeing it" though, automation is possible.

The importance of feature-based navigation to ROV operations simply cannot be overstated.

3 General System Overview

Greensea's feature-based navigation system is constructed on the Open Software and Equipment Architecture's (openSEA) modular and flexible software framework. The system features an integrated aided INS engine, open support for forward looking sonar systems, an open navigation data output, and the option for streaming IP video of the constructed and processed sonar image. Because of the modular architecture, the system supports distributed processing which facilitates many different vehicle and system configurations.

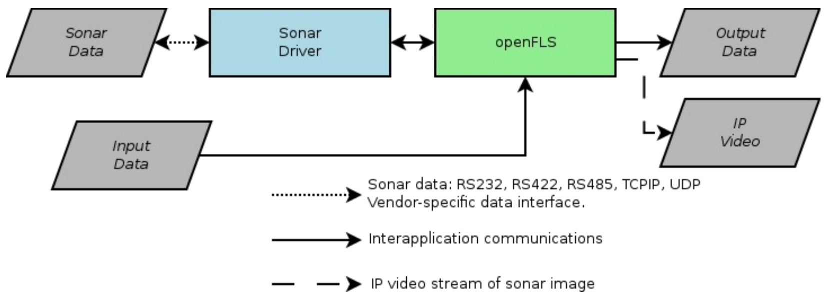

Illustration 2: Generalized feature-based system architecture.

This distributed system consists of multiple processing modules. These modules may be collocated or distributed on different processing nodes. Generally though, there are two components of the system: the back-end processing module and the front-end display and interface module. The back-end module provides for all of the sensor interfaces, processing, and navigation estimates while the front-end module provides visualization and operator input functions for controlling the sonar display and taking manual control of several feature detection functions. The front-end module is not necessary for operation and can be removed for pure headless operation, such as in a stand-alone sensor or AUV, or be replaced by a user's own display front-end.

Also integral to the feature-based system is a comprehensive data logging package that allows high-rate logging of raw and processed sonar data as well as aiding sensor data, INS data, and feature data. The data logging utility logs to a binary file that can parsed and deconstructed by module using a tool set developed by Greensea. This system also supports playback of the logged data.

The openFLS software application within the openSEA framework provides for the sonar integration, image processing, feature extraction, and feature-based pose estimation.

3.1 Generalized Forward Looking Sonar Interface

Critical to the practical adoption of feature-based navigation and positioning technology is the flexibility of using a wide variety of sonars. This presents particular complications however and is largely why other feature-based sonar technologies have been built around a particular sensor. openFLS leverages the native device library within openSEA to provide broad industry support for particular sonars and sonar technologies including both scanning and multibeam imaging. openFLS uses a modular framework to normalize the sonar data input into a common format prior to processing.

An interesting benefit to this generic front end is a standard sonar interface for many industry sonars that provides both control, visualization, and data recording.

3.2 openSEA Software Framework

Greensea's feature-based navigation and positioning technology is built on the Open Software and Equipment

Architecture (openSEA). openSEA is a software framework for robotic software system development. It consists of a core library and multiple independent and modular software applications that provide very specific capabilities: openDEVICE (a sensor fusion and management system), openINS (a multistate Kalman inertial navigation engine), and openFLS (a forward looking sonar integration module), and openCMD (a multistate vehicle control module). All applications and software modules link to the openSEA library.

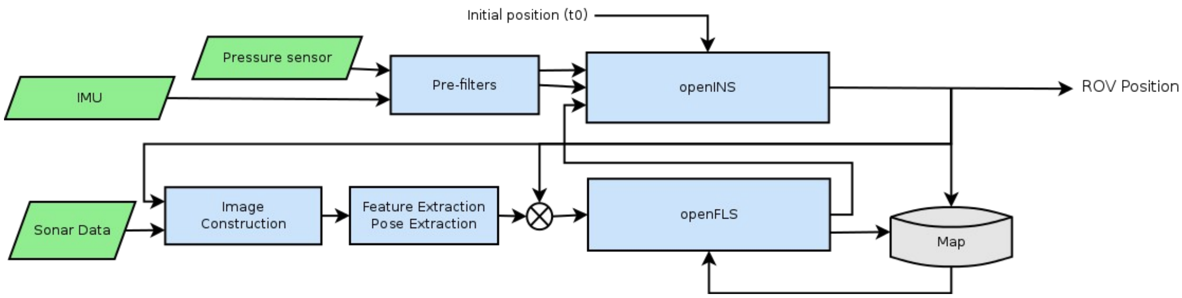

Illustration 3: General architecture of Greensea's feature-based ROV navigation and positioning system.

