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Visualizing the Underwater Behavior of Humpback Whales

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Until recently, scientists knew little about what whales did underwater. Studying the underwater behavior of marine mammals is difficult; light doesn't travel far through water, and divers can't keep within visual range of an animal capable of sustained speeds of 5 knots. Scientists can use sonar technologies to image marine mammals underwater, but sonar records provide only occasional brief glimpses of whales underwater.

A new collaboration between visualization experts, engineers, and marine biologists has changed this. For the first time, we can see and study the foraging behavior of humpback whales. This is important not just for purely scientific reasons. Whales are dying because of ship collisions and entanglements with fishing gear in ever-increasing numbers. Understanding their behavior could lead to changes in shipping regulations or in the nature and deployment of fishing apparatus.

Our study's primary objective was furthering the science of marine mammal ethology. We also had a second objective: field testing GeoZui4D, an innovative testbench for investigate effective ways of navigating through time-varying geospatial data. The study involved two expeditions, one in 2004 and another in 2005, in which we tagged whales and recorded their movements.

1 The digital recording acoustic tag (DTAG) is attached to a whale using suction cups. Scientists place the DTAG on the whale from an inflatable boat using a 45-foot carbon fiber pole.

Recording whale behavior

The digital recording acoustic tag,[1] shown in Figure 1, is the key technology allowing us to see underwater whale behavior. DTAG is a recording device containing several instruments. Three axis accelerometers provide information about the gravity vector's direction, three axis magnetometers measure the direction of the earth's magnetic field, a pressure sensor provides depth information, and a hydrophone continuously records sound. Except for sound, which is recorded at 64 kHz, all instruments record at 50 Hz. DTAG merges and compresses data records to be stored on 3 gigabytes of flash memory. DTAG is about 10 centimeters long, excluding the antenna, and is attached to a whale's back using suction cups. After some preset interval, typically 10 to 22 hours, DTAG automatically releases suction and floats to the surface. Once it's on the surface, a ship can locate it by its radio beacon. The ship picks up the DTAG, and scientists download the data.

To place the tag, scientists attach it loosely to the tip of a 45-foot carbon fiber pole, mounted (as Figure 1 shows) with a gimbal on a rigid hull inflatable boat's (RHIB) bow. Placing the tag on a whale isn't easy given that a whale usually only surfaces for a few seconds at a time. The operation requires careful timing and coordination between the boat driver and pole handler.

Scientists analyze the DTAG data to produce a pseudotrack. This is only an approximate estimate of the animal's path because DTAG doesn't give information about speed through the water. Therefore, scientists must derive the pseudotrack using a form of dead reckoning. The cross-product of the magnetometer vector with the gravity vector (from the accelerometers) provides heading information. Together, heading and gravity provide 3 degrees of freedom of orientation for the tag.

It's still necessary, however, to deduce the tag's placement on the whale. This involves selecting a part of the track where the whale is at the surface and assuming that the animal is horizontal and moving forward. Direct observation can verify this assumption. After scientists

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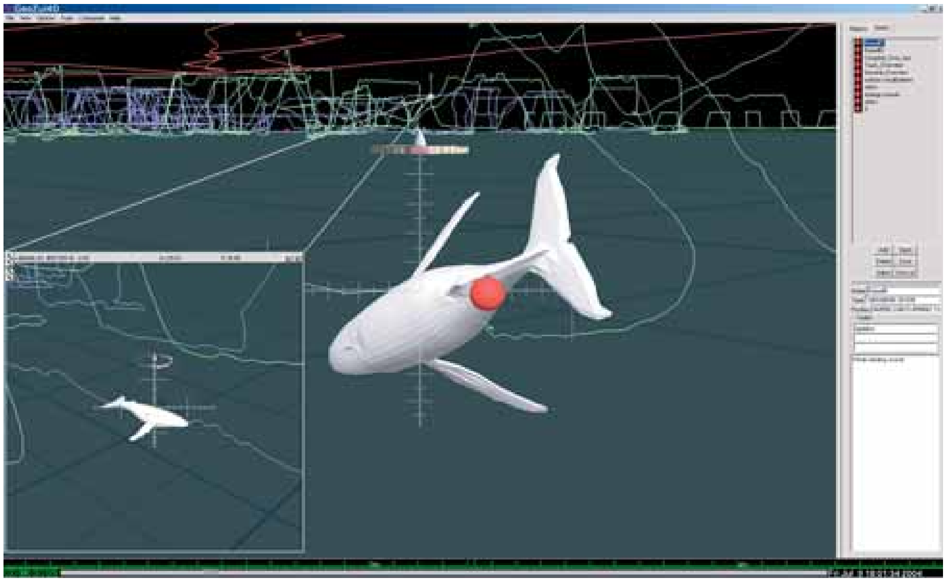
have obtained a continuous record of whale orientation, they assume that the animal is moving forward at a constant velocity except when it's diving steeply. In this case, depth changes from the pressure sensor data provide direct information about downward velocity. Scientists can correct the pseudotrack based on sightings of the whale when it surfaces.

