# Real-Time Visualizations of Ocean Data Collected By The NORUS Glider in Svalbard, Norway

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## ABSTRACT

Modern robotics and sensors have expanded the ability to collect science data in underwater settings. Oftentimes, the collected data are deposited into files and databases where they sit in their separate and unique formats. Without easy to use visualization tools, it is difficult to understand and interpret the information within these data sets. NORUS, the North America-Norway educational program, has a scientific focus on how climate-induced changes impact the living resources and ecosystems in the Arctic. In order to obtain the necessary science data, the NORUS program utilizes the Slocum Glider, a form of underwater robot. We present a compelling, efficient, and easy to use interactive system for visualizing large sets of science data collected by the Slocum Glider. This goal is obtained through the implementation of various methods taken from scientific visualization, real time rendering, and scattered data interpolation. Methods include visualizations of the surrounding terrain, the ability to map various science data to glyphs, control over color mapping, and scattered data interpolation.

KEY WORDS: Scientific Visualization, Slocum Glider, Scattered data interpolation

## INTRODUCTION

The oceans are an important focus of scientific study and exploration. They cover over 70% of the earth's surface, are a significant source of food for a large part of the planet, and due to the impact of global warming, are increasingly central to predicting how our climate will evolve during the next century. An ocean is a complex, highly interconnected environment. A full description of an ocean must include not just physical characteristics, such as temperature and currents, but chemical, biological, and even geological parameters (Bellingham and Godin, 2008).

NORUS, the North America-Norway educational program, has a scientific focus on how climate-induced changes impact the living resources and ecosystems in the Arctic. In order to obtain the necessary science data, the NORUS program utilizes the Slocum Glider, a form of underwater vehicle or robot. To facilitate the understanding of the data acquired from the glider, we have developed a compelling, efficient, and easy to use interactive visualization system. Using methods from scientific visualization, real-time rendering, and scattered data interpolation, the system allows the user to visualize the setting where the data was collected and the science data.

The system uses a generic mesh loader to generate an accurate and compelling environment. The look of the environment is obtained through the use of multitexturing to produce detailed terrain, a quasi-realistic ocean surface with reflection, refraction, and specular highlighting, and simple animated clouds generated by 3-D Perlin noise. Various user configured scientific visualizations allow the user to analyze the measurements taken by the glider. They include glyphs that display the discrete data measurements and interpolated visualizations such as isosurfaces, gradient planes, and volume slices that provide interpolated values across surfaces. An interactive camera control allows the user to freely move through the environment and a virtual glider retraces the physical glider's mission path. Finally, an intuitive graphical user interface provides the user with the highest possible level of customizability across the entire system.

Initial feedback from NORUS biologists working on the project conveyed enthusiasm for a tool that allowed them to visualize their data in a virtual environment. Many of the tools included in the system were defined and refined through feedback from biologists about what they would like to be able to see and what parameters they needed to be able to control. The primary dataset used for this project was from a glider deployment in a fjord of Svalbard, Norway. The glider's mission spanned from longitude 13.3042˚ East to 16.6875˚ East and latitude 78.1042˚ North and 78.7042˚North. The 17-day mission began on June 30, 2009, during which time the glider collected 242,693 measurements for each of the on-board sensors. The visualization system was written entirely in C++, using OpenGL and GLSL for graphics and Qt for rapid development of a platform independent graphical user interface. It allows for the real-time rendering of offline ocean data containing upwards of 250,000 measurement points across more then 20 different sensors.

## RELATED WORK

Several visualization systems have been developed for specific underwater visualizations. While these related works provide solutions for their setting, the system presented in this paper is designed specifically to generate real-time visualizations for ocean science data collected by the NORUS glider. Our system was designed from the ground up, without the use of existing visualization libraries, to achieve the maximum amount of configurability.

Some related systems include the underwater virtual world developed at the Naval Post Graduate School [Bruztman, PhD Dissertation]. The goal of the research was to create an underwater virtual world that could comprehensively model all necessary functional characteristics of the real world in real-time. The virtual world was meant to provide AUV developers with the complete functionality of a submerged environment in the laboratory.