The openSEA framework provides a comprehensive native device library with support for over 800 sensors and devices. This device library enables the feature-based system to have wide support for many sonars and navigation devices within the industry. This capability is critical to fielding a *practical* solution to offshore.

The openSEA architecture allows the feature-based system to be sensor and device agnostic. The software architecture is designed to work with any type of sonar and any type of IMU.

3.3 Lightweight Algorithms and Computational Processes

The image processing, feature extraction process, and SLAM method are extremely computationally intense. Other feature-based navigation and positioning technologies using sonar data have failed to become practical solutions because they were unable to provide a system in a lightweight package. Many ROV systems lack the bandwidth or infrastructure to host large processing equipment topside. Further, a navigation solution that is not just "plug-and-play" will have no hope offshore.

Greensea has developed novel lightweight algorithms and computational processes for the sonar image processing, feature extraction, and SLAM methods. Whereas most SLAM-based systems grow in complexity and computational load with each new feature added to the map, ours does not. Thus, the system remains predictable, constant, and lightweight regardless of the environment. These algorithms and processes provided within openFLS allows this system to run in fanless, embedded hardware architectures such as the ARM9 system. This small and lightweight package allows the technology to be viable offshore.

Illustration 4: Tritech Micron mechanically scanned imaging sonar with Greensea embedded feature-based navigation system and MEMS-based INS.

3.4 Operation

The system can operate stand-alone in a headless deployment, such as for a stand-alone sensor or in an AUV, or in a full headed deployment with a graphical interface and operator controls. For most ROV applications, the system is used in a headed configuration with Greensea's display and interface. A simple benefit of the system is that it also provides a feature-rich sonar display, recording, and processing utility with industry-wide support for forward looking sonars. In the most common configuration — using Greensea's graphical interface on the front-end — the system can either run alongside of the operator's current sonar display or replace it entirely. Operators will find the controls and features provided by the interface are identical to the controls and features found in most OEM display software. With or without the feature system enabled, operators can use the interface just as they would any OEM sonar display.

The feature-based system uses inertial data from an IMU, if available, to smooth and stabilize the sonar image. Once the image is formed, geo-corrected, and stabilized, the feature extraction module pulls features from the image. As features are detected, a matching algorithm determines if they are recurring features or new features. If a feature is determined to be a recurring feature and the system builds confidence that the feature is stable, stationary, and well-defined it makes the feature a landmark and pushes the feature into the map. Once a feature is made a landmark, it can be used in the navigation solution.

When the feature system is enabled, operators will see features detected and graphically represented on the sonar display. The features are defined by geometry and are usually (depending on selected color palette) displayed with a green highlight. While automated in a stand-alone configuration, operators have the tools within the interface to control a few parameters of the feature detection system such as the size threshold of the features.

The SLAM module of openFLS is fused with the INS module to estimate a vehicle pose relative to the feature field. This pose is then used to correct and bound the INS estimate. Once a stable positioning and attitude estimate is available, the system outputs a standard navigation solution on any of the defined output channels in a specified format (binary, NMEA, etc.).

From an interface and operator's point of view, the system performs as a typical sonar interface and a standard navigation sensor.

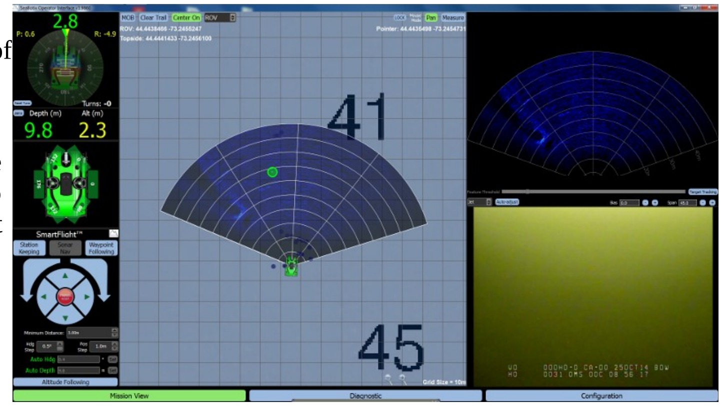

Illustration 5: SeaBotix SmartFlight control interface with Greensea's feature-based navigation system utilizing a Kongsberg Mesotech M3 multibeam imaging sonar.

