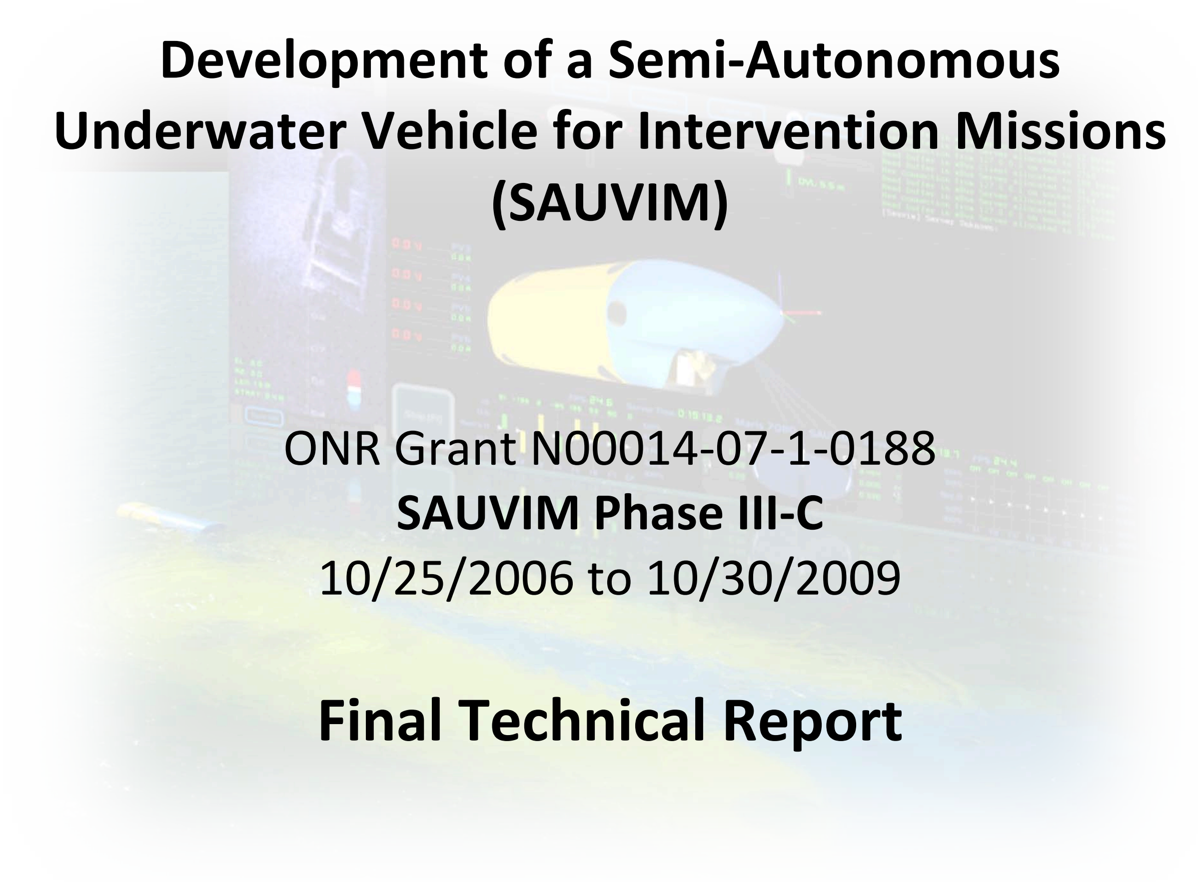
The Autonomous Systems Laboratory
University of Hawaii at Manoa

2540 Dole Street, Holmes 302
Dept. of Mechanical Engineering
University of Hawaii
Honolulu, Hawaii 96822, USA
www.eng.hawaii.edu/~asl

Development of a Semi-Autonomous Underwater Vehicle for Intervention Missions (SAUVIM)



ONR Grant N00014-07-1-0188

SAUVIM Phase III-C

10/25/2006 to 10/30/2009

Final Technical Report

January 28, 2010

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **JAN 2010**	2. REPORT TYPE **N/A**	3. DATES COVERED
4. TITLE AND SUBTITLE **Development of a Semi-Autonomous Underwater Vehicle for Intervention Missions (SAUVIM Phase III-C)**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **University of Hawaii at Manoa Department of Mechanical Engineering 2540 Dole St., Holmes 302, Honolulu, Hawaii 96822**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
SAUVIM (Semi Autonomous Underwater Vehicle for Intervention Missions) involves the design and fabrication of an underwater vehicle that it is capable of autonomous interventions on the subsea installations, a task usually carried out by ROVs or human divers.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**SAR**	**105**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

Summary

Technical Development Report: October 25, 2006 – October 30, 2009

The SAUVIM proposal was initially submitted under the ONR Annual Announcement of the July 11, 1996 Commerce Business Daily, and the project officially began on August 1, 1997 with its firs 18-month, $2.237 million research fund from the Office of Naval Research's Undersea Weapons Technology Program. The project was successively organized into six further phases, from Phase II-A till the conclusive Phase III-C, which is the topic of the current report.

Phase I of the SAUVIM project (ONR GRANT N00014-97-1-0961) officially began on August 1, 1997 with $2.237 million from the Office of Naval Research's Undersea Weapons Technology Program directed by Mr. James Fein. Additional funding of $1,445,000 for *Phase II-A* (the first part of Phase II) was received on May 1, 2000 (ONR GRANT N00014-00-1-0629). The second part of Phase II (*Phase II-B*) fund of $817,000 was received on June 17, 2002 (ONR GRANT N00014-02-1-0840). The third part of Phase II (*Phase II-C*) fund of $630,000 was received on August 1, 2003 (ONR GRANT N00014-03-1-0969). Phase III (*Phase III-A*) fund of $480,000 was received on October 1, 2004 (ONR GRANT N00014-04-1-0751, A0001). The second part of Phase III (*Phase III-B*) fund of $529,950 was received on December 15, 2005 (ONR GRANT N00014-04-1-0751, A0002). The Phase III-B has been extended at no cost until December 20, 2008. The conclusive third part of Phase III (*Phase III-C*) of $421,048 was received on October 25, 2006 and was extended at no cost until October 30, 2009. Table 1 summarizes the timeline and amounts of the SAUVIM grants until December 20, 2008. See also the simplified Gantt chart of Fig. D.

In 1999, with the departure of Mr. James Fein from ONR, Mr. Chris Hillenbrand became the ONR Program Officer for the SAUVIM project. In 2002, Dr. David Drumheller became the new ONR Program Officer for the SAUVIM project. The Advisory Committee (AdCom) was formed to provide technical advice and direction by reviewing research directions and progress, and to provide advice and assistance in exploring potential applications and users. The six-member AdCom consists of Mr. Fred Cancilliere of Aquidneck Management Associates, Ltd (the former program director of the Naval Undersea Warfare Center), Dr. Alexander Malahoff of the University of Hawaii, Dr. Homayoun Seraji of the Jet Propulsion Laboratory, Dr. Paul Yuen of the University of Hawaii, and Mr. James Fein (the former ONR Program Officer for SAUVIM) of Carderock Division, Naval Sea Systems Command. Mr. Dick Turlington of the Pacific Missile Range Facility has retired and will be replaced by Mr. Clifton Ching.

The first progress report was submitted to ONR during Mr. Fein's site visit on October 28, 1997. The second progress report was submitted to ONR during the AdCom's site visit on February 24-25, 1998. The First Annual Report covering 1997-1998 was submitted to ONR in August 1998 and presented during the site visit on September 15-16, 1998. The fourth progress report was submitted during Mr. Hillenbrand's site visit on April 8, 1999. The Second Annual Report describing the overall technical progress of the project during the 1998-1999 year was submitted in July 1999. The next two ONR and AdCom site visits were on May 11, 2000 and November 14, 2000. A Final Report for Phase I was submitted to ONR

in October 2000. During the next four ONR and AdCom site visits on October 29, 2001, July 18, 2002, February 18-19, 2003, and October 6, 2003, initial balancing and motion wet-tests of SAUVIM were conducted, including various surge, heave, sway and yaw motions in the ROV mode for safety precautions. On May 27-28, 2004, SAUVIM performed underwater manipulation tasks and simple navigation motions in the pier area. These initial development results were publicly shown on October 21, 2004 for 80+ attendees of the Undersea Defense Technology (UDT) conference. A Phase II-B Final Report was submitted on March 31, 2005.
The next site visit was on July 14-15, 2005 where MARIS underwater manipulator demonstrated visual tracking performance in the water with a chess board image for target. Successively, during the review of April 27 and 28, 2006, various tasks were performed, including sea floor mapping, vehicle landing on an underwater platform, autonomous object recognition with a camera on the robot manipulator, and autonomous manipulation for target retrieval.
The successive Phase III-B of SAUVIM has seen several major upgrades of the vehicle, including a new power source for enhanced autonomy, a new wireless communication link, the introduction of an Inertial Navigation system and a totally re-designed navigation controller with 6DOF performances. Its associated site visit, done on May 22-23 2007, presented the whole set of the new SAUVIM upgrades to the AdCom members.

Start	End	Amount	Grant No.	Phase
08/01/1997	10/31/2000	$ 2,237,000.00	N00014-97-1-0961	SAUVIM Phase I
05/01/2000	12/31/2002	$ 1,444,993.83	N00014-00-1-0629	SAUVIM Phase II-A
06/17/2002	06/30/2004	$ 817,000.00	N00014-02-1-0840	SAUVIM Phase II-B
08/11/2003	06/30/2006	$ 630,000.00	N00014-03-1-0969	SAUVIM Phase II-C
10/01/2004	06/30/2006	$ 480,000.00	N00014-04-1-0751	SAUVIM Phase III-A
12/15/2005	12/20/2008	$ 529,950.00	N00014-04-1-0751	SAUVIM Phase III-B
10/25/2006	10/30/2009	$ 421,048.00	N00014-07-1-0188	SAUVIM Phase III-C
	TOTAL:	$ 6,559,991.83		

Table 1: SAUVIM Grants

The present final report covers the Phase III-C of SAUVIM. This is the conclusive phase of the project, which hosted further major upgrades and, most important, the demonstration of the first fully autonomous underwater manipulation in an unstructured environment. Submerged in the water, in its final demonstration, SAUVIM first performed the self-calibration routine, initializing its sub-systems. After the calibration step, SAUVIM began its pre-given mission-- to search for and tag an underwater object. The object's location was roughly given. Once the vehicle reached the area surrounding the object, it started scanning the area using a DIDSON camera to locate and identify the target. Once the object was detected, the vehicle approached it and positioned itself for optimized manipulation. Then, while the vehicle was floating in the water column, using the unified coordinated motion control of the vehicle and manipulator system, the vehicle performed an autonomous manipulation task by applying a device to the object for tagging.

After completing the mission, the vehicle came back to the dock by using feature-based navigation. The whole sequence was autonomously done and the same mission was successfully repeated four times.
This demonstration presented a technological breakthrough in the field as autonomous manipulation had been a bottleneck issue for underwater intervention missions.

