An Underwater Vehicle Monitoring System and Its Sensors

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Abstract: This paper describes a virtual collaborative world simulator, DVECS (Distributed Virtual Environment Collaborative Simulator), for underwater robots and its underwater vehicle, SAUVIM (Semi-Autonomous Underwater Vehicle for Intervention Missions). DVECS is used for testing unmanned underwater vehicles (UUVs) of both real and simulated worlds where interaction and cooperation of other real and simulated vehicles, obstacles, situations, conditions and disturbances in a hybrid, synthetic, virtual environment can be observed without physical intervention. This virtual system can be used to determine: (1) the optimal performance and criteria for the cooperating vehicles and its relative application; (2) the determination of the advantages and disadvantages of collaborative application tasks between multiple UUVs; and (3) the optimal communication links between the cooperating vehicles and its remote control stations. DVECS is used as a monitoring system.

1. Introduction

Even with the increased interest in the development of underwater robotic technology, the design, fabrication and analysis of autonomous underwater vehicles (AUVs) are still very complex and expensive. The unpredictable and hazardous underwater environment is extremely unforgiving and remote. With limitations in communication, an AUV must continuously operate in a fully autonomous or near autonomous modes. These requirements immensely complicate the diagnosis and evaluation of an AUV s many subsystems. In order to ensure reliability in these systems, it is imperative to obtain and maintain accurate software and hardware data. For these purposes, it is absolutely necessary to test and re-test these systems under severe or extreme conditions in a controlled laboratory environment before operational or sea-trial deployment. In addition, many military, scientific and commercial tasks in open oceans often require multi-national participation, and it becomes a necessity to rehearse these operations before the actual operation; thus, establishing operational strategy and ensuring the success of the operation without releasing proprietary or secured materials. This is where DVECS becomes the ultimate tool.

Several universities have conducted research in the graphic simulator arena. To mention a few, they are: (a) the Naval Postgraduate School and their NPS AUV Integrated Simulator for their NPS AUV [1]; (b) the University of Tokyo and their Multi-Vehicle Simulator for their Twin-Burger AUV [2]; and (c) the Autonomous Undersea Systems Institute and their Cooperative AUV Development Concept [3]. Both the NPS and UT systems were developed on the IRIX environment of the Silicon Graphics workstation, while the AUSI system runs on the Win32 environment on an Intel based system. All systems, however, are running the OpenGL graphic protocols, which is platform independent.

DVECS was developed with the sole objective of reducing the lead-time required for (1) the tedious aspects of pre-testing software and hardware before deployment and (2) the collaboration of various AUVs without having to consider the transportation of these vehicles. Much of DVECS is based and developed on the graphic test platform architecture for underwater vehicles by Yuh, Adivi and Choi [4], and the SGI GL based 3-dimensional graphics by Choi, Yuh and Takashige [5].

DVECS utilizes a similar software architecture of a combined hierarchical and heterarchical structure of the previous test platforms along with an OpenGL based simulation system and a variety of different wireless communications methods — radio frequency links, commercial cellular telephones, wireless Ethernet, wireless LAN and asynchronous transfer mode — for data transfer. Finally, DVECS incorporates a projection VR system that consists of a RGB high-resolution and high-refresh-rate projector and polarized eyewear with an emitter. Thus, this system creates an immersion effect.

2. DVECS

The design, testing and operation of AUVs and their control systems can benefit immensely from interactive, 3-dimensional (3D) computer simulations. In particular, developing and testing complex systems that involve multiple autonomous underwater robots operating in an uncontrolled environment is considerably safer and cost-effective in a controlled synthetic environment than a real environment, since the research vehicles are not placed at risk of loss or damage. Mission planning, monitoring and analysis can also benefit from an interactive, 3D virtual environment since its performance can be tested prior to actual sea-trials. For these reasons, the Distributed Virtual Environment Collaborative Simulator (DVECS) was developed to be used in hybrid synthetic simulations for testing real and virtual vehicles in a common environment and for mission collaboration, planning, monitoring and analysis of existing unmanned underwater vehicles (UUVs), as described in Figure 1.