Other examples include, Collaborative Ocean Visualization Environment (COVE), which is a set of collaborative tools used to support deep-water ocean observatories. These observatories allow hundreds of scientists from various fields to conduct experiments together, provide real-time sensor and data access though the internet, and create a vast archives of data (Grochow, 2009). Related work designed by the Monterey Bay Aquarium Research Institute (MBARI) in 1999 (McCann, 2002) was aimed at creating 3-D oceanographic data visualizations for the web. Chapman, Wills, Stevens, and Brookes (1999) present a system that generates post-survey visualizations of underwater pipelines using real-time rendering. Research presented by the same authors describes a system that generates real-time visualizations of the clear-up operation of a former U.S. Nuclear Submarine Base located in Holy Loch, Scotland (Chapman, et. al., 2000).

Another important field of related work is scattered data interpolation. As the NORUS glider gathered discrete data points, scattered data interpolation is essential for constructing visualizations of interpolated data. The problem of generating a continuous interpolation function for scattered data is encountered frequently in a wide variety of scientific disciplines and has been researched extensively. Several survey papers exist that provide in depth looks at a wide variety of methods (Alfred, 1989; Barnhill, 1977; Schumaker, et. al., 1976; Franke, 1982). For example, the Shepard's Method utilizes inverse distance weighting, an approach where a sample point's influence on the interpolated value is inversely related to the distance from the input position (Shepard (1968; Alfred, 1989; Schumaker, et. al. 1976).

For this project, we found that scattered data interpolation was best-achieved using radial basis functions. Radial basis functions (RBFs) are a simple and useful tool for interpolating data in almost any number of dimensions. Given a set of data points with associated values, RBFs construct a smooth and continuous function, which interpolates the values at each data point.

## SYSTEM AND ALGORITHMS

The system includes support to visualize the general environment, terrain, ocean, and glider in addition to the visualizations of the science data. The terrain for the mission's extent is generated from bathymetry data retrieved from the National Geophysical Data Center (NGDC). NGDC provides global bathymetry at resolutions of 30 arc-seconds and greater. Figure 1 provides different views of the terrain for the Svalbard mission. To create a compelling looking environment, the bathymetry data is drawn as a triangle mesh, which is multitextured to produce a detailed looking terrain mesh. The multitexturing provides clear differentiation between surfaces that lie above and below the sea level. In an attempt to further that goal, a compelling and quasi-realistic ocean surface was implemented. Using a normal map, dudv map, two additional rendering passes, and GLSL shaders, it is possible to render a compelling ocean surface with only a single quad. Reflections were implemented to create a more realistic and appealing ocean surface. This adds an additional rendering pass where only the terrain above sea level is rendered. The terrain is reflected about the y-axis and rendered to a texture that is then mapped to the quad serving as the ocean surface. The system also provides a simulation of refraction and specular highlights, shown in Figure 1, as well as clouds using a 3D Perlin noise function. An exaggerated vertical scale is used to assist in viewing the data underwater.

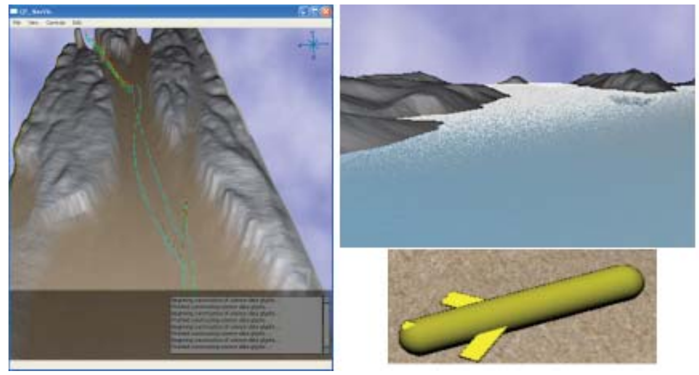

Figure 1: On the left is an aerial view of the Svalbard fjord along with the mission path. On the right is a view of the specular highlighting that occurs on the ocean surface and the graphic representation of the glider.