Objective

Many underwater intervention tasks are today performed using manned submersibles or Remotely Operated Vehicles in tele-operation mode. Autonomous Underwater Vehicles are mostly employed in survey applications. In fact, the low bandwidth and significant time delay inherent in acoustic subsea communications represent a considerable obstacle to remotely operate a manipulation system, making it impossible for remote controllers to react to problems in a timely manner.

Nevertheless, vehicles with no physical link and with no human occupants permit intervention in dangerous areas, such as deep ocean, under ice, in missions to retrieve hazardous objects, or in classified areas. The key element in underwater intervention performed with autonomous vehicles is autonomous manipulation, which refers to the capability of a robot system that performs intervention tasks requiring physical contacts with unstructured environments without continuous human supervision.

This challenging technology milestone has been our long-term objective, through the development of a Semi-Autonomous Underwater Vehicle for Intervention Missions (SAUVIM): *an undersea robot that can intelligently work with arms rather than just swim*, significantly advancing the Navy's ability for undersea intervention missions.

Today only few AUVs are equipped with manipulators. SAUVIM, at its current state of the art, is one of the first underwater vehicles designed to perform autonomous manipulation tasks.

The SAUVIM technical approach to underwater intervention involved the development of a robust autonomous manipulation framework over several years of researches.

Our current results represent an important passage toward the development of a higher level of autonomy for intervention AUVs, providing a cost-effective engineering solution to many new underwater tasks and applications that the fly-by type submersibles have not been able to handle.

Program Implementation

During the overall phases, research for SAUVIM was carried out by continued coordination of three organizations: *Autonomous Systems Laboratory* (ASL) of the University of Hawaii (UH), *Marine Autonomous System Engineering*, Inc. (MASE), and *Naval Undersea Warfare Center*, Newport (NUWC).

Junku Yuh has been the PI of the SAUVIM project from the ASL organization for Phase I, Phase II and Phase III-A. He continued to serve as PI during the Phase III-B of SAUVIM, for ASL.
Frederick Cancilliere was the PI of the SAUVIM project from the NUWC organization for Phase II-B. Due to Mr. Cancilliere's retirement, *Paul Temple* has served as PI for Phase II-C and Phase III-A for NUWC. He continued to serve as the PI for NUWC for Phase III-B.
Song K. Choi has been the PI of the SAUVIM project from the MASE organization for Phase II, Phase III-A and III-B. He will continue to serve as the PI for Phase III-C for MASE.

The ASL is the primary research organization for the SAUVIM project. ASL staff members have developed key technologies of the SAUVIM project such as vehicle control system with real-time operating system, underwater navigation algorithm, sensor handling algorithm, sensor fusion, robot manipulator control system, and underwater image processing system. The ASL at UH has been used to train highly capable engineers and scientist to contribute to the underwater technologies society from various industries.
While Junku Yuh has been the official PI for ASL during all the SAUVIM Phases, the development of the Phase III-B has been coordinated by *Giacomo Marani* from ASL, starting from December 2006. During the same period, Giacomo Marani served also as SAUVIM Acting PI. Tae Won Kim was the Project Co-Coordinator for Phase II and has been the Co-PI from ASL and the Project Coordinator of the SAUVIM project for Phase III-A and the beginning of Phase III-B, until December 2006.
Giacomo Marani contined serving as SAUVIM acting Principal Investigator during the whole current Phase III-C, until the end of the project, and leading the main technical coordination betweent he SAUVIM entities.

MASE is the spin-off company from the ASL, UH. The key MASE staff members are former members of ASL, who were involved in the design, analysis, fabrication and testing of SAUVIM in Phase I and Phase II-A. Song K. Choi served as the SAUVIM Program Coordinator during Phase I and as the Associate Director in Phase II-A. He has been the PI of the SAUVIM project from the MASE organization for Phase II and Phase III-A. MASE's contribution to the proposed research is essential as MASE staff members' profound research experiences and skills especially with SAUVIM as well as their private sector environment are crucial factors to complete this project with respect to research outcome in industrial standards and future technology transfer. MASE plans to continuously provide engineering service for maintenance, modifications, and field operations of SAUVIM. SAUVIM is ultimately owned by UH and will be used for UH and Navy tasks as priorities.

NUWC is the main Navy laboratory where Navy's key projects in unmanned underwater vehicles (UUVs) have been carried out. NUWC possesses a great abundance of research and operational experience of UUVs, especially with the fly-by type AUVs. Mr. Cancilliere has served as a member of the SAUVIM Advisory Committee and is very familiar with the research objectives and progress of SAUVIM. Mr. Cancilliere initiated the maintenance, safety, and testing documentation during Phase II-B. During Phase II-C and III-A, Paul Temple has continued to lead the NUWC work by utilizing UNWC personnel who are already familiar with the SAUVIM project.

While their joint involvements are at different levels in the program, integrated research efforts of all three organizations are essential for the successful completion of the SAUVIM project. ASL is focused on the theoretical investigation and software development; MASE is focused on the experimental testing, hardware development, and sensor and power investigations; and NUWC is focused on the experimental implementation of the proposed research tasks, sea trials, and documentation. From December 2006, until the end of the project, the overall technical coordination between the project entities, particularly among the research institute (ASL) and engineering service (MASE), was managed by Giacomo Marani.

The SAUVIM revised organizational diagram is shown in Figure A and a simplified SAUVIM schedule is shown in Figure D.

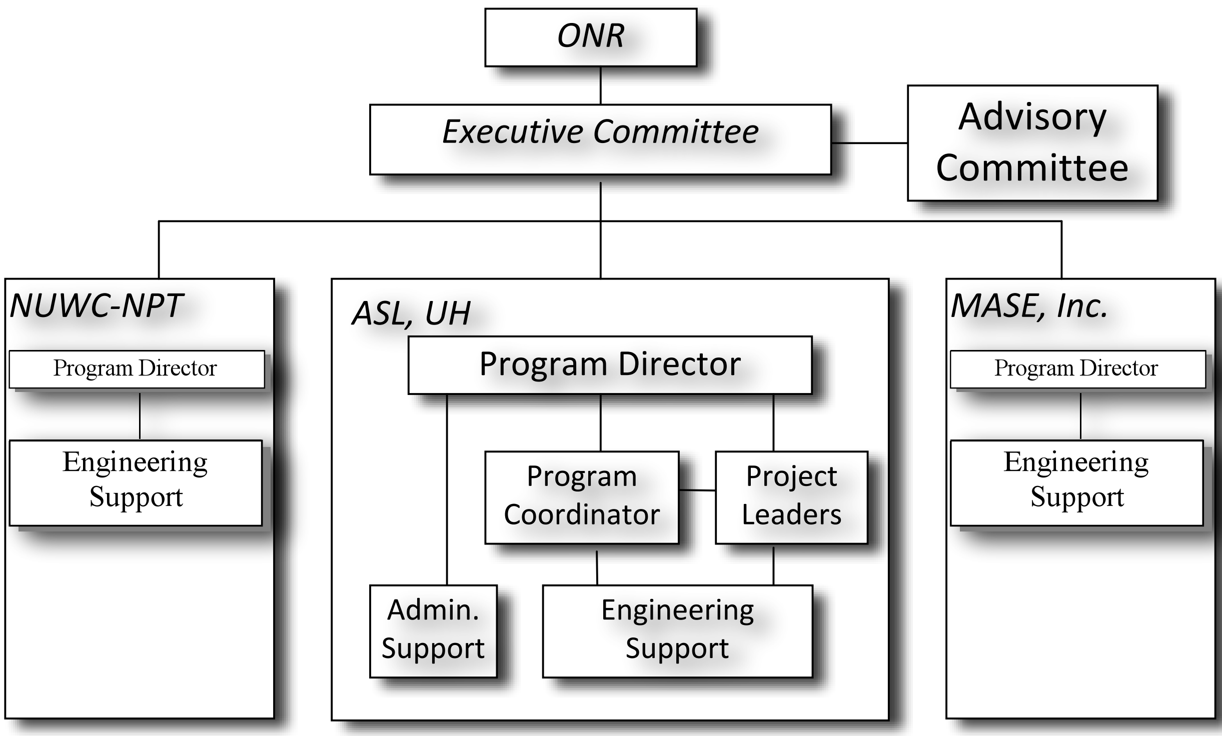


Figure A. SAUVIM Revised Organizational Diagram

Background

It is clear from various meetings with Navy experts and the autonomous underwater vehicle (AUV) community that there is a great need for improving undersea intervention capabilities in terms of autonomy, cost-effectiveness, and performance. Various underwater intervention tasks include underwater plug/unplug, construction and repair, cable streaming, mine hunting, and munitions retrieval. All underwater vehicles currently used for intervention missions are either manned submersibles or remotely operated vehicles with manipulators. These vehicle operations are expensive and often face a number of safety issues. Furthermore, their performance in terms of accuracy and efficiency are questionable, mainly due to human operator fatigue and the time delay in the man-machine control loop in an unstructured environment. Even though recent advances in sensors, communication, computers, and machine intelligence have made it possible to attempt to design advanced AUVs, the AUV development is still mostly directed toward a survey-oriented vehicles.

In literature there are only few examples of Intervention AUVs. These example include the OTTER I-AUV by the Stanford Aerospace Robotics Lab. OTTER, developed back in 1996, is a hover capable underwater vehicle which operates in a test tank at the Monterey Bay Aquarium Research Institute (MBARI). Current and past research includes texture-based vision processing for feedback control and real-time mosaicking, autonomous intervention missions, and hydrodynamic modeling of underwater manipulators. A study on automatic objects retrieval was done in [Wang95].

Another Intervention AUV, ALIVE, was developed in 2003 by Cybernetix. The aim of the EU-funded ALIVE project was to develop an Intervention-AUV capable of docking to a subsea structure which has not been specifically modified for AUV use. A description of the ALIVE vehicle was given in [Evans03].

The key element in underwater intervention performed with autonomous vehicles is autonomous manipulation. This is a challenging technology milestone, which refers to the capability of a robot system that performs intervention tasks requiring physical contacts with unstructured environments without continuous human supervision.

Intervention missions requiring physical contact with the surroundings in the unstructured, underwater environment always increase the level of risk in damaging the system and present completely different dynamic problems from fly-by, non-contact type operation. The overall motion of the vehicle-manipulator system is a high degrees-of-freedom (dof) operation due to additional dof of the manipulator added to the vehicle’s six dof. Operation requires a high degree of precision and accuracy, which accomplishment if often complicated by the presence of an external disturbance such as a current. All of these issues present very complex engineering problems that have hindered the development of AUVs for intervention missions.

Autonomous manipulation systems, unlike teleoperated manipulation systems, that are controlled by human operators with the aid of visual and other sensory feedback, must be capable of assessing a situation, including self-calibration based on sensory information, and executing or revising a course of manipulating action without continuous human

intervention. It is sensible to consider the development of autonomous manipulation as a gradual passage from human teleoperated manipulation.
Within this passage, the most noticeable aspect is the increase of the level of information exchanged between the system and the human supervisor.

In teleoperation with ROVs, the user sends and receives low level information in order to directly set the position of the manipulator with the aid of a visual feedback. As the system becomes more autonomous, the user may provide only a few higher level decisional commands, interacting with the task description layer. The management of lower level functions (i.e. driving the motors to achieve a particular task) is left to the onboard system. The level of autonomy is related to the level of information needed by the system in performing the particular intervention. At the task execution level, the system must be capable of acting and reacting to the environment with the extensive use of sensor data processing.