We also gathered data about several vessels in the vicinity. This included GPS time-series data from the US National Oceanic and Atmospheric Association's *Nancy Foster* and the two RHIBs. We obtained the positions of fishing boats within a radius of approximately 10 nautical miles using the *Nancy Foster*'s radar.



2 GeoZui4D showing two tagged whales together with the whale tracks and the tracks of several surface vessels.

Replaying whale behavior with GeoZui4D

Our first approach to visualizing the data was to construct a tool for interactively replaying whale motion, together with sound recorded by DTAG. To accomplish this, we added features to GeoZui4D, a software application we developed to investigate methods for interacting with time-varying geospatial data.[2]

As a basic navigation method, GeoZui4D uses what we call *center of workspace* navigation. The user positions the cursor on an object or region of interest and clicks the middle mouse button. This causes the point to move to the center of the workspace, a point just behind the screen in the viewing frustum. While holding the button down, the user can scale up or down around that point by moving the mouse. Three-dimensional widgets let the user rotate the scene around the point of interest. A suite of interaction techniques extend center-of-workspace navigation, and have proven extremely useful for analyzing DTAG data.

Attaching to a moving object

Figure 2 shows the GeoZui4D interface. With a mouse click, the user can attach the center of workspace to a moving object. This lets the user follow the whale on its pseudotrack and watch its motions while listening to the various sounds picked up by the DTAG. The user can simply attach the center of the workspace to the whale, or follow along behind, changing orientation as the whale changes its orientation. Clicking on a point not on the whale instantly changes the view to a world frame of reference, providing a different perspective and different insights. In this case, however, the whale will often swim out of the view field.

Users can create an extra window through a menu selection and attach it to a moving object using the same center-of-workspace one-click operation. (In Figure 2, the main window view is attached to the foreground whale and the subwindow view is attached to a whale shown in the distance in the main view.) The second window has several uses. For example, it provides a continuous view of a different whale or tracks the path of a ship in the vicinity. GeoZui4D also provides range markers showing one object's relative bearing and distance relative to another. These features help scientists understand shipping's possible effects on whale behavior.

We added the capability to play back recorded sounds in such a way that the sounds are in temporal synchrony with various other time-varying objects (such as boats, which are also represented in the scene). This gives scientists studying marine mammals an unprecedented way to watch and listen to whales as they forage. Although ethologists studying land animals take this capability for granted, it has not previously been available to those studying marine mammals.

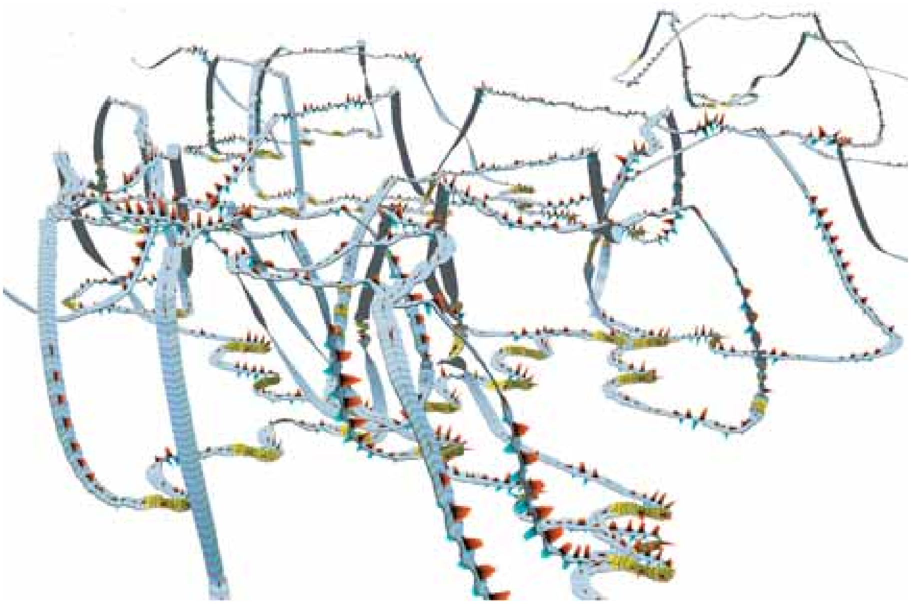
Space-time notes

We implemented space-time notes specifically to support the ethological analysis of whale behavior. Our space-time notes encapsulate the following variables:

- a point in space (the center of the workspace where the note was created) or "look-at" position,
- a view direction relative to the look-at point,
- a view scale,
- a point in time at which the note was created,
- a playback rate,
- a name for the note (entered by the user), and
- typed-in textual information.

