Abstract—There is still much to learn about ocean ecosystems. Long-term, continuous observations of underwater environments can help improve our understanding. This is especially important as we continue to develop ocean energy resources. The Pacific Northwest National Laboratory (PNNL) and the University of Washington have developed a real-time processing system for sonar to detect and track animals, and to extract water column biomass statistics in order to facilitate continuous monitoring of an underwater environment. The Nekton Interaction Monitoring System (NIMS) is built to continuously process real-time streams of sonar data and archive tracking and biomass data, reducing the volume of stored data by orders of magnitude. The prototype system has been tested for real-time performance in the laboratory and in an operational environment on-board a research vessel and as part of a multi-instrument monitoring system. NIMS currently works with three types of sonar: a multi-beam sonar, a split-beam echo sounder and an acoustic camera.

Keywords—signal processing; marine technology; environmental monitoring; echo metrics; marine mammal detection

I. INTRODUCTION

There is still much to learn about ocean ecosystems. Long-term, continuous observations of underwater environments can help improve our understanding. This is especially important as we continue to increase ocean development for energy generation, resource extraction and aquaculture. Broad-scale ocean observatories provide valuable information about currents, temperature and other environmental characteristics at a macro level. For details of local communities that could potentially be affected by the operation of a marine renewable energy device, a different approach is needed. Active acoustics have been used for studying fish populations for decades, and advances in the quality and resolution of imaging sonars expands the applications for ocean ecosystem study. However, with better resolution comes more complex data streams and higher data rates, so that data storage requirements may preclude continuous observations and the analysis becomes more time-consuming. The solution is to process the data stream as it is acquired, extracting the available information in a concise form and discarding “dead time” when nothing of interest is happening.

In the study of environmental effects from ocean renewable energy, there is a shift in focus from individual species management to ecosystem management [1, 2, 3]. The emerging paradigm is to extract information from a stationary sensor for long-term continuous monitoring and reporting [4], [5]. Some effects are common to other ocean development like offshore oil and port construction but other effects are unique to marine energy conversion and must be understood to minimize cumulative effects as development progresses [6]. For example, more research is needed to understand effects of electromagnetic fields from subsea cables and sounds from energy generation on diadromous fish [7]. A framework for applying standardized methods that are scalable and transferable across sites is needed to facilitate ocean energy development [8]. Active acoustics are a promising technology for monitoring ecosystems due to the ability to acquire both individual animals tracks [9] and aggregate measures of biomass distribution [4].

The Pacific Northwest National Laboratory (PNNL) and the University of Washington (UW) have developed a real-time processing system for sonar to detect and track animals, and to extract water column biomass statistics in order to facilitate continuous monitoring of an underwater environment. The Nekton Interaction Monitoring System (NIMS) extracts and archives information about individual tracked targets and aggregate biomass statistics from a real-time stream of sonar backscatter data.

This work contributes to further understanding ocean ecosystems by providing an extensible architecture for real-time sonar processing designed for a stationary deployment. The technical achievements to date are:

- A real-time sonar-independent processing architecture.
- The real-time detection and tracking of individual animals in parallel with the statistical characterization of aggregate biomass.

II. NEKTON INTERACTION MONITORING SYSTEM

A. Operation

NIMS was designed for monitoring the water column around a marine renewable energy device such as a tidal turbine or wave energy device. The purpose of the system is to extract information about the environment from the sonar data stream. The extracted information is of two types: tracks and echo metrics. Tracks are the two-dimensional or three-dimensional motion of animals that move through the volume.
of water insonified by the sonar. Track information helps answer questions about the number and type of individual animals present – fish or marine mammals, when they are present, and possibly their behavior. Avoidance is one type of behavior that could be inferred from track data, and knowing whether animals actively avoid a marine energy device can help inform regulatory and permitting decisions. The echo metrics are aggregate measures of the abundance and distribution of animals in the water column, where the animals include fish and zooplankton. These measures can be used to help answer questions about how marine energy devices may affect patterns and dynamics in the pelagic zone over time. Changes in metric values indicate shifts in composition or behavior of the pelagic community. Comparing track and echo metric information among control and affected sites may reveal differences attributable to development or operation of a marine energy device.

The concept for operations is that a sonar system and NIMS are connected to a common local area network and NIMS receives the sonar data over the Ethernet (Fig. 1). NIMS processes the data as it arrives and archives the track and echo metric data to a storage location which could be a remote server or the cloud. NIMS can provide real-time tracking information over the local network that can be used by other systems to trigger instruments or take some action. A web-based user interface provides remote monitoring and control of the NIMS system as well as a live view of the raw sonar echograms.

