A System for Real-Time Spatio-Temporal 3-D Data Visualization in Underwater Robotic Exploration

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Abstract—This paper reports the development of a real-time human-computer interface (HCI) system that enables a human operator to more effectively utilize the large volume of quantitative data (navigation, scientific, and vehicle status) generated in real-time by the sensor suites of underwater robotic vehicles. The system provides interactive 3-D graphical interfaces that display, under user control, the quantitative spatial and temporal sensor data presently available to pilots and users only as two-dimensional plots and numerical displays. The system can presently display real-time bathymetric renderings of the sea-floor based upon vehicle navigation and sonar sensor data; vehicle trajectory data; a variety of scalar valued sensor data; and geo-referenced targets and waypoints. We report the accuracy of the real-time navigation and bathymetric sonar data processing by comparing the real-time sonar bathymetry of our test tank floor to a high-resolution laser scan of the same tank floor. The real-time sonar bathymetry is shown to compare favorably to the laser scan data.

I. INTRODUCTION

We do not know how to effectively display and assimilate in real-time the quantitative data generated by the huge variety of sensors on remotely operated underwater robotic vehicles. Underwater robots now perform sampling, manipulation, and high-resolution acoustic and optical survey missions in the deep ocean that previously were considered impractical or infeasible [8], [10], [11], [13]. Over 1000 robotic uninhabited underwater vehicles (UUVs) are presently in operation worldwide [6]. For example, [14] reports a 1997 survey in which the Jason and Argo II underwater vehicles were deployed to survey a 2 km² shipwreck site at 4100m depth in the Pacific. Over a year of post-processing of the raw survey data resulted in data products including a detailed bathymetric and debris map of the site; site mosaics; 135,774 electronic still images (each covering about 7m×10m); and hundreds of hours of conventional and high-definition video.

Underwater robotic vehicles now also enable scientists to deploy sensors at full ocean depth depths with unprecedented precision. For example, [2] reports the highest resolution bathymetric survey then performed in the deep ocean, in which the Jason underwater vehicle was deployed to precisely survey a 20 × 50 meter 2nd Century B.C.E. shipwreck site at about 800m depth in the Mediterranean. This survey data comprised millions of sonar pings, thousands of electronic still images (each covering about 3m×4m), and hundreds of hours of broadcast quality video. This survey was performed by flying the Jason vehicle in a precise grid pattern under closed-loop control, at an altitude of 3-4 meters above the wreck site, while scanning the site with a pencil beam 675 kHz sonar and an electronic still camera.

Visibility on the ocean floor is poor, often only a few meters. The human operators must mentally construct a composite 3-D map and image of the overall survey site based on smaller visual images and sonar scans.

The Need for Real-Time Spatio-Temporal Display of Quantitative Oceanographic Sensor Data

Despite the fact that remotely operated robotic vehicles have displaced inhabited submarines as the leading method of U.S. deep-ocean oceanographic research, their human-computer interfaces (HCI) have remained largely unchanged since the invention of underwater robots in the mid-1970’s. At present, much of the quantitative data obtained with these systems is automatically logged for post-processing, but is not easily available in real-time, thus vitiating both data utility to human operators and mission utility to science.

Given that deep sea oceanographic research is frequently conducted at sites for which little a-priori information is available, we argue that rapid real-time presentation of sensor data could significantly improve our ability to explore the unstructured environment of the benthic floor.

This paper reports the development and validation of a system that displays, under user control, the quantitative sensor data that is presently available to pilots and users only as numerical displays. Our goal is to address the following three classes of sensor data:

1) Navigation sensor data comprising vehicle state data (position, orientation, and velocities), waypoints, targets, vehicle trajectories, and survey tracklines.

2) Scientific sensor data comprising sensors such as electronic cameras; sidescan, pencil-beam, and multi-beam sonar; water column velocity profilers; physical...
oceanography sensors such as CTD, transmissometer; fluorimeter; and the like.

3) Vehicle sensor and system status data such as power levels, payload, endurance, operational mode, and error conditions.