In order for the user to best navigate the data and environment, the system includes an interactive camera and heads up display. The heads-up display provides the user with updates on the status of visualizations being constructed in the background. The compass provides directional orientation within the scene and is used primarily for assisting the user in specifying spatial constraints for visualizations. The application provides a simple 3-D representation of the physical glider as it travels along the mission path. Its purpose is to give the user an idea of how the glider moves while collecting science data. An approximation of the glider's mission path is constructed for use in the animation of the computer generated glider and the construction of the mission defined gradient planes. Figure 3 shows a portion of the approximated mission path constructed for the Svalbard mission.

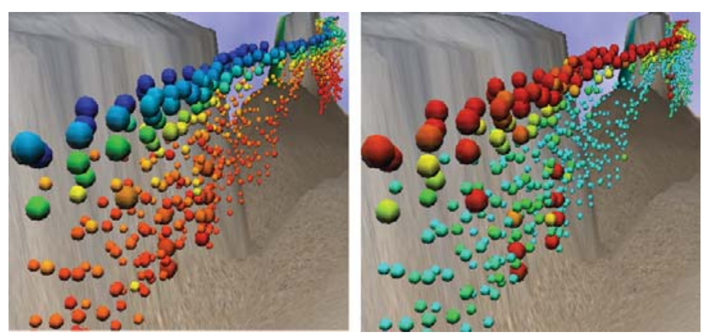

Figure 2: On the left is view with glyph size being mapped to chlorophyll levels and color being mapped to salinity levels. Smaller sized glyphs correspond to lower levels of chlorophyll, while blues correspond to lower salinity values. On the right is a view of the glyphs with both size and color mapped to chlorophyll.

### Scientific Visualizations

The primary goal of the project was to generate scientific visualizations that would allow the biologists associated with NORUS to locate areas of interest within the dataset as well as determine correlation between variables. The biologists are interested in understanding how variables such as salinity, chlorophyll, turbidity, and temperature interact with each other. To meet this goal, the system supports visualizing glyphs and various interpolated data visualizations. Within the application, glyphs are represented as spheres whose color and size can be mapped to different scientific variables. The user is provided with a configuration window to customize all aspects of how the glyph visualizes discrete data. Figure 2 shows a view with the glyph size and color being mapped to different variables. The ability to independently manipulate a glyph's size, color, orientation, and transparency provides the opportunity to map multiple variables to a single glyph. Glyphs can be filtered by value, time and/or space.

The utility of simple glyph visualizations is shown in Figure 2. For example, the image on the right provides a view of the glyphs with size mapped to chlorophyll and color mapped to salinity. Dark blue corresponds to the lowest values. The image quickly conveys that the salt content is lowest at the surface of the water and increases steadily until approximately one third of the glider's maximum depth, where it stays fairly consistent.

The use of scattered data interpolation allows the application to generate compelling visualizations across surfaces where the glider may not have directly traveled but where there is substantial discrete neighboring data. For example, the system allows for the visualization of gradient planes and entire volumetric regions of interpolated data that can be visualized as volume slices or isosurfaces. The next section explains the scattered data interpolation used in the system, while we give example overviews of the interpolated scientific visualization types here.

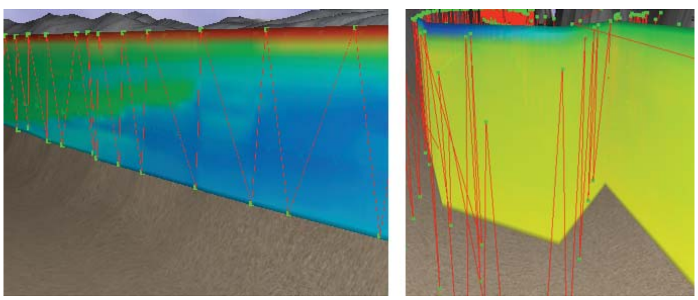

Figure 3: On the left, an image shows a gradient plane that corresponds to the mission path, while on the right, the image shows a user defined gradient plane that crosses the mission path.