The user may provide, instead of directly operating the manipulator, higher level commands during a particular mission, such as "unplug the connector". In this approach, the function of the operator is to decide, after an analysis of the data, which particular task the vehicle is ready to execute and successively to send the decision command. The low-level control commands are provided by a pre-programmed onboard subsystem, while the virtual reality model in the local zone uses only the few symbolic information received through the low bandwidth channel in order to reproduce the actual behavior of the system.

This report presents the solutions chosen to address the above issues for autonomous manipulation, developed during the course of the SAUVIM research project, and concluded with the demonstration of the first fully autonomous underwater manipulation in an unstructured environment.

The proposed study is in response to current local and national needs for the development of this technology and will ultimately be useful in many intervention missions. SAUVIM technologies could be extended for *harbor security* that would be part of *homeland security*, one of our nation’s current interests and concerns. One potential user is the Pacific Missile Ranging Facility (PMRF) of the U.S. Navy in the State of Hawaii.

Research summary

The SAUVIM project was proposed as a two-phase research and development program. Phase I had three parts: (1) to study the major research components, (2) to develop and integrate the basic software and hardware of SAUVIM, and (3) to test the vehicle in a shallow water environment. Phase II is a continuation and completion of the research and development of Phase I with water environment testing.

As stated in the original proposal, the project consists of five major components:

- Adaptive, Intelligent Motion Planning;
- Automatic Object Ranging and Dimensioning;
- Intelligent Coordinated Motion/Force Control;
- Predictive Virtual Environment; and
- SAUVIM Design.

During the Phase I period, there have been approximately sixty people supported by this ONR project. In 2007, there were 7 people working on the project in ASL - 1 faculty members, 3 full-time staff members, 2 undergraduate students, and 1 administrative assistant. The Advisory Committee was formed to provide technical advice and direction by reviewing research directions and progress, and to provide advice and assistance in exploring potential applications and users. The four-member Advisory Committee consisted of Mr. Fred Cancilliere of the Aquidneck Management Associates, Ltd., Dr. Alexander Malahoff of the University of Hawaii, Dr. Homayoun Seraji of the Jet Propulsion Laboratory, and Mr. Dick Turlington of the Pacific Missile Range Facility. Two additional members - Dr. Paul Yuen of the University of Hawaii and Mr. James Fein, the former ONR Program Director - have been included in the Advisory Committee.

- <u>Adaptive, Intelligent Motion Planning (AIMP)</u> – The AIMP aims at developing SAUVIM's motion planning, which is intelligent and adaptive in that the system is capable of decision-making at a task or mission level and can deal with unknown or time-varying environments. Motion planning for an AUV can be decomposed into path planning and trajectory generation, although they are not completely independent of each other. Path planning is a computation and optimization of a collision-free path in an environment with obstacles. Trajectory generation is the scheduling of movements for an AUV along the planned path over time. To simultaneously compensate for these objectives, a genetic algorithm (GA) based 3D-motion planner was studied both off-line and on-line cases. In general, and for any algorithms, an off-line case is when an environment is known and static, while an on-line case must be capable of modifications in response to dynamic, environmental changes. The utilization of GA-based approach has two advantages: 1) it is adaptive and 2) the dimension of space has less effect on performance than other methods.

  The AIMP software has gone through three version upgrades. The first was *Version 1.alpha*, which integrates the off-line and on-line algorithms in C with a graphic user interface using OpenGL. This software version was tested on the Autonomous Systems Laboratory's autonomous underwater vehicle - ODIN. The second was *Version 1.0*, which integrates the path planning and trajectory generation algorithms. The third was

Version 1.1, which optimizes the original software organization and data structures, and includes a database of mapping data on the main memory. Also, a Software Development Process (SDP) has been developed and implemented to oversee the various developments in software version changes. Several papers have been published in these subjects.

During an attempt to make an on-line version of AIMP in Phase II-C, it was found that there was no ending condition of genetic evolution to build a 3-D motion planner. There was no measure to guarantee optimality of the generated 3-D path or trajectory as well. Thus a conventional math-based motion planning method is implemented in Phase III-A, and a new motion planning algorithm has been investigated for complex motion in 3-D as well as minimizing computing burden.

Phase III-B has seen an increase in the degrees of freedom that the motion planner is able to handle, in order to better cope with the requirements of an underwater intervention. The conventional math-based motion has been extended in order to optimize the rotational and translational movements of the vehicle, allowing precise positioning of the robotic arm in the area of interest. This is usually different from the fly-by type AUV where the primary goal is to survey a generic area.

- <u>Automatic Object Ranging and Dimensioning (AORD)</u> – The main objective of the AORD is to develop a multiple sensor system to be utilized during SAUVIM's intervention missions to locate the target. This system *originally* consisted of three-sensors:
  1. Laser ranging sensor (LRS),
  2. Passive arm sensor (PA)
  3. Manipulator homing sensor (MHS)

  The laser ranger, the homing sensor, and the passive arm have all been designed and prototyped in the previous phases.

  The underwater prototypes of the LRS has been fabricated, assembled and tested, with the camera housings manufactured using 6061 aluminum with vacuum-sealed lens. The software has been developed using the prototypes.

  The PA, in its original configuration, was made of 6061-Aluminum, and it had two three-axis gimbaled joints and a single-axis hinge joint. The entire PA structure was compensated with mineral oil. It utilized the original software developed for the prototype. The kinematics of the PA has been re-verified using various symbolic math packages. The passive arm has also been rewired for optimal performance. It was simulated with the active arm to conduct feasibility studies in obtaining active manipulation position. However, after a long investigation, it was concluded that the PA cannot be easily deployed and retrieved in the water due to the lack of active power in the arm. Thus, an underwater version of the ultrasound motion tracker has been introduced as replacement of the passive arm system. Since there are no commercial versions of similar devices, a prototype version of the ultrasonic motion tracker had to be developed in house.
  The original idea of the homing sensor was to use a dedicated PC104 computer with camera to detect a simple circular barcode. It was originally tested to confirm its

performance in the water, and, despite results were good enough to use the bar code in the water, it suffered of obvious application limitations. During the past years, and especially starting with the Phase III-B, the idea shifted toward a more organized and range dependant Target Identification procedure.

The localization subsystem has been subject of major upgraded during the Phase III-B, and finalized to a fully-working and extensively tested subsystem during the last Phase III-C. The target localization process, which is the main support for the capabilities of the autonomous manipulation of SAUVIM, in its final configuration, is performed by using and fusing different technologies (acoustical and optical) in order to guarantee a suitable, range dependent, level of reliability, precision and accuracy. The SAUVIM AUV switches through three main sensing methods in order to acquire reliable data. As shown in Figure B, the sensor technology changes according to the combination of range and accuracy needed.
In *long range* (over 25m), 375KHz image sonars are used for initial object searching. The accuracy in this range is necessary only to direct the vehicle toward the target zone.

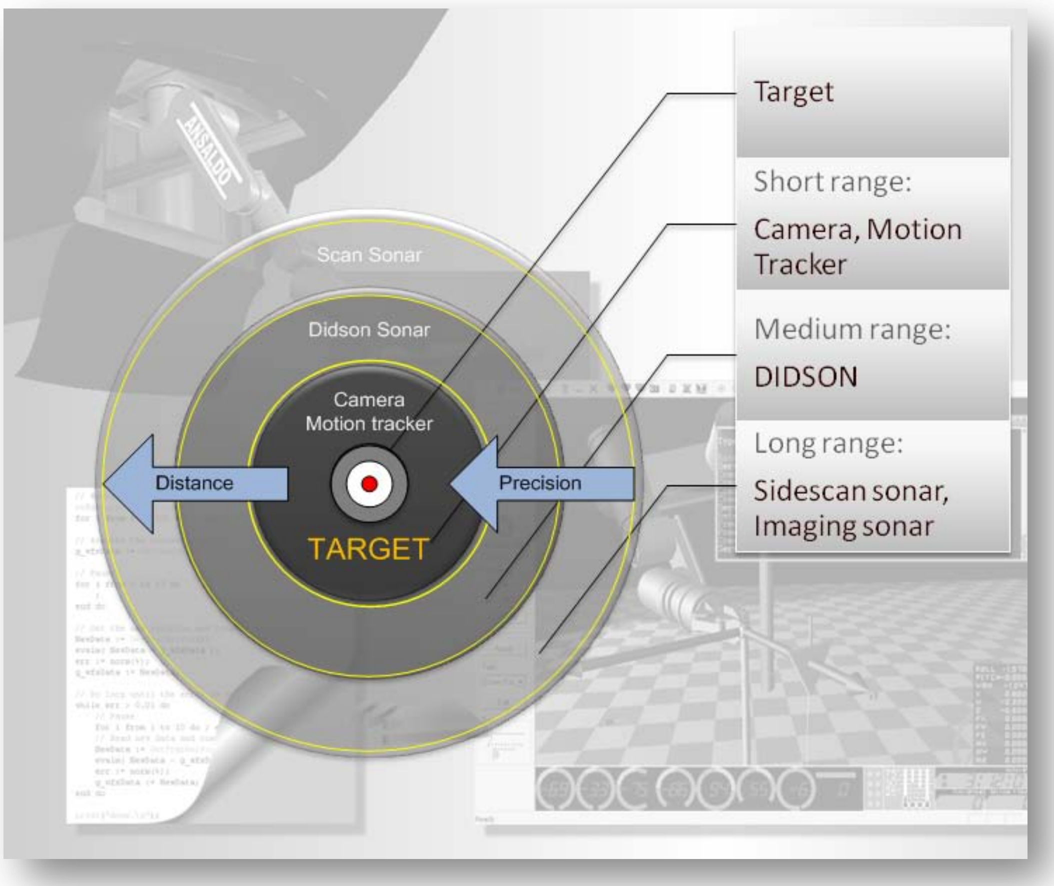


Figure B. The phases involved in a search for the target.

In *mid-range* (2-25m), a Dual frequency IDentification SONar (DIDSON) is used for object recognition and the vehicle positioning. This is the phase where the vehicle has to position itself in order to have the target confined within the manipulation workspace.

At this range, and in case of turbid water, it is virtually impossible to use conventional optical cameras to identify an object. This justifies the use of the DIDSON, which has been used as a ranging sensor from Phase II-C onwards. During the Phase III-B our focus has been directed toward refining the algorithms of autonomous target identification with the DIDSON. In the final Phase III-C the algorithms have been implemented and successfully tested in repeatability and robustness, thus allowing the SAUVIM vehicle to reliably find a path toward the target area.

Finally, when the target is within the manipulator workspace, *short range* and high accuracy sensor are used in order to perform the actual intervention task. This goal is achieved with the combined use of underwater video cameras and the ultrasonic motion tracker described above, used to retrieve the real-time 6 DOF position of the target during the manipulation tasks. The device utilizes high frequency sound waves to track a target array of ultrasonic receivers. The use of 4 transmitters at the stationary positions with 4 receivers on the target can be used to determine the 6 DOF generalized position (rotation and translation) of the object.