4 Feature-Based ROV Positioning

A powerful application of this technology is, of course, closed-loop positioning control of an ROV within a work environment. Using the structures within the work environment, the feature-based navigation system provides a highly stable, object-relative positioning solution. Using this solution as the input for closed-loop positioning controllers — such as station keeping and dynamic positioning systems, as well as for higher levels of object-relative autonomy such as pipeline inspections, riser inspections, and target tracking — has proven far superior and more robust than using conventional positioning solutions provided in world or ship-relative coordinates.

The following sequence of images shows the feature-based navigation and positioning system used in a dynamic positioning exercise. In this configuration, the system used a MEMS-based IMU, a magnetic heading sensor, and a mechanically scanned imaging sonar produced by Tritech International.

The vehicle navigation solution for this exercise was provided by the feature-based system. During the following trial, the vehicle started out station keeping with respect to the features in view and then transited laterally to the left 15m.

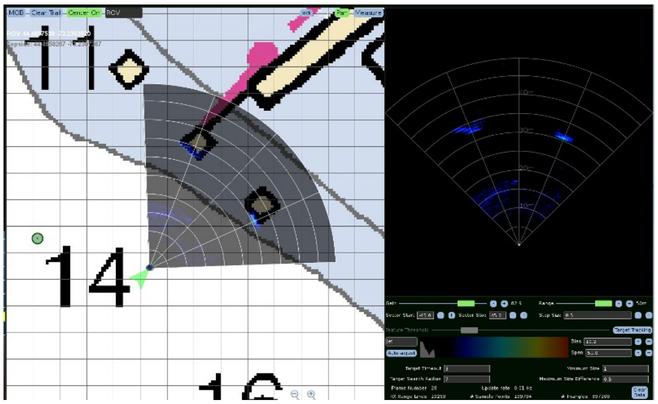

Illustration 6: Typical run-time sonar and navigation display with the feature system disabled. In this mode, Greensea's interface provides a simple sonar interface with industry-wide support for forward looking sonars.

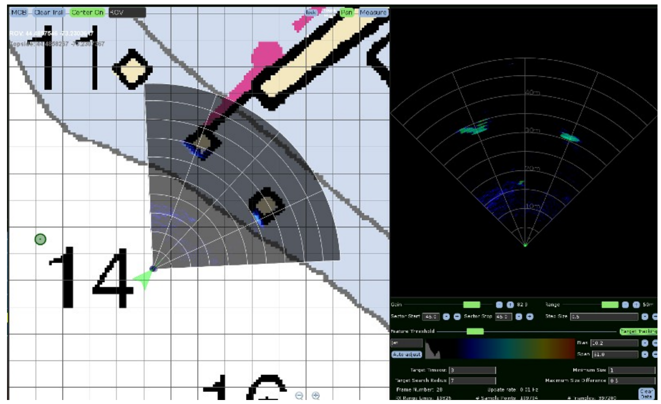

Illustration 7: The operator has enabled the feature system and three features are defined. The features geographically align with the pilings in the chart. Note the two larger features in the far-field and the smaller object nearby.

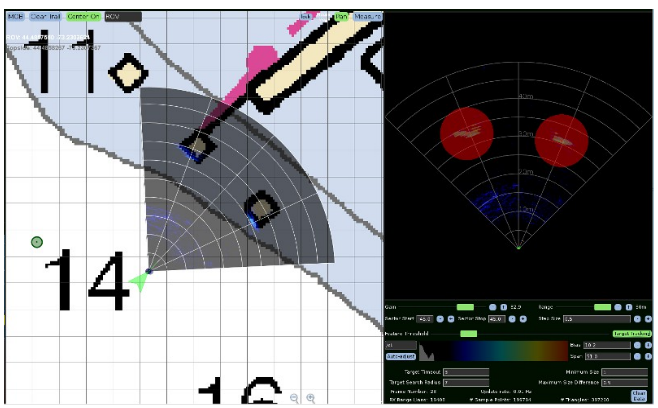

Illustration 8: The openFLS feature detection module has built confidence in two of the features and has made them landmarks and pushed them into the map. The navigation module is now using these two features to correct the INS and calculate a vehicle positioning solution.