NIMS was designed to be agnostic to the specific sonar transducer producing the backscatter data. Support for a sonar device is achieved by writing a code that translates the sonar’s raw data format to the NIMS internal data structure; more details on this are provided in the next section. NIMS currently supports three sonar devices: M3 multi-beam sonar (Kongsberg), EK60 split-beam echo-sounder (Simrad) and BlueView multi-beam imaging sonar (Teledyne). These devices are common tools used for bioacoustic studies, each having a particular strength. The EK60 provides long range coverage and three-dimensional spatial information; the M3 provides near to medium range coverage with a wide field of view and the BlueView is best for near range and higher resolution imaging. In the future, NIMS can be extended to handle data from additional devices.

The detection and tracking performance can be tuned by the user through configuration parameters (Table I). A NIMS deployment scenario would include a period of tuning the system to the particulars of the local environment, such as current speeds and directions. An operator would monitor the detections and tracks shown on the NIMS real-time display, and adjust the runtime parameters to find the right balance between false positives and missed detections, given the objectives of the deployment. Ideally the parameters would be tuned periodically to adjust for changing conditions.

The output of the system consists of both track information and echo metrics. The information saved for each track includes the start and stop time, the minimum and maximum ranges and minimum and maximum bearing angles at which the target was observed, the average speed of the target, the average size of the target, the total number of pings that the target was visible. The echo metrics consist of the following measures:

- Mean volume-backscattering strength as an indicator of nekton density,
- Area-backscattering strength as an indicator of abundance,

### Table I. NIMS Configuration Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Default Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Detection</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Background Moving Average Length</td>
<td>30 seconds</td>
<td>The interval of time over which the background mean and standard deviation are calculated. A longer window is less affected by transient signals at the cost of requiring more memory.</td>
</tr>
<tr>
<td>Detection Threshold</td>
<td>3 standard deviations</td>
<td>The threshold is given in units of standard deviations above the mean backscatter intensity.</td>
</tr>
<tr>
<td>Minimum Target Size</td>
<td>1 range bin</td>
<td>The minimum size for a detection.</td>
</tr>
<tr>
<td><strong>Tracking</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum gap in track</td>
<td>1 seconds</td>
<td>The maximum length of time a target may be undetected before considering the target lost.</td>
</tr>
<tr>
<td>Minimum track length</td>
<td>10 pings</td>
<td>The minimum number of pings in which a target was detected in order to consider the track valid.</td>
</tr>
<tr>
<td>Process Noise</td>
<td>0.1 (unitless)</td>
<td>For Kalman filtering, this noise can be considered the randomness of an animal’s motion through the water column.</td>
</tr>
<tr>
<td>Measurement Noise</td>
<td>0.001 (unitless)</td>
<td>For Kalman filtering, this noise is related to the spatial resolution of the sonar and the precision and accuracy of its acoustic response.</td>
</tr>
<tr>
<td>Maximum Prediction Error</td>
<td>15 range bins</td>
<td>The maximum difference between the position of a detected target and the predicted position of a tracked target in deciding whether the detected target is indeed the tracked target.</td>
</tr>
</tbody>
</table>

![Fig. 1. NIMS operational concept.](image)
Center of mass as an indicator of the location in the water column of the biomass
Inertia as an indicator of the dispersion of nekton
Proportion occupied and equivalent area as indicators of the evenness of the distribution of biomass
Aggregation index
The number of distinct scattering layers in the water column.

B. Architecture

NIMS was designed to process sonar data in real-time. The system architecture is composed of multiple processes running in parallel, using shared memory and messaging to share data (Fig. 2). The prototype is built on a small-footprint, fanless computer (Table II). The operating system is Linux Mint and the code is written in C++ and Python. The first stage of processing is a translation from an instrument-specific data format to the NIMS internal data structure. The echo metrics are calculated on this raw data. For tracking, the second stage of processing is the detection of strong scatterers and Kalman filter tracking.

The ingester module receives the data from the sonar device, translates it into the NIMS data structure and posts it in shared memory for consumption by the detector and echometrics modules. The ingester uses a pure virtual data source class so that the type of sonar can be specified at runtime. The NIMS data structure includes a header containing metadata and the ping backscatter data as a two-dimensional matrix $I$ of intensity values. Each row of the matrix corresponds to a range bin and each column corresponds to a bearing angle. The matrix cell $I(m,n)$ is the intensity of the backscatter at range $m$ and bearing $n$.