- Intelligent Coordinated Motion/Force Control (ICM/FC) – The major objective of the ICM/FC is simple yet complex. The control of an AUV and its manipulator is a multi-bodied, dynamic problem of vast unknowns; therefore, this task was subdivided into four sub-tasks, which were:
  - Theoretical Modeling (TM)
  - Low-Level Control (LLC)
  - High-Level Control (HLC)
  - Dry Test Design and Set-up (DTDS).

  However, with the arrival of the 7-dof underwater manipulator, the TM and DTDS were combined to form a common group – Manipulator Control and Test Platform (MCTP). Also, a Localization and Navigation (LN) group was spun-off the LLC group due to the vastness and complexity of the LN material. The LN group was trying to devise a hybrid localization and navigation methodology that will suffice in understanding the geophysical, terrain-matching and dead-reckoning aspects for proper navigation. An integrated data fusion methodology was also being devised to quickly and correctly digest the immense amounts of data from the sensors, which undoubtedly has mass abundance of noise and errors. However, it was found that the map-based localization method is a task computationally intense and, despite this aspect, does not meet the accuracy requirement for the vehicle control. Thus, a Ultra Short Base Line (USBL) device has been used as a vehicle monitoring sensor as well as a position feedback sensor.

  The MCTP was developed to accelerate the progress in the **TM** and **DTDS** sub-tasks. With the acquirement of the MARIS 7080 manipulator and constraints in time, the focus has been changed to the development of the arm software in conjunction with the manipulator kinematics, dynamics, force-control and coordinated motion control modules. During the Phase II of SAUVIM the Maris 7080 manipulator initially ran off the VME bus system using VxWorks and Matlab with Simulink. Development in the "rapid prototyping, graphic software" has been the central point in enhancing the complex, underwater dynamic actions and reactions. The manipulator control code has been developed to perform force/torque tasks, path optimization around singularity points, and collision avoidance techniques. Successively the development approach moved from the rapid prototyping mode to the stand-alone mode, in order to optimize the performances in the vehicle.

In phase II-B, a new parking procedure was developed and tested in the water. This is one of the most critical tasks of the manipulation system, due to the limited space for the manipulator in the vehicle. The Arm Programming Language (APL) was developed for high level control of the manipulator without changing system S/W, and an ultrasound motion tracker was interfaced (in the air) to the manipulator to get precise position feedback information, used either for calibration purposes and for initial dry tests of target tracking. The underwater version of the motion tracker is under development for substituting the passive arm which was originally planned to measure relative position/orientation between the target object and the vehicle. Preliminary results obtained during the Phase II-B showed a very high precision in position measurement.

In Phase III-A, image processing module in robot system was upgraded including new frame grabber and image processing library for Intel CPU. The phase III-B has seen further improvements of the camera system, with added procedure for auto-calibration to be performed directly on the target site (underwater) in order to compensate for the local water condition.

The Phase III-C brought to the manipulation subsystem further upgrades and extensive testing of the system: a more accurate object detection capability, a workspace optimization controller and a reliable collision avoidance system. The final demonstration confirmed great repeatability and robustness of the robotic subsystem.

The **LLC** was created with two objectives: 1) to design and develop an advanced vehicle control system for navigation and hovering, and 2) to design and develop an advanced coordinate motion/force control system of the vehicle and manipulator during the intervention mode. However, with the creation of the LN group, the emphasis was on the integration of the localization and navigation techniques to the basic motion and hovering tasks. During the Phase III-A the development of the coordinated motion/force control system was being explored from two separate platforms. As the MCTP development continued, the LLC was optimizing the hovering and station-keeping methodologies on the ODIN vehicle. Various types of modern controllers, such as Adaptive controller, Disturbance Observer (DOB) controller, Adaptive DOB controller, and Neuro-fuzzy controller, were investigated in order to find the best controller for the underwater vehicle.

In all the SAUVIM Phases, the focus of the LN group has been on efforts in obtaining high performance in navigation and hovering. Before the current phase III-B the navigation and hovering techniques made use of the data from the on-board scan sonar, altimeter sonar, inertial navigation unit, Doppler Velocity Logger (DVL), and pressure sensors. The Ultra Short Base Line (USBL) and Global Positioning System (GPS) were added as a global vehicle position feedback sensor during underwater navigation and surface navigation, respectively.

However, at the end of the Phase III-A, it was evident how the accuracy and precision of this sensor system was insufficient, in particular conditions, during the manipulation tasks. Thus it was necessary, during the phase III-B, to introduce a more reliable Inertial Navigation System aimed to produce the position data with the reliability necessary to the autonomous intervention.

This important change, together with a complete re-design of the navigation controller, allowed the SAUVIM vehicle to successfully perform in compliance with the precision, accuracy and stability requirements of our manipulation task.

Another important upgrade of the Phase III-B, aimed to improve the coordinate motion between the arm and the vehicle, was the standardization of all the communication protocols. This was accomplished with the extension of the xBus protocol, once dedicate to the arm subsystem only, to the entire vehicle. xBus showed a great flexibility in handling every kind of communication (data, program code, messages..) and thus it was chosen as the SAUVIM standard.

xBus uses a client-server approach for delivering information from and to each distributed module. Each subsystem (as a backset module or a generic sensor) embeds a custom TCP-IP client-server communication system (see [Marani05]). Within this architecture, every server can deliver the requested information on-demand to any number of clients, and this configuration allows a different utilization of the bandwidth, since every data is broadcasted only on demand.
This approach is similar to the Publish-Subscribe Middleware paradigm [Ben07], where the term `middleware` refers to the architecture software that coordinates the set of software modules collectively comprising the backseat-driver system running in the payload. Publish-subscribe middleware implements a community of modules communicating through a shared database process that accepts information voluntarily published by any other connected process and distributes particular information to any such process that subscribes for updates to such information.
In the SAUVIM approach the information is not published by a central database, but every source acts as a server that may send only the requested information to the requesting client. The distributed client-server architecture also provides a security hand-shaking mechanism, which provides direct feedback on the execution of any instance of data exchange. This is particularly desirable in issuing security commands (such as for aborting the mission).

During the Phase III-C, in its final configuration, xBus serves more than 15 client-server subsystem and brings all the available information in the central interface Sauvim Explorer.

HLC's objective is to develop a supervisory control module that will minimize human involvement in the control of the underwater vehicle and its manipulation tasks. In the gradual passage from human tele-operated manipulation to autonomous intervention, the most noticeable aspect is the increase of the level of information exchanged between the system and the human supervisor. In teleoperation with ROVs, the user sends and receives low level information in order to directly set the position of the manipulator with the aid of a visual feedback.

As the system becomes more autonomous, the user may provide only a few higher level decisional commands, such as “unplug the connector”, interacting only with a higher level task-description layer. The management of lower level functions (i.e. driving the motors to achieve a particular task) is left to the onboard system. The level of autonomy is related to the level of information needed by the system in performing the particular intervention.

With the above considerations in mind, the HLC module initially involved the development of high-level task planning where a mission is always composed of two parts: the goal and the method of accomplishment. In other words, "what do I need to do" and "how do I do it." Following this strategy, a new high-level architecture of vehicle control, named the Intelligent Task-Oriented Control Architecture (ITOCA), was developed for SAUVIM.

In phase III-B there was a major upgrade of this configuration. The high level control layer of both the manipulation and the navigation systems have been standardized and upgraded to a powerful custom programming language.

A software emulated CPU, where the mission control resides, hosts this new dedicated programming language developed in order to address the above issues [Marani05]. This language, suitable for real-time embedded control systems, offers at the same time flexibility, good performance, and simplicity in describing a generic complex task. Its layer abstraction approach allows an easy adaptation to the hardware-specific requirements of different platforms. For example, the same module can be found in the manipulator platform for describing a generic manipulation task and in the main navigation controller for driving the vehicle to the target area. The client-server approach allows the necessary communications between the arm and the navigation module.

The language is completely math-oriented and capable of symbolic manipulation of mathematical expressions. The last is an important distinctiveness from most of the currently available robot programming languages. The procedural approach has been chosen in order to enhance the performance while maintaining the flexibility required for executing complex tasks. It is particularly suitable for real-time embedded systems, where the interaction of a generic algorithm with the time is critical.

The Phase III-C made an extensive use of the above environment, with several upgrade of the language, and an important addition of the Central Intelligence Data Manifold module. The latter is a third environment that hosts a higher level decisional layer, for coordinating the priorities between the vehicle and arm MLC subsystems.

<u>Predictive Virtual Environment (PVE)</u> – The PVE was aimed at developing a supervisory monitoring system for SAUVIM to smoothly and realistically integrate mapping data with on-line sensory information even in the midst of delayed and limited information. This virtual reality (VR) based system must also be able to accurately predict the current status and location of the vehicle under these conditions. The

development for the PVE has been modular. The various modules are: the SAUVIM Simulation Software (SSS); the SAUVIM Video Overlay Software (SVOS); the Communication Software (CS); and the artificial neural network (ANN) Video Prediction Software (VPS). In the Phases I and II of SAUVIM the SSS has been upgraded from its *Version 1* to *Version 1.1*, which includes the incorporation of a Magellan spaceball mouse, an accurate 3D graphical model of SAUVIM and the Maris 7080 manipulator, scene-smoothing methods using interpolation techniques, and an easy-to-use user interface. The SVOS was developed to overlay video images of the seafloor (texture and color) to the graphic images to provide a more accurate monitoring of the vehicle, manipulator and environment. The CS for SAUVIM was an extension of the NSF's DVECS (Distributed Virtual Environment Collaborative Simulator) project. At that time, the DVECS system used a cellular phone to communicate the vehicle data from the test-site to the monitoring computer located on campus for data fusion. Experiments have been conducted with the ODIN AUV. The experiments of ODIN were projected via an ElectroHome Marquee 8500 CRT projector coupled with multiple Stereographics (SG) emitters and SG CrystalEyes glasses. Finally, the VPS has been tested, and, although in its early stage, with positive results.

Successively, due to the high maintenance costs of SGI workstations, the overall virtual reality and monitoring system, which includes the video prediction, has been transformed to a much more stable and inexpensive personal computing system, taking advantage of the emerging market of high performance hardware video accelerators (mostly targeted to PC games).

MarisGL was, during the Phase II, the preliminary version of the virtual environment targeted to the MARIS 7080 Manipulator and making use of a standard OpenGL PC video accelerator. During the Phase III-A the application was extended in order to introduce the vehicle model, mainly for collision avoidance verification. But the most important transition toward the global virtual environment happened in the Phase III-B and the current III-C.

Here, the name of the application, once targeted to visualize only the configuration of the arm, has been changed to Sauvim Explorer (Figure C). Sauvim Explorer collects in a unified application the data from all the sensors of SAUVIM, including data from the DIDSON that can be overlaid over the graphical reconstruction of the floor.

It also hosts the remote console clients for both the Arm Programming Language and the Sauvim Programming Language servers, and may act as remote control (ROV mode) when a sufficient bandwidth channel is present. At this aim Sauvim Explorer contains software interface with several input device hardware, including 6 DOF space controllers.