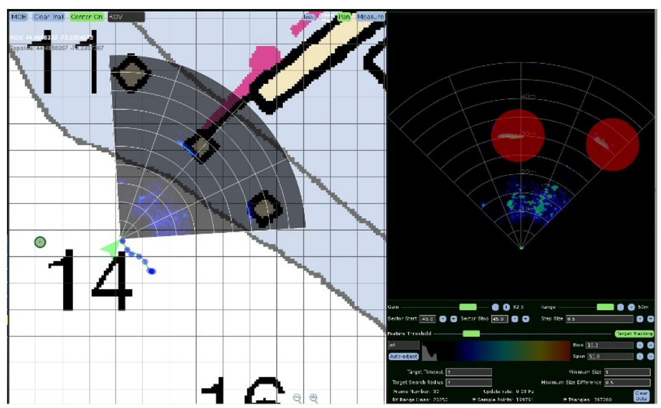

Illustration 9: The vehicle has started a 15m move to the left. The landmarks are well tracked and provide quality positioning corrections to the inertial solution. Note the low confidence features rejected in the near-field. The feature-system tracks the features well during motion.

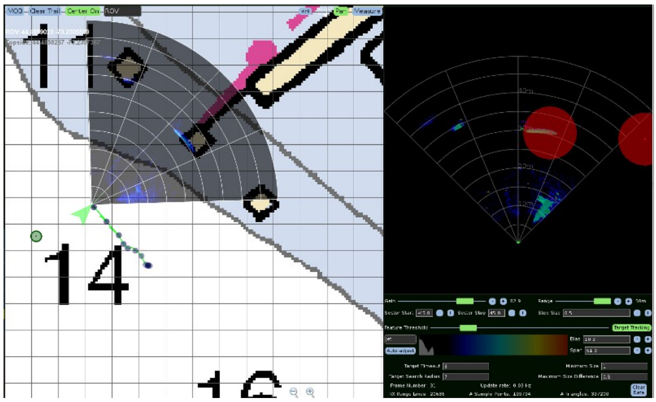

Illustration 10: As the vehicle transits on a lateral move, a new feature is identified to the left.

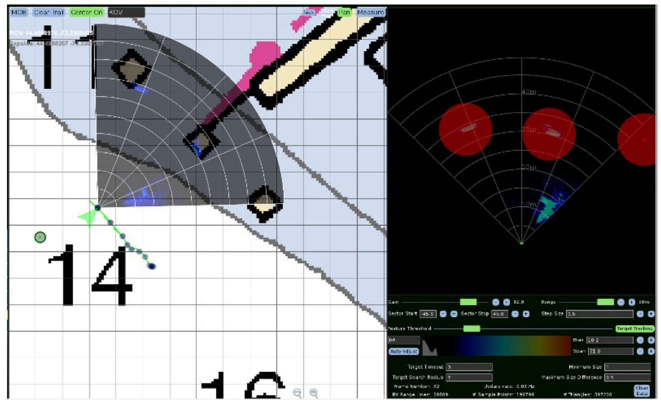

Illustration 11: The new feature has become a landmark and now the system is using three landmarks to stabilize the positioning solution.

The exercise above was conducted with a mechanically scanned imaging sonar. Mechanically scanned sonars present significant challenges for feature-based navigation due to the slow scan rate. The feature-based system uses inertial data from an IMU to provide an estimate of the tracked landmarks between scans and can thus provide a very high-rate positioning solution independent of the scan rate. As landmarks are imaged, the system can correct the inertial system, bounding error and drift with absolute environmental observations. The larger the scan interval, the greater the noise in the positioning solution will be due to the free inertial drift of the INS. This can be controlled, however, using higher-grade IMUs and faster scanning sonars, aiding the feature-based system with another input such as velocity from a DVL, or using a multibeam sonar. We have found the best results came from using a multibeam sonar. We show these results from a scanning sonar because the data illustrates the capabilities of this system in even the worst-case scenario.