The detector module detects targets—strong scatterers—in the backscatter data from each sonar ping. Strong scatterers are identified by comparing the current ping backscatter data to the time average backscatter of the scene (Fig. 3). The backscatter statistics are calculated independently for each cell in the backscatter data matrix over a moving window, the length of which is specified by the user. A binary mask is used to select the strong scatterers in the mean-standard deviation representation [10],

$$I_D(m,n) = I(m,n) > (\mu(m,n) + T\sigma(m,n)),$$

where $m$ is the index of the range bin of the cell and $n$ is the index of the beam, $I$ is the backscatter intensity matrix, $\mu$ is the mean intensity of the cell, $\sigma$ is the standard deviation of the intensity, and $T$ is the detection threshold specified by the user.

![Fig. 2. NIMS Architecture](image)

![Fig. 3. Targets (c) are detected by comparing the current ping backscatter data (a) to the time average backscatter of the scene (b). The data is from a BlueView recording of a fish passage structure.](image)

**Table II. NIMS Computing Platform**

<table>
<thead>
<tr>
<th>Computer</th>
<th>Fit-PC IPC2 i7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Processor</td>
<td>Intel i7-4600U, 64-bit dual core, 2.1 GHz with turbo boost up to 3.3 GHz</td>
</tr>
<tr>
<td>Memory</td>
<td>16 Gb</td>
</tr>
<tr>
<td>Networking</td>
<td>2 x GbE ports</td>
</tr>
<tr>
<td>Storage</td>
<td>250 Gb solid state drive</td>
</tr>
<tr>
<td>Operating System</td>
<td>Linux Mint</td>
</tr>
</tbody>
</table>
Connected cells in the mask are grouped together into a single detection that is characterized by a center of mass, maximum intensity, length, width and orientation. The detected targets for each ping are sent in a message to the tracker module.

The tracker module maintains a list of active tracks. A track is defined as a sequence of detections. A track is initialized with a Kalman filter that is used to predict the next position of the tracked target. The detections reported by the detector module are compared to the predicted positions of each active track and assigned to the closest match within a user-specified maximum prediction error. If a new detection is assigned to an active track, then the position of the new detection updates the track’s Kalman filter and the detection counter for the track is incremented. New tracks are started for any detections that are not assigned to an active track. If an active track is not updated for a user-specified amount of time, then the track is removed from the active track list. If the track contains the minimum number of detections, then it is archived in the track database. The tracker then sends the updated list of active tracks to the webapp module and to the external track server.

The echo metrics are calculated using the open-source Python code available at:


The details of the calculations are provided in [8].

III. TEST AND EVALUATION METHODS

The prototype system has been tested in the laboratory using annotated pre-recorded sonar data files and simulated data to verify real-time data throughput and long-term, continuous operations. The system has also been tested in an operational environment onboard a UW research vessel and as part of a multi-instrument monitoring system deployed in Sequim Bay at PNNL’s Marine Sciences Laboratory.

A. Laboratory Tests

To test the operation of the software, an M3 simulator was developed that played back pre-recorded M3 data files. The M3 sonar has the highest data rate of the three supported sonar devices, so it is most computationally intensive to process. The simulator plays a recording first forward then in reverse, then forward again in a continuous loop. The simulator modifies the ping numbers in the recorded data so that the output stream of ping data has monotonically increasing ping numbers. This forward-reverse looping prevents the discontinuity in both background statistics and target motion induced when playback is restarted from the beginning of the file. The simulator can run at a user-specified ping rate. The simulator was configured to run at 10 Hz and to play back a pre-recorded M3 data file in order to test both long-term operation and real-time data throughput. NIMS was started and left to run for 48 hours. The NIMS log files were then analyzed to verify that all pings were processed, and to determine the processing time per ping for each module. The system was also checked to verify that there were no memory leaks in the software and no failures over the 48-hour test period.

B. Field Tests

In addition to the laboratory tests, NIMS was tested with the Adaptable Monitoring Package (AMP), a multi-sensor package that was deployed in Sequim Bay, WA from January 6, 2016 through May 2, 2016. The AMP includes an M3 multi-beam sonar, along with hydrophones, an acoustic camera and optical cameras [11]. NIMS was connected to the AMP’s instrument network and configured to receive the AMP’s M3 data packets and to send tracking messages to the AMP software. The purpose of the test was to verify NIMS operation as part of an instrumentation network.