DVECS architecture is designed to operate in a networked environment such that each component of the simulation can be run on a separate system, processor or virtual machine within a single computer; thus, distributing the computation load. This feature offers several advantages over a single system layout.

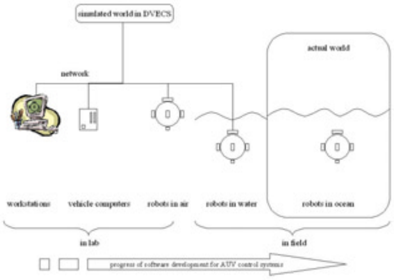


Figure 1: DVECS Development Environment

First, it is possible to modify or create new components with minimal restrictions on internal architecture. As long as each component adheres to specifically prescribed requirements for communication, language and operating system, the design and implementation of each component is irrelevant to the rest of the system.

Second, users can design and test their AUV simulations across the Internet using common servers. This allows computationally intensive 3D simulation of interaction between multiple objects in the virtual world to be simulated on one or more centralized high performance computers, while the processing requirements for the user's AUV simulations are no more than what their physical AUVs would normally require. Thus, this optimizes the computation time and allows users to accurately evaluate their vehicle's computation performance and requirements.

Finally, multiple simulated or physical entities can interact over a networked environment without requiring them to share code or knowledge of each other's capabilities so proprietary or secured algorithms can be tested in a common environment without making them public. This allows for collaboration from many different sectors of the underwater community that wish to evaluate their AUV in conjunction with pre-tested AUVs, as shown in Figure 2.

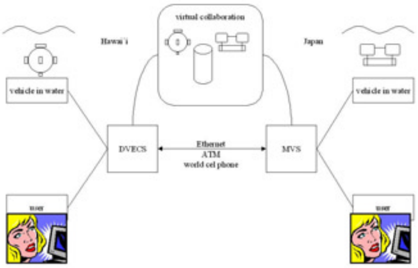


Figure 2: DVECS and MVS Collaboration

2.1 Vehicle Dynamics

DVECS, when in a monitoring mode, does not consider vehicle dynamics since transmitted data directly reflects the motions of the vehicle in the real-world environment. However, when in the simulation mode, the interacting system must consider the basic underwater vehicle dynamics. The following vector equation:

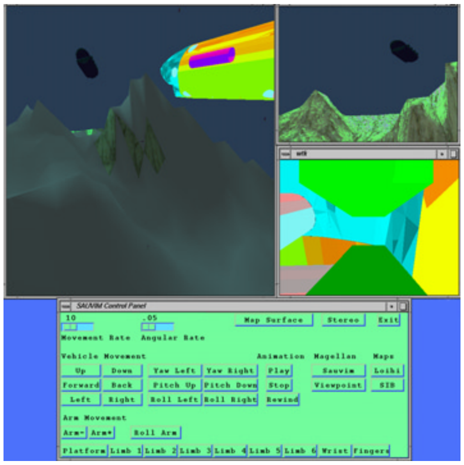
$$M\dot{V} + A(V)V + h = F$$

where $V \in R^6$ is the linear and angular velocities in the vehicle coordinates; $M \in R^{6x6}$ is the inertia matrix; $A \in R^{6x6}$ includes all the nonlinear dynamic terms with velocity terms; and $h \in R^6$ is a vector representing other forces and torques except $F \in R^6$, which represents the forces and torques generated by the thruster forces. [6]

2.2 Virtual User Interface

As mentioned, DVECS uses a multiple Silicon Graphics workstation setup that comprises of an Onyx, an Indy and an O^2, and interfaces with an Electrohome Virtual Reality Projection unit and Stereographics CrystalEyes eyewear and emitter system.

The DVECS software is a multi-layered C++ program modularized by its subsystems and utilizes the inheritance properties. It uses OpenGL graphics libraries to generate the background, vehicles and obstacles, and uses Open Inventor 3D toolkit protocols to create the 3-dimensional, virtual images.