Space-time notes mark and record interesting behaviors. They're also effective in presentations because they let presenters select a few interesting or representative actions from hours of recording.

The panel on the right-hand side of Figure 2 is the space-time notes interface panel, which supports note creation and activation. Fields in the panel support the



3 **TrackPlot showing several hours of whale foraging behavior. This is an oblique view looking down on the water. The animal is mostly either at the surface or on the bottom, with steep transitions between.**

behavioral coding performed by ethologists. Clicking on the "save" button produces a file with a simple XML tagged format.

TrackPlot

Although GeoZui4D is an effective tool for observing whales' underwater behavior, it suffers from the problem of all visualizations that show time-varying data as an animated replay. Showing instantaneous behaviors might not be the best way to reveal patterns occurring on longer temporal scales.

Often, the best way to look at temporal sequence data is to turn it into a spatial pattern. Accordingly, we developed TrackPlot, a tool that uses a custom-designed ribbon to represent tracks. TrackPlot effectively reveals a variety of behaviors.

The ribbon's center is the pseudotrack center. It's two meters wide and is twisted around the along-track direction to show roll behavior. A pattern of chevrons on the top surface of the ribbon reveals travel direction and gives an additional orientation cue. Figure 3 shows a ribbon representing several hours of foraging behavior. As the figure shows, the whale is either at the surface getting air, or on the bottom—about 90 meters below the surface—searching for food. Ascents and descents between the surface and the bottom are steep.

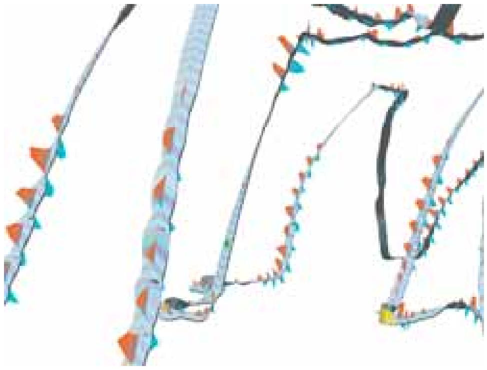
In GeoZui4D replays, we occasionally saw cyclic attitude changes that we took to indicate the whale's fluke strokes. We added a feature to TrackPlot to make these more visible. We differentiated the pseudotrack twice about a lateral axis to obtain angular accelerations. The sawtooth patterns in Figure 4 (red above, blue-green below the dorsal and ventral sides of the ribbon) represent these angular values. The sawtooth's amplitude reveals the amount of angular acceleration at any given instant.

This visual representation reveals several interesting behaviors. Figure 4 shows a clear difference between swimming on ascent and on descent. On ascent, the whale swims strongly up to within about 20 meters from the surface, then glides the rest of the way. Conversely, on descent (only one of which is shown, the third track from the left), the whale swims down for only a few meters and glides the rest of the way as its lungs collapse and it loses buoyancy.

In Figure 5, the angular acceleration plot reveals burst and glide swimming, a mode of swimming that conserves energy. Whales generally use this mode for longer traversals.

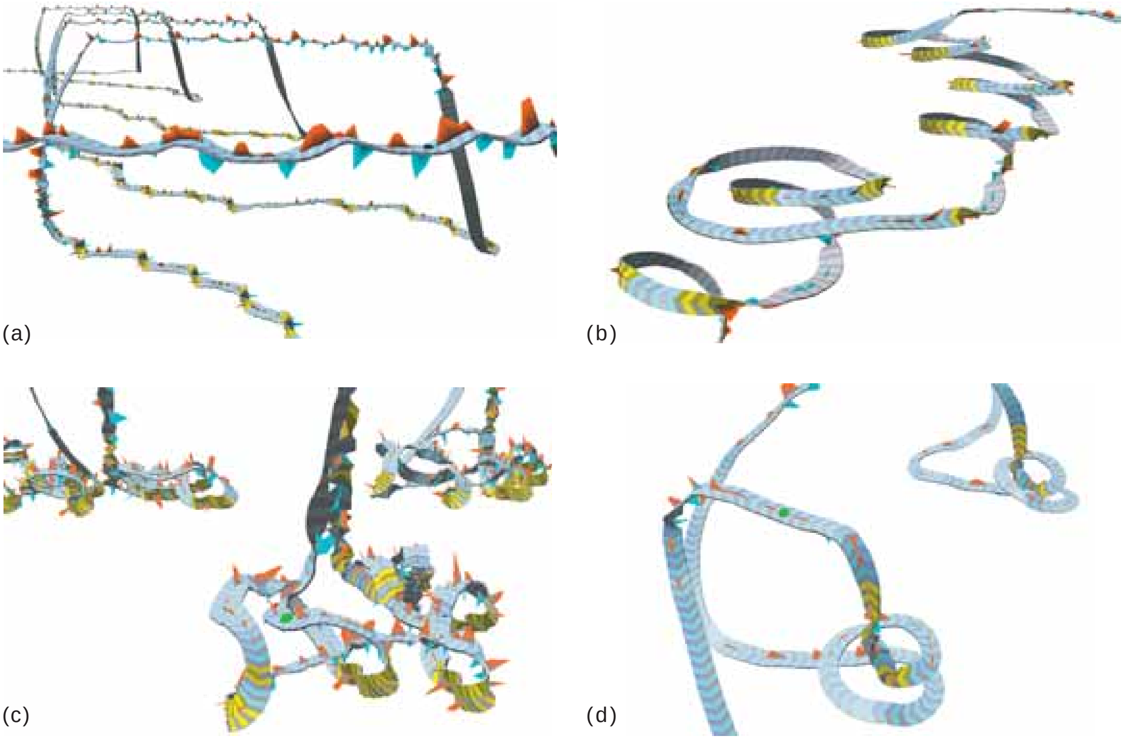
Prior to our study, researchers had hypothesized that humpback whales sometimes forage for sand lance (a small fish species) by rolling on their sides and opening their mouths while at the seabed. One piece of evidence of this behavior was scarring on some whales along one side of their mouths.