This paper then reports that the realtime system’s accuracy was experimentally validated based upon its comparison to a ground truth laser scan. This validation was based upon a mean matching comparison of the meshes from the two systems.

The remainder of this paper is organized as follows: Section II describes the implementation of the system. Section III describes the system’s capability to replay previously acquired data. Section IV reports comparison of this realtime system to a laser scan. Section V concludes and outlines future work.

II. SYSTEM DESIGN AND IMPLEMENTATION

The system has the three parts: a navigation subsystem, a realtime data display subsystem, and a subsystem to geo-reference sensor data. Figure 3 shows the process by which a single sonar ping is geo-referenced for display in GeoZui.

A. Navigation

The navigation subsystem employed in this project is DVLNAV, an interactive program for precision 3-D navigation of underwater vehicles. DVLNAV employs a bottom-lock Doppler sonar and a North-seeking gyro to compute accurate vehicle XYZ displacements in a true North coordinate grid. It is also equipped to initialize the bottom track to external sources such as long-baseline acoustic navigation systems, global positioning systems (GPS), or manual input. The software provides an interactive user-interface for real-time display of all sensor and navigation information. The system is currently deployed on six operational underwater robotic vehicles and on the Alvin inhabited oceanographic submersible. Recent sea trials with this navigation system are reported in [5].

B. Realtime Spatio-Temporal Data Display with GeoZui3D

The visualization component of the system is provided by a customized version of GeoZui3D, a 3D GIS research platform. GeoZui3D, which stands for Geographic Zooming User Interface 3D, is an innovative 3D Geographic Information System (GIS) interface [12] [1]. The interface is illustrated in Figure 2. The following describes the features relevant to vehicle visualization and control.

1) Real-time Input Rendered to a 3D display: GeoZui3D receives real-time geospatial data from UDP data packets broadcast over the local network. Different kinds of data may be received on one or more ports. The following real-time objects are presently supported:

1) Dynamically generated bathymetric surfaces.
2) Vehicles and their tracks.
3) Targets displayed as spheres, cubes, cones or cylinders.
4) Scalar 3-D sensor values displayed as tubes with color and/or size mapping.

To allow for real-time surface visualization, resolved 3D soundings from the vehicle’s Imagex scanning pencil beam sonar are integrated into a dynamically growing surface using a weighted spatial averaging method. The surface is composed of a tree of regularly spaced grids. Each grid contains 100 by 100 square cells with a cell size predetermined by the user through a configuration file. As the surface grows, new grids are added to accept soundings that fall outside existing grids. The grids are organized by a tree data structure: each leaf node can contain up to 100 cells (10x10) and each non-leaf node can contain up to 100 (10x10) tree nodes. The spherical objects in Figure /reffig.geozui1 represent targets that can be thought of as 3D Post-It notes, saving geo-referenced textual comments. Clicking on a target reveals the comment. More real-time objects are planned as future work.

2) View Control and Linked Views: Conceptually, in GeoZui3D the center of the 3D workspace is a point located just behind the user’s monitor screen, and this workspace center provides a focus for interactions. Rotation is accomplished using the 3D widgets shown in Figure 2 and scaling is done about the workspace center at a carefully calibrated rate of 8 times magnification per second. Vehicle position and orientation information is shown using a 3D model geo-referenced in the 3D scene. Clicking on the model causes the view to be linked to the vehicle’s movement as though from a camera mounted on the vehicle [7]. Clicking on some other part of the scene “unmounts” the camera and changes the view’s frame of reference back to the static scene.

GeoZui3D has specific capabilities for integrating multiple simultaneous views of the same 3D scene. Multiple windows can be created and attached to static or moving objects to support different tasks. For example, an “over the shoulder viewpoint” above and behind a vehicle may be best for steering it through an environment that has already been mapped. A simultaneous top-down overview can show a wider context. Visual “tethers” show the relationship of the detailed forward-looking view window to the overview window. Such views can be set-up either through user interactions, or through scripting.