Gradient planes are used to visualize interpolated science data as color mapped 2D planar surfaces rendered in the 3D environment. Using a radial basis function interpolator, the application generates smooth value gradients across the surface of the plane from the original sampled data. By constructing the interpolation function with overlapping data samples, the system is able to interpolate more appropriate values for regions lacking adequate data samples. The system supports both mission path defined gradient planes and user defined gradient planes. Figure 3 shows how the mission defined gradient plane corresponds to the control points of the mission path. Figure 3 shows a user defined gradient plane that does not correspond to the mission path. The user defined gradient planes allow the user to specify time constraints on the data samples used to generate the radial basis functions because the glider does move at a fairly slow speed, so some samples may be excluded if they are from a significantly different time frame.

In order to minimize the number of triangles required to render the gradient planes at an adequate resolution, a simple form of texture mapping was implemented into the system. Bounding vertices can be computed for any gradient plane, which is then subdivided in order to obtain an adequate resolution. Rather then store and render these quads the application generates textures that store the interpolated data. In order to maintain the highest possible level of customizability, all aspects of the user and mission defined gradients planes are customizable, including, color range, color value range, time constraints, and spatial constraints.

Data can be interpolated both across a single gradient plane and in a volume of space in the environment. Such an interpolation makes sense in regions where the glider's path has crossed a region twice (see Figure 3 and 4 for example regions). Scattered data interpolation is applied to an entire volumetric extent defined by the user. Volume slicing provides a method for visualizing interpolated values across planar surfaces within a volume of interpolated data. Volume slices can be oriented in the X-Y, X-Z, or Y-Z planes. The user is able to specify the volume extent that the slices span, the resolution of each slice, and the variable used to generate the interpolation functions.

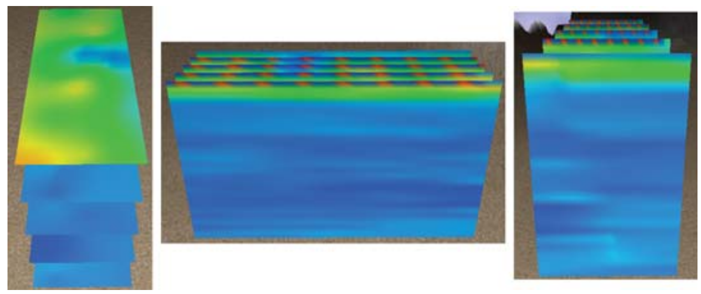

Figure 4: These images show the three different orientations for the chlorophyll mapped volume slices, on the left is X-Y planes, the center is X-Z planes, and the right is Y-Z planes.

Another compelling visualization option for the interpolated volume data is to extract an isosurface of a given scientific data value. An isosurface is a surface that represents points of a predefined constant scalar value within a volume. Isosurfaces are extracted using the Marching Cubes algorithm (Lorensen and Cline, 1987). Also, the ability to map an alternative science data value to the colors of the isosurface provides an effective means of visualizing the correlation between two different variables. See Figure 7 for an example of an isosurface of chlorophyll with salinity mapped to color. When generating an isosurface, the user can specify the volume extent, isovalue, surface resolution, and the color mapping. One unique component for the construction of the isosurface interpolators is that the use of multiple variables requires the construction of two sets of interpolation functions. One set is used to generate the isosurface and the second is used to generate the colors for the surface.

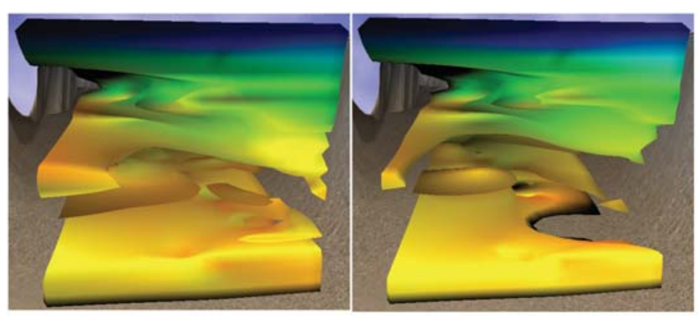

Figure 7: Two views for an isosurface of interpolated chlorophyll data. Figure 7 (A) is mapped to an isovalue of 0.9 and Figure 7 (B) is mapped to 0.95. The colors of both isosurfaces are mapped to the salinity levels within the region, with a color range of dark blue to red