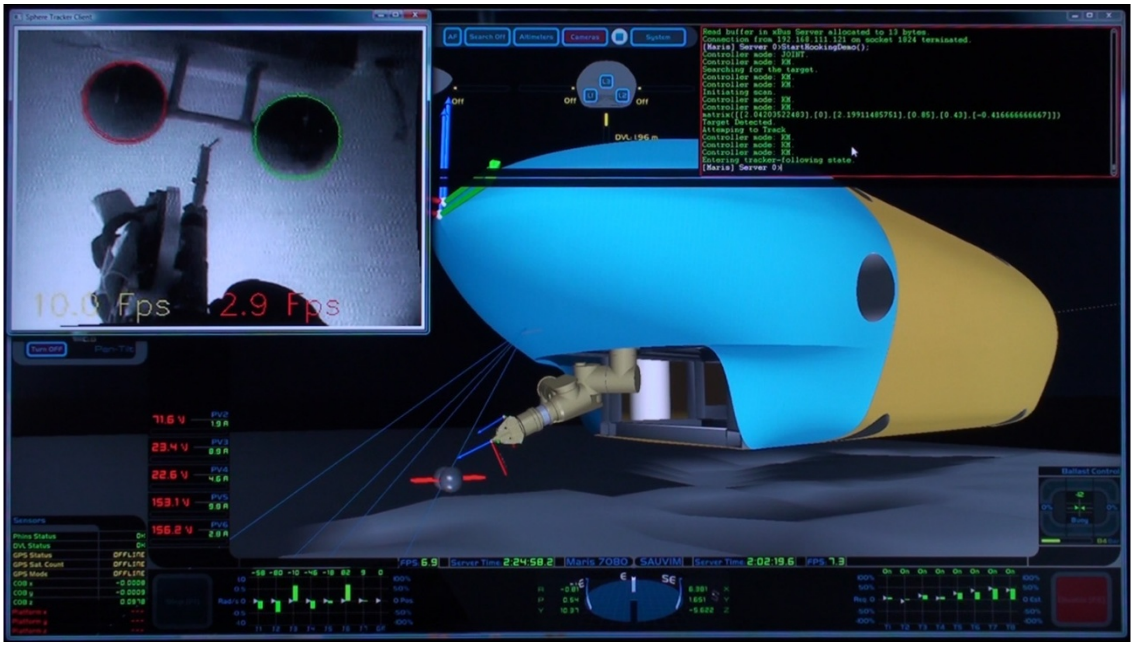


Figure C: Sauvim Explorer

This represents an enormous step forward toward the unification of the whole system, since it required a huge effort on the standardization of the communication protocol between every module of SAUVIM (sensors, actuators, controllers…). With this modular approach it is now extremely easy to add further sensor modules to SAUVIM and add their input and outputs to the SE application with a minimal effort.
During the last Phase III-C Sauvim Explorer was integrated with a global data recorder, thus allowing data storing and replaying of all the mission of the vehicle.

SAUVIM Design (SD) – This task was one of the main objectives of the SAUVIM project. It was an effort to design and develop efficient, reliable hardware/software architectures of SAUVIM. Due to the immense demand of this task, it has been divided into five sub-tasks, which are:

- Reliable, Distributed Control (RDC)
- Mission Sensor Package (MSP)
- Hydrodynamic Drag Coefficient Analysis (HDCA)
- Mechanical Analysis and Fabrication (MAF)
- Mechanical-Electrical Design (MED).

The goal of **RDC** was to develop a reliable and efficient computing architecture for signal and algorithmic processing of the entire SAUVIM system. The proposed system is a multi-processor system based on a 6U VMEbus and the VxWorks real-time operating system. This system is capable of high processing throughput and fault tolerance. Currently the system consists of:

- Two VMEbuses, which are the navigation control system and the manipulator control system

- Two PC104+ computers dedicated to sensor data acquisition, processing and sharing;
- One PC104+ that hosts the video processing algorithms for the target detection and tracking system
- One PC104+ for the ultrasonic tracker (currently in development).

The main VMEbus, or the navigation control system, has one Motorola MC68060 CPU boards and a digital/analog I/O board, and two Pentium-M processor-based PC104+ boards, which share data through the Ethernet-based standard protocol xBus. The navigation control system handles the communication, supervision, planning, low-level control, self-diagnostics, video imaging, etc.

The second VMEbus, or the manipulator control system, has one Motorola MC68060 CPU and several hardware-dedicated I/O board. One PC104 board aids the manipulator control system in performing the video processing operation necessary to detect and track the target. Data resulting from the video processing subsystem are shared with the whole SAUVIM system (including the Sauvim Explorer interface), again using the standard xBus protocol.

The manipulator control system, once independent and dedicated to the manipulator control, can now share its programming language subsystem with the navigation controller, a very important feature to perform underwater intervention.

Many of the hardware components have been tested and are interfaced with its respective software systems. Various optimization changes have been implemented to minimize communication and computation. The overall hardware and software architectures have been completed and integrated. Tests for the RTOS architecture has been integrated with the SAUVIM vehicle hardware and tested as individual components. The overall vehicle control with sensor feedback has been conducted at Snug harbor. This development will continue throughout the vehicle's development process.

The objective of the **MSP** was to provide semi-continuous records of underwater environment such as water depth, temperature, conductivity, computed salinity, dissolved oxygen, magnetic signature of the seafloor, pH, and turbidity, during the survey mode. In the intervention mode, the MSP also provides compositional parameters at a selected seafloor target, including pumped samples from submarine seeps or vents. The MSP is an independent system with its own PC 104 CPU and its own power supply residing in a separate pressure vessel. All of the sensors have been purchased and mounted, and an initial field test at the Loihi Seamount has been conducted. Other tests have been conducted to optimize the scientific sensor data-gathering capabilities. The communication from the MSP and the vehicle CPUs was initially based on RS-232C serial link.

The **HDCA** was used to determine the hydrodynamic coefficients via a numerical solution of full Navier-Stokes equations using PHOENICS, a commercial computational fluid dynamics (CFD) code. Initial results from the PHOENICS software have produced mixed results. The current vehicle fairing has produced a drag coefficient of 0.40; however, it has not yet been verified. Other CFD software and model testing is being conducted to verify the drag coefficient results before the implementation of the vehicle fairing on SAUVIM. There has been no significant development in this task group. The hydrodynamic coefficients will be obtained through vehicle motion experiments in the near future to aid in simulator developments.

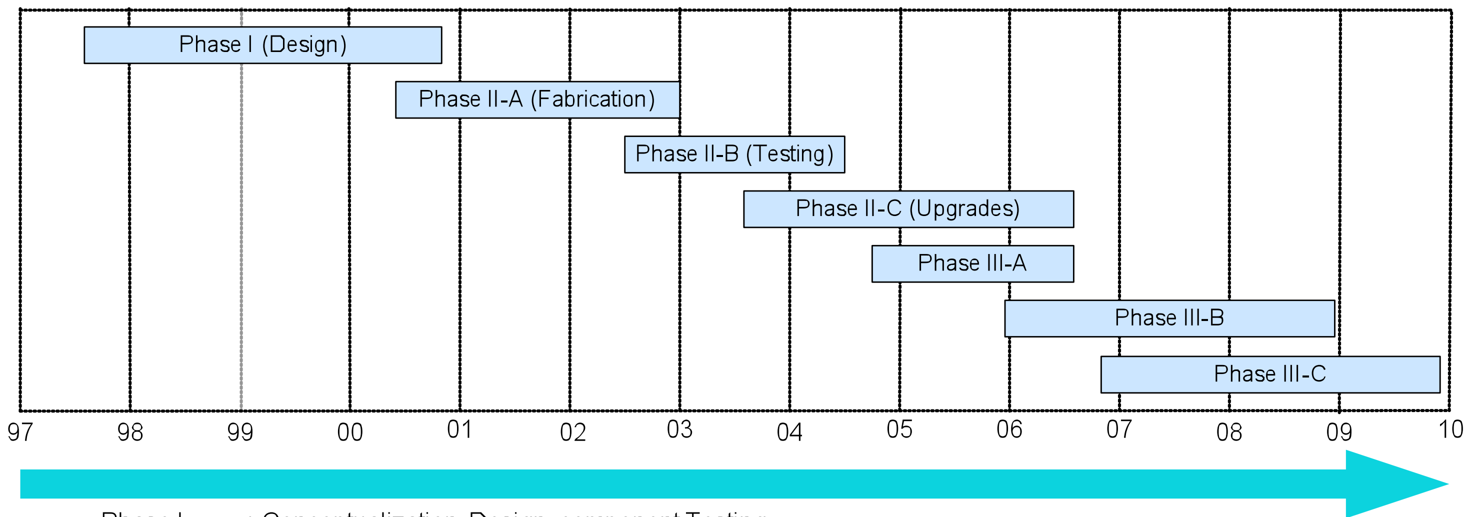
The **MAF** had three objectives. Its primary goal is to design and fabricate composite pressure vessels with end caps and connector openings for full ocean depths taking stress, buckling, hydrothermal effects, and fatigue analysis into account; and its two secondary goals are to design and fabricate the SAUVIM fairing and to analyze the SAUVIM frame. A thorough analysis and comparison of the Ti-6Al-4V, AS4/Epoxy, and AS4/PEEK pressure vessels manifest the advantage of composite materials in reduction of weight, size and strength. Using these results, a scaled model prototype using AS4/PEEK has been fabricated and tested. A 1/3 sized prototype is being fabricated and will also be tested. For the shallow water vehicle test, a full-sized, fiberglass pressure vessel with aluminum end caps have been manufactured and tested. These vessels are being used to determine the final hardware layout. The aluminum frame has been designed and fabricated. A full-ocean depth pressure vessel of AS4/PEEK has been developed and tested. However, due to several unknowns regarding composite pressure vessels, the vehicle has been equipped with 1000 meter-depth aluminum pressure housing. These aluminum housings will be used for the shallow and mid water depth experiments. The fairing analysis has been developed and expanded. After exploring various manufacturing and molding methods, the initial fairing was fabricated in-house in Phase II-B.

The **MED** was the integration of the mechanical and electrical components for SAUVIM. First, the design specifications were established for the fairing, frame, instrument pressure vessels, buoyancy systems, mission sensor, passive arm and robotic manipulator tasks. Second, after scrutinizing review of SAUVIM's major components - i.e. sensors, actuators and infrastructure - in terms of power consumption, compatibility, weight distribution, buoyancy distribution, hydrodynamic effects and task effectiveness, all major components have been purchased. Technical drawings of the vehicle frame, fairing, and related sub-structures have been completed. Most of the mechanical and electrical components have been fabricated and integrated with the overall electrical layouts. There were two wet-tests in Phase II-A, several autonomous shallow water tests were conducted in Phase II-B, and, from Phase II-C onwards, several vehicle navigation and underwater manipulation works.

The main body of this report is devoted to the detailed descriptions of the major technical developments and achievements during the period of Phase III-C, from October of 2006 to the October 2009.

A detailed description of the work of the prior phases was given in the previous SAUVIM final reports.