Movement Rate 10

Angular Rate .05

Figure 3: DVECS for AUV in an Undersea Environment Testing and Evaluation

Currently, DVECS consists of multiple windows that represent a 3-dimensional environment, a front camera view with video overlay capabilities, a manipulator camera view and a control panel. Figure 3 shows DVECS showing the Semi-Autonomous Vehicle for Intervention Missions (SAUVIM) at the Loihi Seamount test site off the Big Island of Hawaii.

3. SAUVIM

The Semi-Autonomous Undersea Vehicle for Intervention Missions (SAUVIM) is a class of AUV that extends the envelope of missions from the traditional wide area survey and fly-by missions to include close-in navigation and interactive tasks that are accomplished by means of its robotic manipulator and sensors. As seen in Figure 4, SAUVIM is a free-flooded deep-water AUV that has six primary pressure vessels, batteries, sensors and other ancillary systems mounted onto a 6061-aluminum frame.

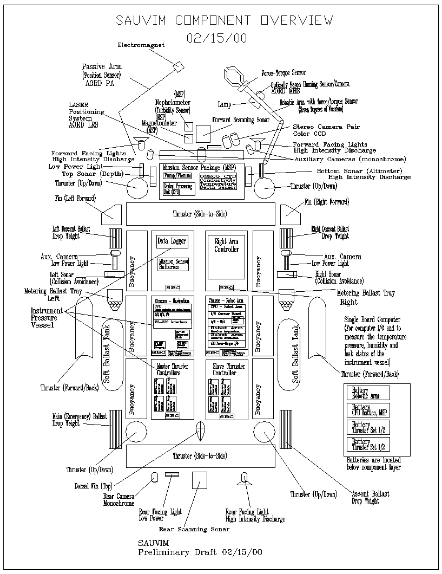


Figure 4: SAUVIM Components

The floatation foam is primary located on the topmost and lateral sides of the vehicle. Inside the frame on the upper of the two levels are aft lateral thruster, six primary pressure vessels, electrical junction boxes, forward lateral thruster, and primary sensor rack. On the lower level proceeding are battery banks, ballast carriage and robotic arm storage bay with the active and passive robotic arms slug underneath a retractable platform. Located outboard of the frame are the four vertical thrusters, three fins and decent ballast mounts. Out on each side of the vehicle are pylons, which are easily collapsible and contain a Tecnadyne Model-2010 brushless thruster that is capable of 130lbf output. The other six thrusters consist of two lateral and four vertical units that are a Tecnadyne Model-1020 model capable of 47lbf output. Figure 5 shows SAUVIM during its construction and assembly phases.

Figure 5: SAUVIM during Assembly

The vehicle has twin VME-bus computers housed in the middle set of pressure vessels. These are outfitted with Force Computing CPU boards based on the Motorola 68060 processor, navigation tasks will be dedicated primarily to the port-side bottle bus while arm control and coordination while be handled by the starboard-side VME CPU. The two computers will be linked together with a RS-232 serial line for time synching and backup communication along with a RJ-45 10-base-T twisted pair Ethernet connection. The various vehicle sensors (ranging sonar, scanning sonar, video cameras, etc.) and actuators (fins, thrusters, ballast release, etc.) are in a split configuration that allows the vehicle to self-recover from failure scenarios involving leakage and localized component failure.

To help insure fault tolerance, the batteries - six DeepSea Systems model SB48-18 and six SB24-38 - are feeding power buses that are isolated to each respective pressure vessel. These batteries, although having a relatively low energy density for a given volume were chosen for their ease of maintenance and potential turnaround time between missions.

The vehicle will be initially launched and tested in shallow water during the vehicle development and debugging missions. To facilitate easier systems maintenance and handling during this period, the floatation foam and pressure vessels employed on the vehicle will be pressure rated to only 600 feet of depth - upgrades to versions capable of sustaining 20,000 ft dives will be made; in so doing the dry mass of the SAUVIM will climb from 8,500 lbs to 13,500 lbs. The syntactic foam used on the full ocean depth vehicle will be standard glass micro-sphere and epoxy matrix foam, and the shallow water foam is rigid polyurethane foam. The SAUVIM will undergo shallow water testing with an abbreviated fairing. The front and aft areas will have fiberglass shields for flow development mounted to the frame. For the deep-water vehicle a much more complete carbon fiber/kevlar composite fairing shell will be fabricated for the vehicle to allow for drag minimization and some measure of collision damage absorption.