### Scattered Data Interpolation

Scattered data interpolation is the broad category for methods that construct a continuous function $f : R^n \rightarrow R$ given $N$ sample values $f_i \in R$ at $N$ scattered data points $x_i \in R$. The methods of particular interest are those that construct the continuous function as a linear combination of $N$ basis functions, where $f(x) = \sum_{i=0}^{N} \lambda_i \phi(\|x - x_i\|)$. Methods of this form use radially symmetric basis functions, which are centered at each of the data points (Hart, 2005; Narcowich, 2005).

Radial Basis Functions (RBFs) are a simple and useful tool for interpolating data in almost any number of dimensions. Given a set of data points with associated values, RBFs construct a smooth and continuous function, which interpolates the values at each data point. The procedure is to represent the function as a sum of radial basis functions each weighted by a coefficient with the addition of a linear polynomial term. It is a requirement that the interpolated surface honors the original data points, so $f(x_i) = f_i$ for $i=1$ to $N$. This leads to a simple system of linear equations where we solve for the coefficients of the basis functions and polynomial terms. The effectiveness of radial basis functions in scattered data interpolation relies heavily upon the selection of proper basis functions.

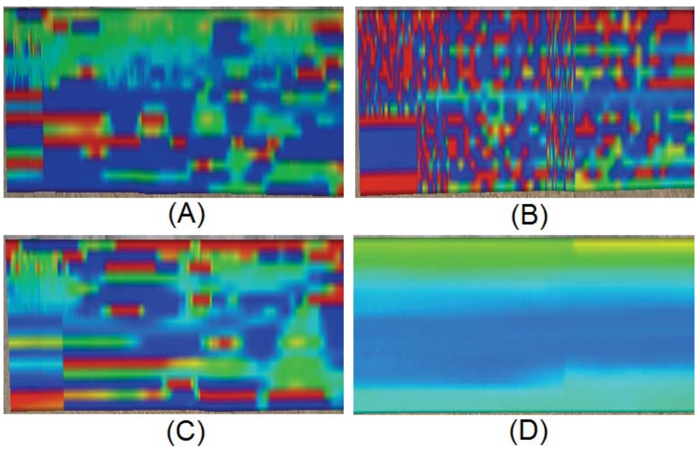


Figure 5: A comparison of radial basis function interpolation with different basis functions. (A) shows the result of a multiquadric $\left(\sqrt{r^2 + B^2}\right)$ basis function. (B) shows a polyharmonic spline $\left(r^{2n-1}\right)$. (C) shows a Gaussian $\left(e^{-Br^2}\right)$ basis function. (D) shows the shifted log $\left(\sqrt{\log_{10}(r^2 + B^2)}\right)$

Basis functions are often sensitive to a user-defined parameter whose appropriate value will often times depend upon the function values and point distributions. Figure 5 provides a comparison of three popular basis functions with the shifted log $\left(\sqrt{\log_{10}(r^2 + B^2)}\right)$ that was ultimately chosen as the most desirable basis function. Each of the other basis functions produces interpolation functions that create local minimums and maximums that do not correspond to the discrete data samples. The polyharmonic spline, shown in Figure 5 (B), produces values, which increase as the distance increases, generating an interpolation function whose initial points have more influence the further away the input point is. The Gaussian, shown in Figure 5 (C), generates values that approach 0 as the distance increases. The problem is that due to the path of the glider, there are regions outside the influence of any particular point, resulting in regions of correct values primarily where the glider traversed. The multiquadric, shown in Figure 5 (A), produces an interpolation function, which is more accurate than the two previously described, but still does not adequately fit the data. One major problem is that regions with sparse data samples, such as the bottom left quarter of the figure, produce inaccurate results. Given that we are in an ocean environment and expect that most data will change smoothly, the shifted log, shown in Figure 5 (D) generates the best interpolation function. The growth of the basis function is severely dampened by the log and square root. This generates a radial basis function whose weight coefficients fall into a reasonable spread, generating a smooth interpolation function.