NIMS was tested with an EK60 and an M3 in an operational setting onboard the R.V. Centennial in the waters around San Juan Island, WA. The EK60 is mounted to the vessel’s hull and connected to the ship’s instrumentation network. The M3 was temporarily mounted with a pole to the side of the vessel. During the test, NIMS was connected to the network and configured to receive the EK60 data stream during some periods when the vessel was underway and to receive the M3 data stream for a controlled target test while the vessel was stationary. The controlled target test consisted of moving a calibration sphere through the water column within the M3’s field of view.

IV. RESULTS AND DISCUSSION

C. Real-time Performance

The critical path of data throughput is from the ingester module to the detector module to the tracker module. The processing time of each of these modules was measured using the timestamps of the log messages that indicate the start of each module’s main loop (Table III). The log messages are timestamped to the nearest microsecond. Each module processes the data from one sonar ping in its main loop, blocking at the start of the loop to wait for a message from the previous module in the processing chain. The message queues act as buffers, so that a module can put its results in the queue and move on to start processing the next ping. In other words, more than one ping will be in the pipeline at any given time. Therefore, the maximum processing time of the three modules in the critical path is a good indicator of the expected throughput.

Based on these results, NIMS could process M3 sonar data in real-time up to a ping rate of 2 Hz, which is sufficient for long-term monitoring applications. No explicit attempt at optimization was made for the initial prototype beyond best programming practices. With optimization, future versions could conceivably achieve higher rates, if that was needed.

D. B. Data Reduction

Data reduction was quantified in terms of the bytes required to save track information and echo metrics relative to the raw
data rate of the sonar instruments (Table IV). The actual data reduction during a period of time depends on raw data rate of the sonar, the number of animals detected and tracked, and on the frequency at which the echo metrics are calculated.

<table>
<thead>
<tr>
<th>Sonar</th>
<th>Estimated Data Rate¹ (Megabytes per hour)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M3 multi-beam sonar (Kongsberg), Imaging 15 mode, 5 Hz ping rate</td>
<td>8800</td>
</tr>
<tr>
<td>EK60 70 kHz split-beam sonar (Simrad), 1 Hz ping rate</td>
<td>200</td>
</tr>
<tr>
<td>BlueView 900 kHz acoustic camera (Teledyne), 9 Hz ping rate</td>
<td>744</td>
</tr>
</tbody>
</table>

¹ Data rates were estimated based on file sizes recorded during testing.

The track data are recorded as text in a comma-separated variable (csv) file. For each completed track, a total of 158 characters including a newline are written to the file. Assuming 8-bit characters, each track requires 158 bytes of disk storage. The echo metrics consist of eight values that are calculated for each ping. Storing the values as text with a fixed width of 6 characters generates 54 bytes per ping including commas and a newline character.

To quantify the data reduction, consider a hypothetical one-hour recording where 100 animals were tracked. The data stored would be the track csv file and the echo metrics csv file. The track csv file would have 100 data rows and a total size of less than 20 kilobytes. The echo metrics time series of 3600 pings (metrics calculated at 1 Hz) would have a size of less than 200 kilobytes. Therefore, the data reduction for the EK60, the sonar with the lowest raw data rate, would be 200 Mb reduced to 0.220 Mb or a 1:1000 reduction. The reduction would be greater for the other higher data rate sonars. The data rate of less than a quarter of a megabyte per hour is one that is sustainable over long periods of time, with data being stored onboard NIMS and periodically offloaded via cellular or satellite communications. Saving the data in a binary database format would increase the data reduction further.

IV. CONCLUSION

As sonar technology continues to evolve, NIMS can be extended to grow along with it. The combination of aggregate biomass statistics and individual animal tracks presents a more nuanced picture of the marine ecosystem than either one of those measures alone.

Future work will be focused on improving the detection and tracking algorithms, improving the format and content of extracted information, and adding an off-line processing mode to batch process recorded raw data. To improve the detection function, dynamic mode decomposition could be incorporated to increase the signal-to-noise ratio of targets and reduce false detections. The tracking could be improved by using shape and target strength to discriminate between true and false target detections more accurately. Another future improvement will be to archive the track and echo metric data in a binary database format that is more efficient than the current text-based csv file format. The development of benchmark data sets with annotated tracks would benefit further development of NIMS and other similar systems aimed at automated detection and tracking in sonar.

The ability to process sonar data in real-time opens up new possibilities for understanding ocean ecosystems at a level of detail and temporal scale previously unavailable. The ability to use the same system with different sonar instruments gives researchers and regulators flexibility in selecting instrumentation to meet their objectives, and helps standardize the use of sonar for ocean observations.

ACKNOWLEDGEMENTS

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REFERENCES