Giacomo Marani
SAUVIM Acting Principal Investigator
January 28, 2010



Phase I : Conceptualization, Design, component Testing
Phase II-A : Vehicle design, Component design, Fabrication, Initial testing, Navigation testing in shallow water
Phase II-B : Design modification, Navigation testing in shallow water
Phase II-C : Upgrades, Manipulator testing in shallow water
Phase III-A : Upgrades, Navigation + Manipulator testing in shallow water
Phase III-B : Upgrades toward increased autonomy, Navigation + Manipulator testing
Phase III-C : Upgrades toward increased autonomy, Autonomous Intervention test

Figure D: SAUVIM: Simplified Gantt Chart

Table of Contents

SAUVIM Final Demonstration: the first fully autonomous mission

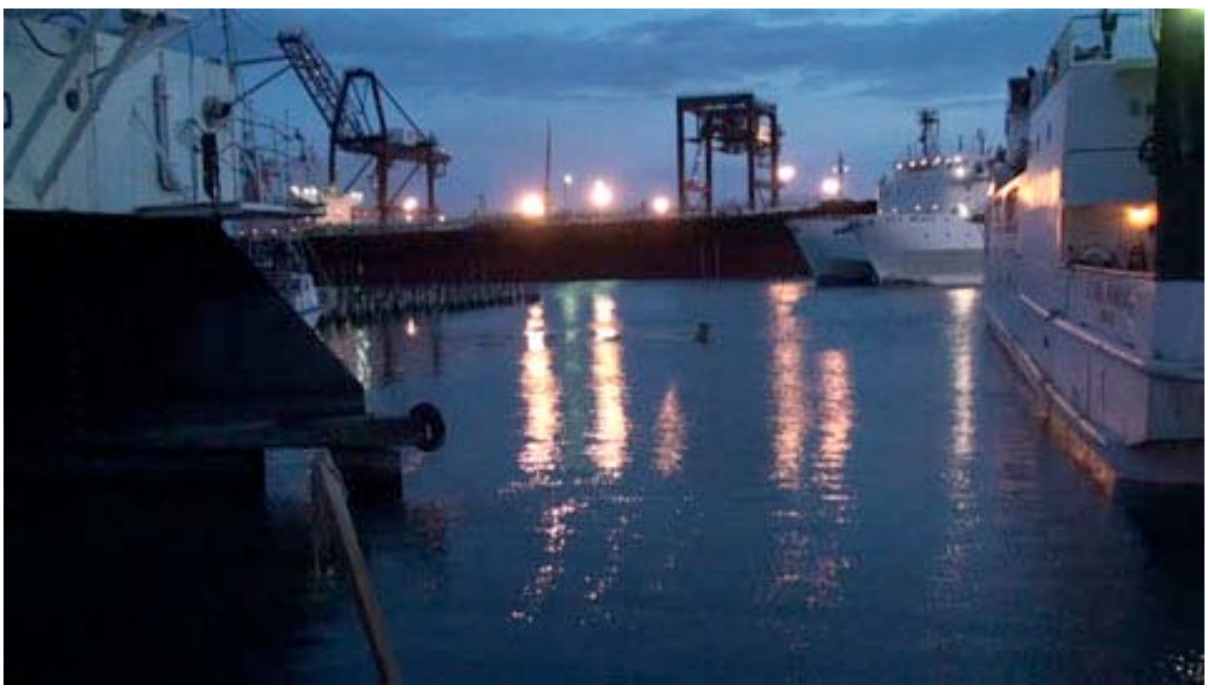
Project Leader(s): Giacomo Marani
Personnel: Giacomo Marani, Song K. Choi, Aaron Hanai, Kaikala Rosa

Objectives

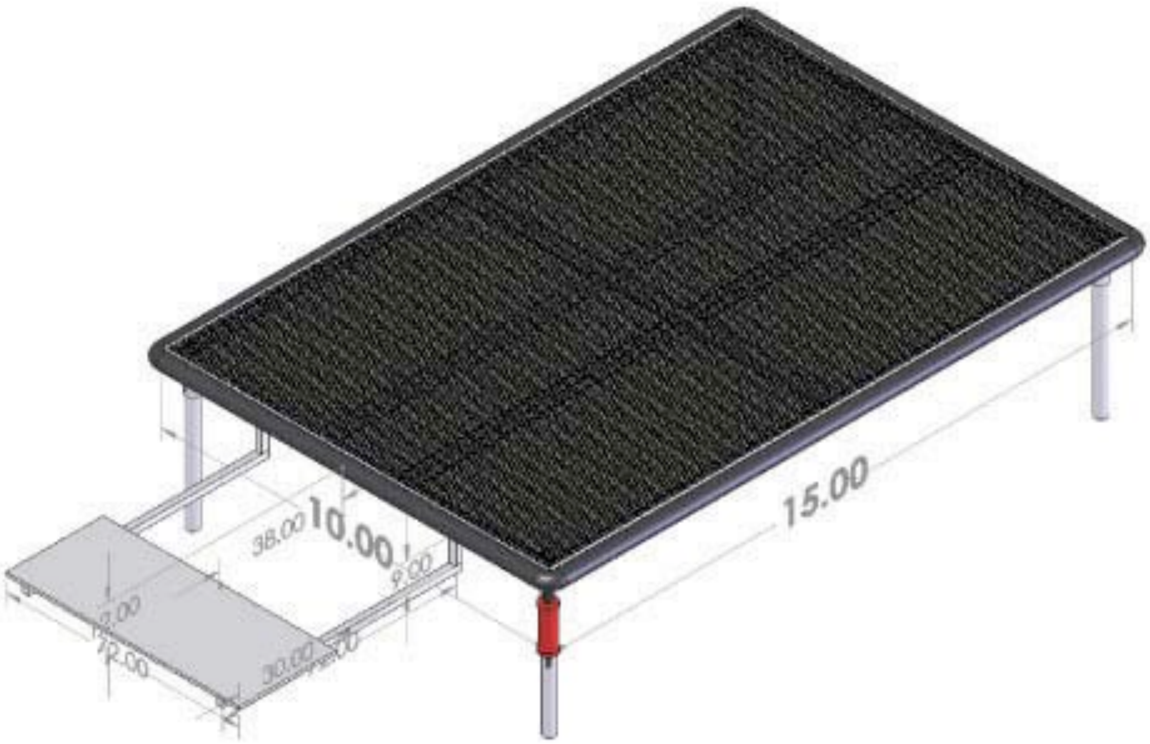
The aim of the SAUVIM final experiment is to demonstrate the capabilities of the overall system, with particular care to the autonomy aspect.

Introduction

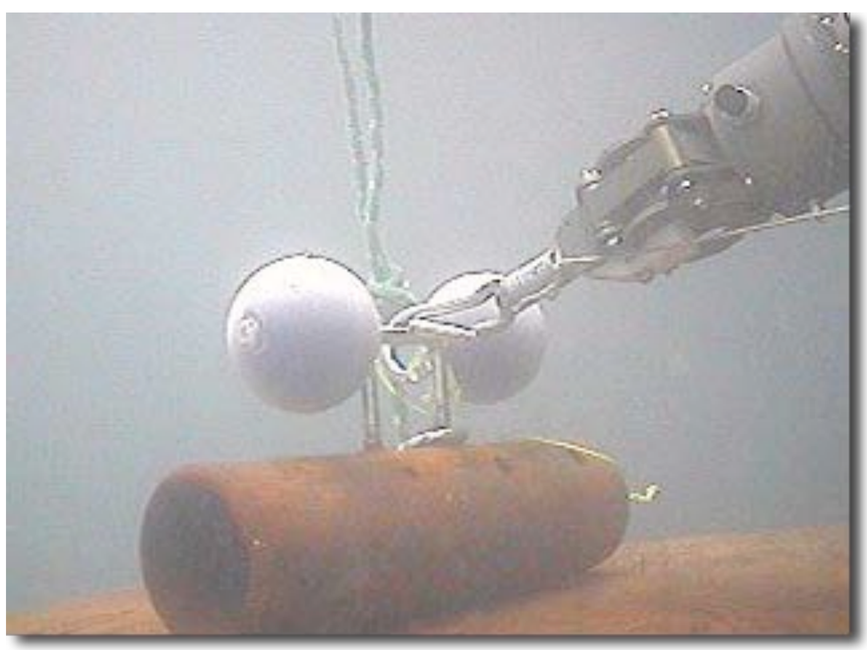
The first fully autonomous underwater manipulation in an unstructured environment was demonstrated at the Snug Harbor, Honolulu, Hawaii at the end of the project. The SAUVIM vehicle performed a fully autonomous navigation and manipulation task. This live demonstration presents a technological breakthrough in the field, as the autonomous manipulation had been a bottleneck for underwater intervention missions.



The SAUVIM in water first performed the self-calibration routine, initializing its sub-systems. After the calibration, the SAUVIM started its motion for a pre-given mission, which was to search for an underwater object and to securely hook a recovery device the object.



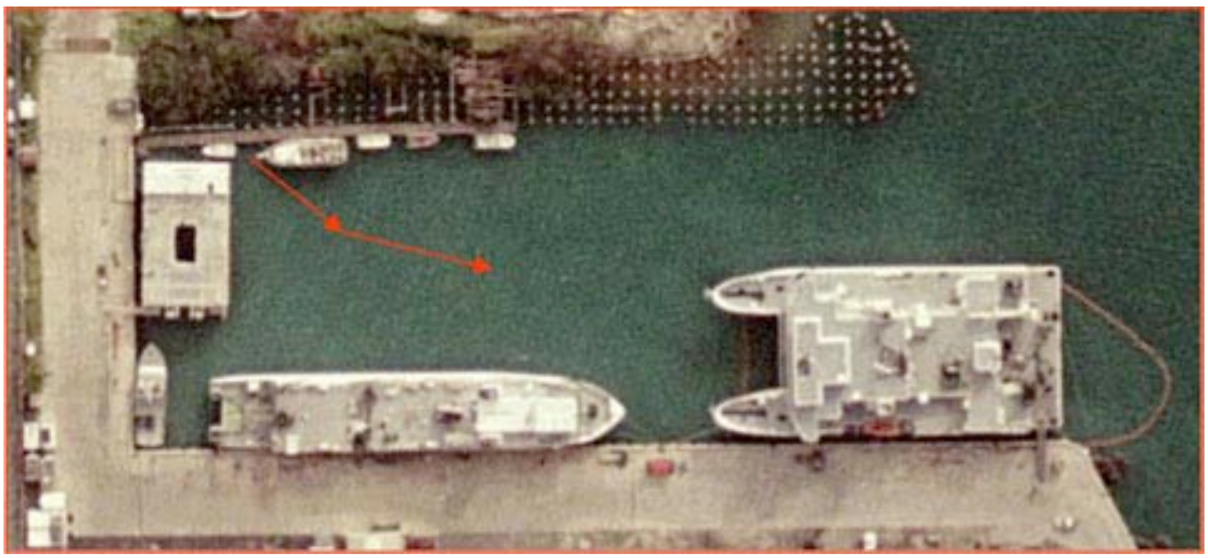
The object’s location was roughly given. It was know to lie somewhere in the front of the platform above. The platform location was submerged in an unknown location of the SNUG harbor.



Once the target was detected, the vehicle approached to it and positioned itself for the optimized manipulation. While the vehicle was floating in the water column, using the unified coordinated motion control of the vehicle and manipulator system, the vehicle performed an autonomous manipulation that was tagging-the-object. After completing the mission, the vehicle came back to the dock by using feature-based navigation. The whole sequence was autonomously done and the same mission was successfully repeated four times.