3) Time Control: In addition to displaying real-time data, the data is recorded to allow for instant replay of the vehicle’s position. For example, GeoZui3D’s time control bar may be moved back 3 minutes to review the vehicle’s position at that time, then real-time viewing of the vehicle’s current position may be instantly resumed.

C. Real-Time Fusion of Navigation Data and Scientific Sensor Data

Commonly used oceanographic sensors such as sonar, CTD, and ADCP provide raw sensor data via a diverse variety of hardware interfaces (RS232, RS422, RS485, Ethernet, and Analog are presently the most common), data formats, and sampling intervals. In present day remotely operated underwater vehicles, sensor data (e.g. sonar range and angle, conductivity, temperature, depth, altitude, speed) are typically displayed in real-time as a number on an instrument panel, or as a sensor-specific display in sensor instrument coordinates. These raw data are normally logged and time-stamped in real-time. In subsequent offline post-processing, the data are fused with logged vehicle navigation data and sensor calibration data to geo-reference the sensor data values. Plotting and interactive display programs (such as GeoZui3D) generally can not accept raw sensor data; they require processed geo-referenced data.

We have developed a computer program, called “Al-dente”, to combine sensor, navigation, and calibration data in real-time, under user control, and to transmit the resulting geo-referenced sensor data via Ethernet to GeoZui3D for interactive display. Al-dente has a graphical user interface that enables the user to control its operations. The program utilizes the following data:

1) Vehicle Sensor Calibration Data Input: Vehicle instrument calibration and sensor information is loaded from a user-selectable initialization file. Vehicle information includes a definition of the vehicle’s coordinate system, and the 6-DOF position and orientation of each sensor as mounted on the vehicle. Sensor information includes calibration, setting, and communication parameters. Sonar data can be filtered in realtime based upon a maximum and minimum depth value that is entered into the user-selectable initialization file.

2) Raw Navigation Data Input: Al-dente is presently configured to receive vehicle navigation data via UDP packets in a standardized format from the DVLNAV navigation program [5].

3) Raw Oceanographic Sensor Data Input: Al-dente is designed to directly interface to certain sensors such as the Imagex 881A scanning pencil beam sonar. A graphical interface enables the user to examine and control the sonar’s frequency, pulse sequence and all other internal sonar parameters. Raw real-time sensor values are then processed and logged in real-time.

4) Incrementally Processed Geo-Referenced Sensor Data Output: Al-dente combines the sensor, navigation, and calibration information to compute the exact geo-referenced coordinates and UTC time of each sensor reading. The incrementally-processed data is transmitted to GeoZui3D and is logged to disk.

The program has two modes of operation:

1) Real-Time Mode: Provides real-time centralization of sensor, navigation, and calibration data to compute geo-referenced data. Each sensor datum is consolidated upon receipt, logged, and forwarded to GeoZui3D via UDP for display.

2) Replay Mode: Previously logged sensor, navigation, and calibration data can be loaded, geo-referenced, and transmitted to GeoZui3D via UDP. This process
Fig. 4. Photograph of Imagenex 881A pencil beam sonar shown as mounted on the JHU ROV.

Fig. 5. Al-dente provides a conventional polar plot depicting color-mapped return intensities, bottom profile, and range rings.

can be performed either as a batch process or incrementally.

For the representative case of processing sonar bathymetric data from an Imagenex 881A scanning sonar, the system works as follows:

1) At program start, Al-dente loads a file containing all vehicle calibration data.
2) In real-time, Al-dente receives navigation data packets via UDP broadcast from the vehicle navigation system.
3) Al-dente configures the sonar internal parameters and initiates sonar pings as specified by the user.
4) Upon receipt of each sonar-ping data packet, Al-dente uses the most recent vehicle 6-DOF navigation position, the previously loaded calibration data, and the scanning-angle and range of the sonar ping to compute the 3-DOF position and approach vector of the sonar reflection. Al-dente also provides a conventional polar-scan and a grid plot, as shown in Figure 5, of the scanning sonar depicting color-mapped return intensities and bottom profile.
5) The spatially fused sonar data is transmitted to GeoZu3D via UDP, and logged to disk.