The construction of the radial basis functions requires the inversion and multiplication of matrices to solve for a linear system. Depending on the amount of initial data samples provided, these can be rather lengthy calculations. The construction of any visualization requiring radial basis functions occurs within a thread in order to allow the user to continue to navigate while the interpolation is being constructed. A heads-up display, or HUD, provides updates on the status of the visualization's construction. A common query used during the construction of a radial basis function is to find all data points within a specific spatial region. In order to accelerate these queries, a bounding volume hierarchy using axis-aligned bounding boxes was implemented.

Severe depth constraints are placed on the data samples used in the construction of the radial basis functions. These constraints arose from biologist input on the rate of change for the underwater variables of interest. Specifically, they noted that the variables of interest change approximately 100 times faster in the vertical direction then in the horizontal direction. When constructing an interpolated visualization, an interpolation function is generated for each depth value associated with the visualization. In constructing the interpolators, the application attempts to use only data samples within half a meter up or down, and will only increase the depth if it did not find enough data samples. Using this method, the interpolation function is influenced primarily by data samples at the same approximate depth.

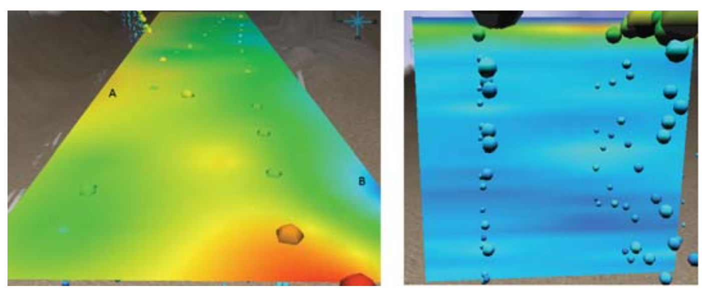

Figure 6: On the left is a view of a chlorophyll mapped volume slice along the ocean surface. On the right is a chlorophyll mapped volume slice in the YZ plane

Figure 6 provides a view of a chlorophyll mapped volume slice along the ocean surface. The slice is being rendered at a resolution of 50x50 with a value range of 0.8712 to 3.4606 and a corresponding color range of dark blue and maximum color of red. The glyphs represent discrete data samples used to generate the interpolation function for the region. The important thing to note is the correlation between color of the glyphs and the color of the volume slice. Figure 6 provides a view of a chlorophyll mapped volume slice along the YZ plane. The slice is being rendered at a resolution of 50x50 with a value range of 0.8712 to 3.4606 and a corresponding color range of dark blue and maximum color of red. The slice generates interpolated values for the area in between the two distinct glider passes that are defined by the position of the glyphs. Also, the dark blue region at the top of the slice results from a lack of data samples at that depth.

## CONCLUSION

We have presented a compelling, efficient, and easy to use interactive system for visualizing large sets of science data collected by the Slocum Glider. An interactive camera allows the user to navigate through accurate terrain generated from bathymetry data. The visualization system constructs glyphs, mission defined gradient planes, user defined gradient planes, volume slices, and isosurfaces. Although the glyphs are generated from discrete data measurements taken by glider, all other visualizations use scattered data interpolation to allow continuous sampling over regions containing a discrete number of data measurements. The system was developed iteratively to ensure that it would be a useful tool for the biologists involved in analyzing and interpreting the glider data. Overall, user feedback was extremely positive, and the biologists were excited to have an additional tool for visualizing the glider data.

The primary bottleneck in constructing the interpolated visualizations is the construction of the radial basis functions. Specifically, finding a solution to the linear system requires the inversion of a matrix, which has a run time of $O(n^3)$. The creation time for a single volume slice with a resolution of 25x25, oriented in the XY plane is affected by the number of data samples used in the creation of the radial basis functions. For example for 202 data points it takes 217 milliseconds, while for 1463 data points it takes 50,765 milliseconds to create the volume slice.

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