The main robotic manipulator is the Ansaldo/Maris Corporation Model 7080, which is an oil-filled 7-dof (degree-of-freedom), robotic manipulator that is capable of carrying 6kg payloads at full extension. The resolvers for commutation and positioning of the brushless motors within the arm are carried in the right-forward pressure vessel. The software and control architecture of the manipulator systems is being jointly developed with University of Genoa in Italy.

The vehicle and support systems are collapsible into one standard shipping container, facilitating deployment of the SAUVIM to worldwide locations. Command and control for the vehicle development missions will be done over a tether line that will feature serial and RJ-45 links to the Navigation computer CPU bottle. This link will swapped over to an acoustic modem towards that end of the vehicle systems testing in shallow water.

3.1 SAUVIM Navigation and Positioning Sensors

In order to successfully complete the far-field navigation to a worksite, close-in navigation around the site and manipulative tasks, SAUVIM carries an array of sensors. The first two classes of tasks are performed autonomously while the last class of task is performed in a terse command loop structure allowing for low-bandwidth command and control. SAUVIM will carry the following sensors for far-field navigation and collision avoidance: ranging sonar, scanning sonar, INS units, pressure sensors and a Doppler velocity log. For close-in navigation and intervention, task accomplishment will comprised of three custom-build Automatic Object Ranging and Dimensioning (AORD) sensors, which consist of a laser ranging array (LRA), passive arm (PA) and manipulator homing sensor (MHS). Consideration to carrying a stereo camera pair for ranging is also being considered, and other CCD cameras will be mounted for semi-autonomous event monitoring. Other supplemental sensors will be available to the SAUVIM Navigation and Arm Control computers via an RS-232 link to the oceanographic Mission Sensor Package (MSP), which will also be onboard.

The six ranging sonar, Perry Tritech PA200/20-S units, are bundled on RS-485 interfaces. Two bundles of three lead into each of the two VME computers. Mounted one to each of the six principle directions around the vehicle, these sonar, which feature a 200kHz pulse with a 20E conical beam-front and 100m effective range, are intended primarily for collision avoidance, and bottom and free-surface ranging. Based on pool tests, these units have a minimum range of 1.5m and repeatability within 5cm, and will be quite useful as altimeters and depth-meters for the vertically orientated units.

Two Imagenex 675kHz Model 881-000-105 radial scanning sonar will be used for bottom mapping and collision avoidance. One unit will be mounted on the forward end of the vehicle while the other will be mounted aft. The data return from these units is the sonic based analogue to a radar sweep. RS-485 based and highly programmable, these units will be used for collision avoidance as well as bottom characterization and mapping. The main challenge is to code the image and data garnishing software. These units feature and fan shaped beam of 1.7E horizontal by 30E vertical spread with a maximum range out to 100m with a 360E scan horizon capacity.

Within the forward pressure vessel is the primary vehicle primary inertial navigation sensor (INS), which is a Watson AHRS-BA303. Not a true INS, this unit is a RS-232-based gyro-unit that gives heading, pitch and roll angles and velocities. A secondary INS unit, which is the Precision Navigation Model TCM-2, will be housed within the Arm Control CPU pressure vessel. This unit features a 2-axis inclinometer and 3-axis fluxgate compass that will yield orientation much like the Watson unit.

Two pressure sensors will be aboard SAUVIM. These are both Data Instruments/Honeywell DS-2 units, which feature a 4-20mA current loop output. Each of these unit outputs will be feed to the arm control and navigation computers. These units have a range from 0-10,000psi absolute with a –1% FSO accuracy. These will be used for mid-water depth tracking and for bottom proximity tracking. Ballast release of the vehicle will be coordinated based on the output of these sensors primarily, and from the ranging sonar secondarily. To allow for dead reckoning via single-integration techniques, the addition of a Doppler Velocity Log (DVL) to the SAUVIM vehicle is being considered.