For a detailed discussion of high resolution sonar bathymetry, the reader is referred to [9]. Although it is hard to depict in static images, the real-time spatially accurate display of survey bathymetric and vehicle trajectory data provides the user with an instant comprehension of the progress of the survey, the completeness of the bathymetric sonar coverage, and the quality of the data. Our preliminary impression is that this system provides the user with spatio-temporal awareness superior to that of conventional ROV instrumentation displays.

III. REPLAY OF SURVEY DATA FROM MEDITERRANEAN EXPEDITION

Al-dente has the capability to load log files from previous vehicle deployments, and to replay the logged data as if it were real-time data. In replay mode, the logged data is loaded and fused by Al-dente, and then incrementally transmitted to GeoZu3D. This enables the user to interactively review previously logged underwater surveys. Figure 2 shows a screen shot of GeoZu3D as it received georeferenced data from a survey of a 750 B.C. deep-water shipwreck conducted by the Jason 1 ROV in the Eastern Mediterranean in 1999. The figure clearly depicts the central cargo pile, and the shapes of individual Amphora can be seen in the bathymetry.

IV. COMPARISON OF REAL-TIME SYSTEM IMPLEMENTED ON THE JHU ROV TO A LASER SCAN

To validate the accuracy of the data displayed in GeoZu3D several bathymetric surveys of the Johns Hopkins University Hydrodynamics Test Tank [4] were conducted using the realtime system. The resulting sonar bathymetry was compared to data obtained from an entirely separate laser scan of the Test Tank floor performed by Cullinan Engineering Inc, a commercial survey firm.

Figure 7 depicts the JHU Hydrodynamics Test tank and Figure 10 identifies major bottom features in the tank.
4.1.1 Realtime Survey Experimental Setup

The realtime system has been implemented on the Johns Hopkins University Remotely Operated Vehicle (JHU ROV), a research testbed vehicle developed at Johns Hopkins University.

The JHU ROV is equipped for full 6-DOF position measurement. Vehicle heading, roll, and pitch (and their time derivatives) are instrumented with a 3-axis KVH ADGC gyro-stabilized magnetic compass and a Phins North seeking 3-axis fiber-optic gyro. Depth is instrumented by a 5 meter Paroscientific depth sensor. A 1200kHz Doppler Sonar provides XYZ velocity measurements, and in combination with the gyro and depth sensor, enabling doppler navigation via the DVLNAV software program [5]. Vehicle XYZ position is instrumented with a 300kHz time-of-flight acoustic navigation system. An Imagex 881A scanning sonar (280 kHz - 1.1 MHz) provides bottom bathymetry. Figure 6 shows the JHU ROV and identifies the major elements of its sensor suite [4].

Figure 8 depicts GeoZui3D real-time interface showing the vehicle and test-tank bathymetry generated in real time. Sonar data from an Imagex 881A sonar and navigation data from DVLNAV was fused by the Al-dente program in real time and transmitted for display by GeoZui3D.

4.1.2 Laser Scan Experimental Setup

The test tank was drained following the completion of the realtime sonar surveys. Cullinan Engineering, a survey company was contracted to perform a laser scan of the Test Tank using a Leica Geosystems HDS2500 laser scanner as depicted in Figure 11. Figure 12 depicts the fiducial spheres used in combining individual scans.

4.2.1 Realtime System Experimental Results

Using the system installed on the JHU ROV several bathymetric surveys were conducted of the JHU test tank. The survey path was designed to have maximum coverage of the tank bottom and approximately uniform sonar returns per section of the tank. At the beginning of each survey DVLNAV was reset to the most recent 300kHz time-of-flight acoustic navigation fix. The relative position of the vehicle was then calculated based upon velocity measurements from the Doppler Sonar and in combination with the 3-axis gyro, enable doppler navigation via the DVLNAV software program [5].