GeoZui4D showed side rolls near the bottom, as shown by the whale's orientation in the main window in Figure 2. But TrackPlot was much better at bringing out patterns of side-roll behavior, revealing that they occurred on almost all dives, for all whales, and usually with several per dive. To make side rolls more distinct in the visualization, we color-coded them yellow when the roll exceeded 40 degrees. Figures 6a, 6b, and 6c show side-roll patterns from three different animals. All



4 **The red and green sawtooth patterns above and below the ribbon reveal whale fluke strokes.**

5 **Burst and glide swimming patterns.**



6 **Four examples of foraging patterns: (a) straight lines with side rolls, (b) repeated side-roll loops with inversion, (c) tightly clustered swimming patterns with side rolls, and (d) bubble-net production.**

of them exhibited this behavior but in the context of several different foraging patterns. The ubiquitous nature of side rolls leads us to believe that the whales tagged in 2004 were almost exclusively engaged in foraging for sand lance on the seabed.

We found one other foraging pattern in the whales tagged in the 2004 season. One of the whales showed three patterns we believe represent bubble-net feeding. Figure 6d shows the TrackPlot view illustrating this behavior. Here, the whale swims in a circle at about 30 meters depth emitting bubbles from its blow hole. The bubbles form a net containing the fish and the whale then lunges up with its mouth open to engulf the trapped fish.

We centered the TrackPlot interface both conceptually and literally on the ribbon at a particular point in space and time designated the *current_point*. TrackPlot always translated this point to the workspace center. We navigate forward and backward along the track by tabbing and shift-tabbing, respectively, causing the *current_point* to move forward and back along the track while remaining locked to the workspace's center. Users can rotate the view around the center using the mouse and the left mouse button.

To analyze track sections, we can set a marker at the *current_point* with a key selection, causing a small sphere to appear at that point on the track. When we move the *current_point*, the marker defines a section of the track (between the marker and the new *current_point*). We can then subject this section of track to various kinds of analysis through menu selections. For example, we can automatically compute fluking wavelength or the number of side rolls.

Different behavior

Thus far we've concentrated on visualizations developed to help analyze the behavior of whales tagged in 2004. In the 2005 expedition, the whales showed very different behaviors.

We thought the whales tagged in 2005 to be foraging mainly for krill, which were abundant at that time. When foraging, they were usually only a few meters below the surface, as Figure 7 shows. This behavior makes them highly vulnerable to ship collisions, because

7 **The pink transparent vertical band shows the whale, foraging for krill, to be extremely vulnerable to ship strikes from vessels such as the tanker (top) that we spotted in the shipping lanes departing from Boston.**

they're mostly out of sight just beneath the surface. To illustrate this vulnerability, we added a pink vertical color band running though the whale track to a depth of 8 meters. This is about the draft of a modern tanker or freighter, making it dramatically clear that the whale is spending most of its time in the danger zone.

Future directions

We plan another tagging project for June 2006. One thing we hope to accomplish is a better understanding of how the foraging whales interact with the seabed. No detailed maps of the seabed existed for the region of the 2004 expedition (it's a little-known fact that we have much better maps of the entire surface of Mars than of 95 percent of the ocean floor). This year, we'll have a state-of-the-art multibeam sonar on the ship that will let us map seabed features, such as large sand waves, and incorporate them into the visualization. This should help us understand how the whales maneuver with respect to the terrain beneath them. In the meantime, we're continuing our investigation into the best ways of letting users interact with time-varying geospatial data. ■

Acknowledgments

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