Phase 1: Undock

In this initial phase SAUVIM leaves the pier, where is normally docked, to reach the center of the harbor.



SNUG Harbor

The navigation, in this undocking phase, was aided by the DGPS, which in our case was giving an accuracy of about 2-3 meters. This accuracy is more than sufficient to select a target area where to begin the search for the platform.

Phase 2: Platform Search

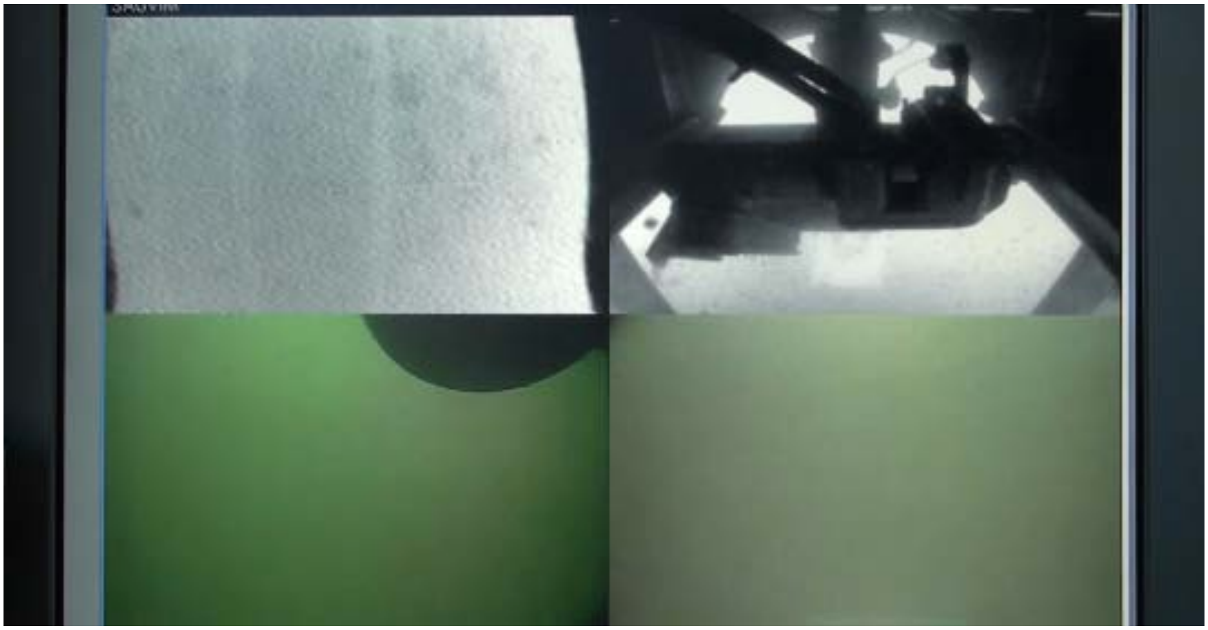
Once reached the center area of the harbor, SAUVIM begins searching for the main platform. In this phase it uses the DIDSON sonar as explained in the DIDSON section.

After detecting the platform, SAUVIM aligns itself to it, preparing for the dive and the autonomous approach.

Phase 3: Navigate and dive toward the platform

After the precise location of the platform has been measured in the previous phase, the vehicle initiates the approaching phase.

Using the PHINS corrected by the DVL, SAUVIM performs dead reckoning in order to position itself just 30 cm above the platform.



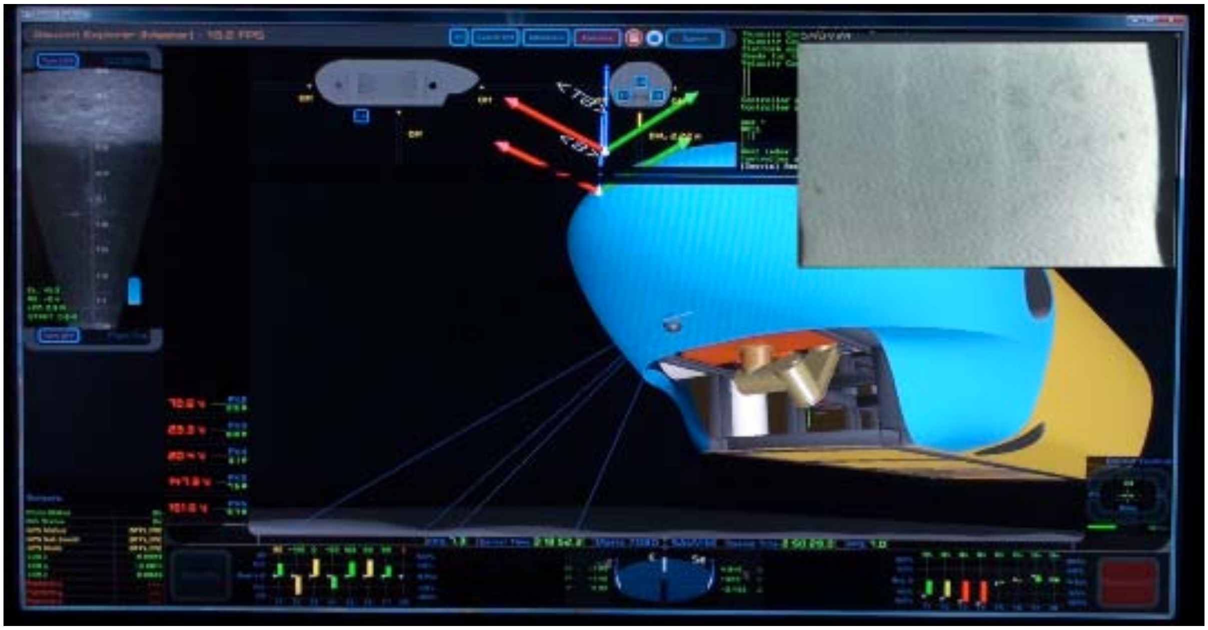
The above snapshot shows a view from the SAUVIM cameras while approaching the platform. Note the top-left camera: on different trials, the platform bar has been always centered in the view with a standard deviation of about 10 cm. This is a very impressive result in underwater object identification, which I believe has never been accomplished with the DIDSON sonar.

Phase 4: Hovering

SAUVIM is equipped with an advanced navigation control capable of precise station keeping (hovering). This is accomplished with a 6 DOF dynamic controller and an extended Kalman filter for real-time identification of the center of buoyancy (COB).

The COB identification is a remarkable and unique feature of the system: it allows to maintain active the control on pitch and yaw while minimizing the energy required. As a matter of fact, the reference position for roll an pitch is chosen in order to align the COB over the center of mass (COM).

The video shows the impressive stability and a very precise position control, in the order of sub-centimeter in translation. In particular, note the stability in pitch and yaw, a clear sign that the controller is active. This is a fundamental requirement for stabilizing the vehicle during manipulation.



Phase 5: Preparing the arm

SAUVIM is now hovering above the main platform, and the short-range search for the target is about to begin. During the previous navigation, the arm was safely docked in the bay area. Now it is time to wake, pick-up the recovering tool and fully undock ready for the final search.

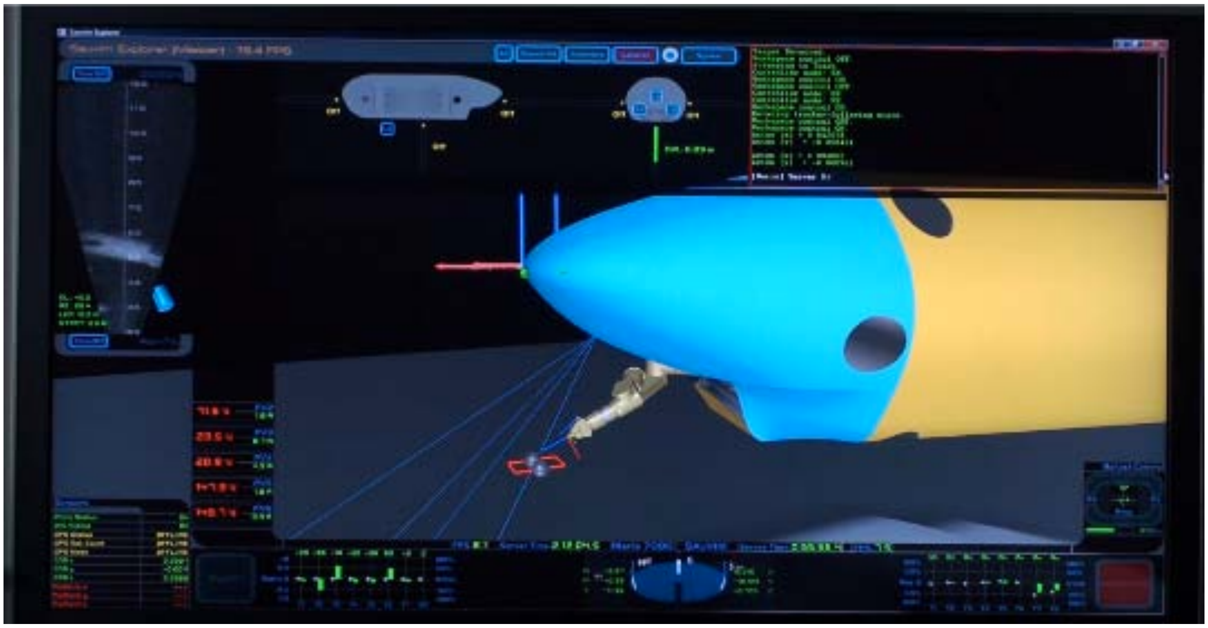
Phase 6: Autonomous Manipulation

Finally the most distinctive feature of the AUV: the capability of performing autonomous manipulation tasks in the underwater environment.

In this final phase the manipulator starts searching for the target using the camera that carries (short-range optical vision). The video below shows also the real-time processed view from the arm camera.

Once the target has been detected, MARIS enters in a tracking mode and, after successfully locking the target, performs few movements finalized to hook the carabineer. Note that the carabineer is a modified one, without the front part, so that we could repeat the task several time without the need to undo the hooking.

One important feature in this phase is the workspace optimization. The vehicle is set to adjust its position in real time in order to optimize the manipulation. This it is not really noticeable from the previous image, since the target was luckily found in a good position for the arm. Instead, in following snapshot, the target was found to the margin of the workspace. This time, the adjustment in the vehicle position was more evident and at the end the arm was not in the fully stretched position.



Note the excellent stability of the vehice, while performing the autonomous manipulation in hovering.

Phase 7: Return to the pier

Finally, with the task successfully accomplished, the vehicle begun its way back to the docking pier. Precise docking with the GPS is of course unfeasible, because the accuracy is limited to 2 meters.

Here, the vehicle showed another remarkable feature: feature-based navigation. After surfacing, SAUVIM went to the center of the harbor looking for again for the submerged platform. Then, knowing the relative distance of the docking pier with respect to this reference, SAUVIM set the course for its home. With this method, the standard deviation of the final position is about 10 cm, a respectable result in this kind of tasks.