With a multibeam sonar, such as a Tritech Gemini, and just a low-cost MEMS IMU, we find the positioning solution to be DVL+INS quality in a well structured environment.

5 Conclusion

Feature-based navigation and positioning has tremendous potential for ROVs. This technology provides a stable, robust, and accurate positioning solution relative to the ROV's work area. Recent technology advances in computational methods and software architecture have finally made this technology viable in a compact, embedded, and lightweight format. Further, the flexible and modular software framework provided by openSEA has enabled support for many forward looking sonars and other navigation instruments making this technology widely adaptable throughout the industry. Performance data illustrates the effectiveness and practicality of this technology for ROV positioning.

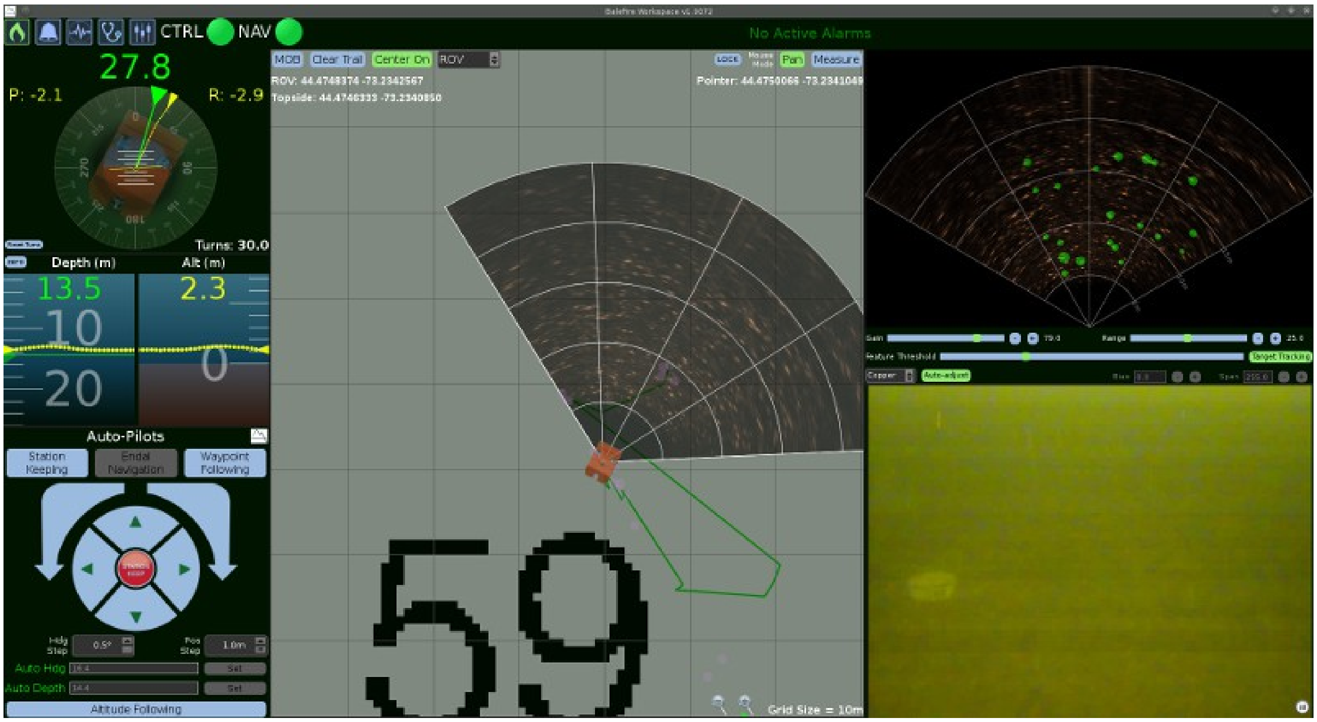

Illustration 12: Greensea's Balefire ROV control system interface with feature navigation active utilizing a Tritech Gemini multibeam imaging sonar.

6 Acknowledgements

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