The sonar data shown in Figure 8 was obtained with an Imagex 881A Profiling Sonar configured to run at a frequency of 800kHz, maximum range of 5 meters, pulse length of 60 microseconds, absorption of 1.65 dB/meter and gain of 9dB. The sonar’s scanning parameters were set to a sector width of 78 degrees, train angle of -9 degrees, and step size increment of 1.2 degrees. GeoZui was setup to have spatial averaging parameters: grid size of 0.01 meters and beam shape of radius 0.05 meters. The survey compromised 71,795 sonar pings and had a total track length of 32.16 meters.
4.2.2 Laser Scan Experimental Results

Five laser scans of the test tank floor were performed. Each scan has an accuracy of +/- 4mm. These scans were performed with a Leica Geosystems HDS2500 laser scanner. The laser scanner was placed on the catwalk, which is situated around the JHU Test Tank, to perform these scans. The catwalk is 10 meters from the center of the tank bottom. The composite laser scan, shown in Figure 9, is comprised of over 3.5 million laser range points.
A. Comparison of Laser Scan to Realtime System

A comparison of the laser and sonar survey data is complicated by the fact that the two systems acquire 3-D spatial data in independent cartesian frames of reference. To compare the quality of the sonar bathymetry to the laser scan bathymetry, we (a) clipped bathymetric data to include only the tank floor features, i.e. excluding the tank wall data; (b) computed a best fit 6-DOF rigid body transformation between the two sets of bathymetry; and (c) computed the histogram of depth differences between the sonar and laser bathymetry maps.

Figure 14 displays the 3-D plot of the error between ground truth laser scan to a set of bathymetry from the realtime system. The standard deviation of the bins with sonar data is 0.0469 meters the mean absolute error is 0.0041 meters. Given that the intrinsic resolution of the sonar used at 5 meters is 0.01 meters, the observed accuracy of the realtime sonar bathymetric map is reasonable. While it is noted that careful post processing of navigation and sonar data may yield improved bathymetric accuracy [9], the purpose of this system is to present reasonably accurate "first cut" bathymetric data in real time to the vehicle pilots and observers, which we have achieved.

V. CONCLUSION AND FUTURE WORK

This paper has reported the design and development of a real-time human-computer interface to enable a human operator to more effectively utilize the large volume of quantitative data (navigation, scientific, and vehicle status data) generated in real-time by the sensor suites of underwater robotic vehicles. The system provides an interactive 3-D graphical interface that displays, under user control, quantitative spatial and temporal sensor data presently available to pilots and users only as alpha-numerical and two-dimensional displays.

The system has been experimentally evaluated based upon a comparison to a ground truth laser scan. The comparison of the accuracy of real-time system to a laser scan has shown a standard deviation of 0.0469 and absolute mean of 0.0041 meters. This proves that the system does accurately display data within the capabilities of the sensors and will provide accurate spatial awareness to the user.

Although it is difficult to depict in static images, the real-time spatially accurate display of survey bathymetric and vehicle trajectory data provides the user with an instant
comprehension of the progress of the survey, the completeness of the bathymetric sonar coverage, and the quality of the data. Our preliminary impression is that this system provides the user with spatio-temporal awareness superior to that of conventional ROV instrumentation displays.

In the future, we plan to add several additional object types to Al-Dente and GeoZui3D to support additional scientific sensors, support for multiple vehicles, and additional spatial and temporal controls. We hope to test this system at sea in actual underwater vehicle oceanographic survey operations.

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The laser scan of the JHU test-tank was obtained in collaboration with Dr. Hanumant Singh (and his students) of the Woods Hole Oceanographic Institution.

The survey data depicted in Figure 2 depict survey data obtained by Whitcomb and collaborators with the Jason 1 ROV on an expedition to the Eastern Mediterranean in June 1999, on which the chief scientists were Robert Ballard, Lawrence Stager (Archaeology), and Dana Yoerger (engineering) [3].

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