Most of the above sensors are intended for far-field navigation, vehicle positioning and collision avoidance although most will be used in the close-in navigation and intervention task phases as well. The next class of sensors is all primarily intended for use during the close-in navigation and intervention tasks. These are the three AORD sensors, which are being developed in-house.

The first is a laser ranging array (LRA) that in its second-generation configuration consisting of sixteen diode lasers in a grid array along with a CCD camera centered in the array. Data processing of the laser dot locations is done by a PC-104 based computer with an Imagenex frame grabber board. The effect of parallax migration of the laser dots across the array is exploited by this unit. The effective range in water was determined to be about 5-6 meters through fresh water. A four-laser unit was tested with about –5% relative positioning accuracy in a darkened room from 0.5 to about 5m. Testing and establishment of the accuracy of the underwater unit is now underway as well as making the software more robust to deal with turbid water conditions and unit calibration.

The next element of the AORD sensor array is the PA (Figure 6). This is a two segment robotic arm that is constructed from aluminum 6061 alloy. Filled with white #9 mineral oil, this unit has two three-axis gimbals at each of two end canisters and a single-axis hinge joint between the two arm segments. The larger, base canister is mounted to the retractable arm tray on the vehicle portside, opposite to the active arm. The tubing segments are approximately 0.5 and 0.75 meters in length each use neoprene bellows to allow joint flexibility and have wiring strung internally within the arm. The arm has seven JDK MicroDevices open-wiper potentiometer assemblies, which have a 10kOhm range. These are powered by a twin set of rails at 5VDC and all of the wiper voltages are feed back on individual lines and are routed to the arm control bottle VME computer Matrix A/D board.

Figure 6: Passive Arm Set-up

Typically, the Ansaldo arm will deploy the lower canister of the PA from a storage cradle position on the arm tray to the seabed bottom or the task area. Initial task sites will be highly structured and ferrous in nature. This will allow the electromagnet within the PA arm to attach to the task site. Deployment of the PA will allow the reference frame of the seabed and task site become known with respect to the SAUVIM coordinate system and will allow for active arm correct for vehicle drift due to currents and or second law action-reaction motions that the SAUVIM experiences.

The last element of the AORD suite is the MHS unit, which consists of a CCD camera and a SuperCircuits Model PC74WR with a 512x512 pixel resolution, mounted above the sixth joint of the Ansaldo arm. This unit is linked to a PC-104 (Real Time Devices CMH486DX100HR) computer also equipped with an Imagenex frame grabber board. The unit is programmed to identify circular bar codes and range to them to allow for final orientation and guidance of the manipulator. This unit gives the range and off-axis orientation to the bar code as well as an identifier number for the code. Effective range based on preliminary dry testing is from about 0.6m in to about 25cm. Relative accuracy is about –1-2cm in the near limit range.

The remaining sensors are supplementary sensors for the SAUVIM vehicle. These consist of video cameras and the MSP sensors. Video cameras are of both monochrome and color varieties and will be mounted onto SAUVIM. These consist of SuperCircuits PC75WR and PC74WR CCD camera units, respectively. Five monochrome cameras will be mounted, one to each side of the vehicle as well as the rear and two in the nose for general video feedback for any supervisor monitoring the vehicle progress topside. A color stereo pair of cameras will face into the arm workspace. The will be used for stereo ranging and visualization data gathering. These will be slaved to a PC-104 based architecture with one to two frame grabber boards. The MSP sensors include a nephlometer, CTD sensor, 3-axis field magnetometer, and a pH and dissolved oxygen sensor. The outputs of these sensors can be polled from the MSP CPU over a RS-232 link if so needed during a SAUVIM mission and can be made available for navigation tasks.

4. Conclusion

This paper presents a brief description of the Distributed Virtual Environment Collaborative Simulator (DVECS) and the Semi-Autonomous Underwater Vehicle for Intervention Missions (SAUVIM) developed at the Autonomous Systems Laboratory of the University of Hawaii. Various tests have shown that the combined system can greatly help reduce the development time of underwater vehicle hardware/software testing and verification. Further tests are scheduled to refine the monitoring system and vehicle to allow higher degree of robustness.

5. Acknowledgement

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