Adaptive, Intelligent Motion Planning (AIMP)

Project Leader(s): Giacomo Marani
Personnel: Giacomo Marani
Past Project Leader(s): Dr. Tae Won Kim, Dr. Kazuo Sugihara & Dr. Song K. Choi
Past Personnel: Mr. John Smith, Dr. Shenyan Zhen, Mr. Haidong Chang, Ms. Hongshi Chen, Mr. Xihua Xu, Mr. Dwayne Richardson, Mr. Sonny Kim. Mr. Jangwon Lee & Mr. Yongcan Zhang

Objectives

This sub-project aims at developing the motion planning system for SAUVIM. It is intelligent and adaptive in the sense that the system is capable of decision-making at a task or mission level and can deal with an unknown or time-varying environment.

There are three basic objectives.

- To develop an off-line 3D motion planning algorithm.
- To develop an on-line 3D motion planning algorithm.
- To develop an adaptive, intelligent motion planning system by integrating the off-line and the on-line planning algorithms.

Current Status (Tasks Completed)

The task has been completed in the previous phases. Refer to previous reports for its descriptions.

Automatic Object Ranging and Dimensioning (AORD)

Project Leader(s): Dr. Giacomo Marani
Personnel: Mr. Luca Gambella, Dr. Giacomo Marani
Past Project Leader(s): Dr. Son-Cheol Yu, Dr. Tae Won Kim, Dr. Junku Yuh, & Dr. Curtis S. Ikehara
Past Personnel: Dr. Tae Won Kim, Mr. Marc Rosen, Mr. Mike Kobayakawa, Mr. Henrik Andreasson & Mr. Anders Andreasson, Mr. Aaron Hanai, & Mr. Oliver Easterday

Objectives

The main objective of the AORD is to develop a multiple sensor system to be utilized during SAUVIM's intervention missions to locate the target. The system will allow accurate vehicle positioning, workspace dimensioning and ranging, and manipulator homing to the task object. The localization task, that is the main support for the capabilities of the autonomous manipulation of SAUVIM, is performed by using and fusing different technologies (acoustical and optical) in order to guarantee a suitable, range dependent, level of reliability, precision and accuracy

Current Status (Tasks Completed during 10/25/2006 - 10/30/2009)

Overview

The original idea of the homing sensor was to use a dedicated PC104 computer with camera to detect a simple circular barcode. It was originally tested to confirm its performance in the water, and, despite results were good enough to use the bar code in the water, it suffered of obvious application limitations. During the past years, and especially starting with the Phase III-B, the idea shifted toward a more organized and range dependant Target Identification procedure.

The localization subsystem, that is the main support for the capabilities of the autonomous manipulation of SAUVIM, is performed by using and fusing different technologies (acoustical and optical) in order to guarantee a suitable, range dependent, level of reliability, precision and accuracy. The SAUVIM AUV switches through three main sensing methods in order to acquire reliable data. As shown in Figure B, the sensor technology changes according to the combination of range and accuracy needed.

In *long range* (over 25m), 375KHz image sonars are used for initial object searching. The accuracy in this range is necessary only to direct the vehicle toward the target zone.

In *mid-range* (2-25m), a Dual frequency IDentification SONar (DIDSON) is used for object recognition and the vehicle positioning. This is the phase where the vehicle has to position itself in order to have the target confined within the manipulation workspace. At this range, and in case of turbid water, it is virtually impossible to use conventional optical cameras to identify an object. This justify the use of the DIDSON, which has been used as a ranging sensor from Phase II-C onwards. During the Phase III-B our focus has been directed toward refining the algorithms of autonomous target identification with the DIDSON, thus allowing the SAUVIM vehicle to find a path toward the target area.

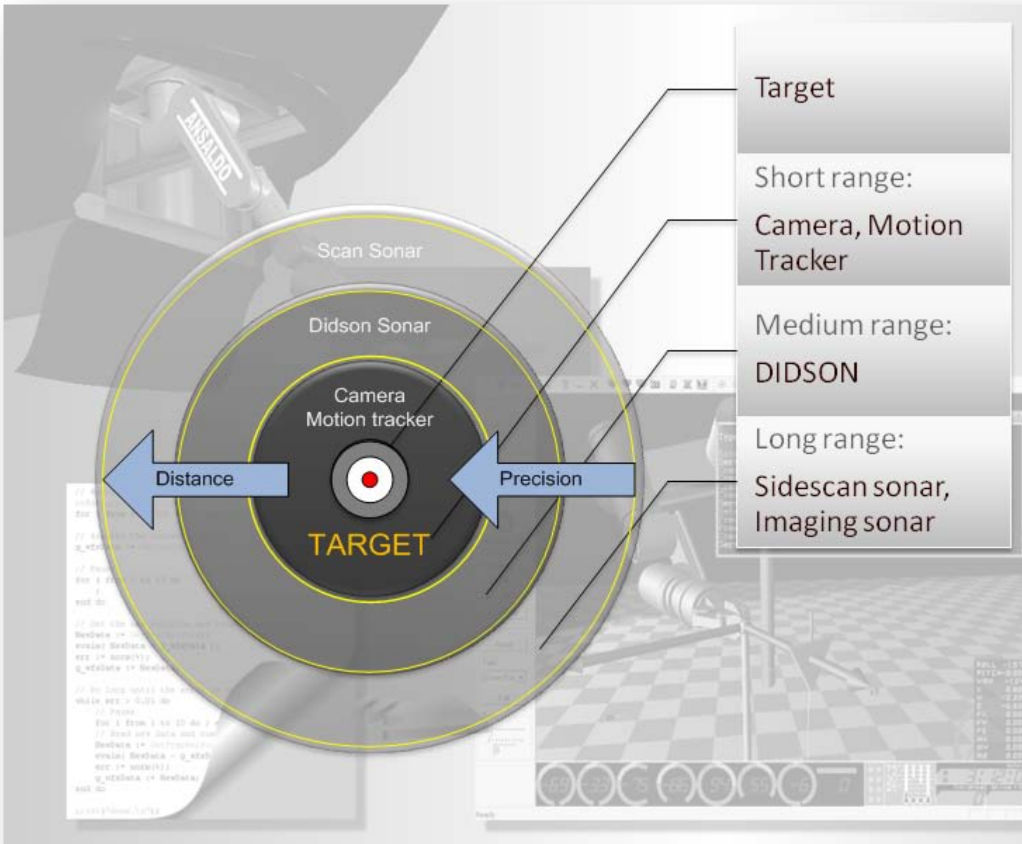


Figure AORD-1. The phases involved in a search for the target.

Finally, when the target is within the manipulator workspace, *short range* and high accuracy sensor are used in order to perform the actual intervention task. This goal is achieved with the combined use of underwater video cameras and the ultrasonic motion tracker described above, used to retrieve the real-time 6 DOF position of the target during the manipulation tasks. The device utilizes high frequency sound waves to track a target array of ultrasonic receivers. The use of 4 transmitters at the stationary positions with 4 receivers on the target can be used to determine the 6 DOF generalized position (rotation and translation) of the object.

During the Phase III-C the main effort was to upgrade and implement the medium range object identification with the DIDSON, for guiding the vehicle toward the target area. Based on the use of the DISDON sonar, the goal is to acquire the Earth-referenced cartesian coordinates of a known target, with the necessary accuracy required for positioning the vehicle so that the target falls within the manipulator workspace.. The task has been successfully accomplished, leading to the realization of a robust and repeatable module for guiding the vehicle toward the target.

In order to achieve the above objective, extensive product engineering works have been necessary, other than several further developments of the hardware/software control system.
The final objectives include the following:

- Development of the Ethernet communication protocol for the DIDSON parameter setting, sensor control and management and data acquisition with extensive lab testing in order to verify the consistence and stability of the data exchange in a structured known environment.
- Development of theoretical solutions for the DIDSON data processing, user-friendly visualization, model estimation and target identification tasks.
- Development of software for the DIDSON management which includes a low level sensor management and model estimation and high level user visualization, bottom exploration and target identification. This requires extensive testing in a real sea water environment.
- Integration of the DIDSON sonar on the vehicle.

The final step, after the above developments, was the first underwater middle range exploration, target identification and localization experimented by DIDSON sonar.

Summary

1. DIDSON sonar main features:
   - Specifications
   - Acquisition characteristics

2. DIDSON sonar data exchange protocol:
   - DIDSON communication and management

3. DIDSON sonar SAUVIM applications

4. Fine middle range exploration:
   - Development of drivers and interface software for the DIDSON sonar SAUVIM xBus framework
   - Development of software for data processing and user-friendly visualization

5. Object recognition and vehicle positioning:
   - Development of software for model estimation
   - Development of software for target identification and absolute position localization

6. Underwater DIDSON tests:
   - Bottom mapping
   - Known object identification and localization

Didson sonar features

The DIDSON (Dual frequency IDentification SONar, Figure IDUTI-2) is a sonar with acoustic lenses that operates at two frequency, 1 MHz and 1.8 MHz, at an operative range up to 40m. Its dimensions are 30.7 cm long by 20.6 cm high by 17.1 cm wide with a weight in air 7 kg while in water 0.6 kg; the housing is suitable for operating up to more than 152 m deep (see [1], [5]).
The device uses acoustic lenses to form very narrow beams during transmission of pulses and reception of their echoes. This hardware solution has the advantage of low power consumption: in fact, no power for beamforming is required and it uses only 30 watts to operate; this is an important feature for the power budget of an AUV. A second advantage is the ease to transmit and receive from the same beam. Images are also cleaner and sharper thanks to the reduced acoustic cross talk and the higher resolution.
The DIDSON is physically composed by a linear array of transducers that covers a cone of 12 degrees height and 29 degrees width respectively, using 96 elements regularly spaced each 0.3 degrees: in high frequency all the set of transducers is used while in low frequency only even lenses are used (half set of transducers). In both cases, the frame rate is up to 20 frame/s.
The sonar is connected and control through Ethernet connection using its Windows application; moreover, a NTCS video output is available only for data visualization.

The aim of this work was to use the DIDSON within SAUVIM framework in a fast, direct and reliable way with a full control of the device and of the collected data: in order to achieve such result an alternative way to the Windows application has been realized.

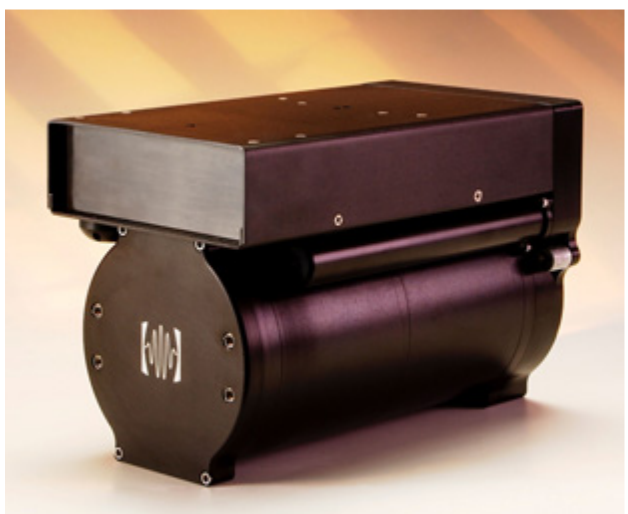


Figure IDUTI-2. The DIDSON (Dual frequency IDentification SONar)

Didson control protocol

The DIDSON is controlled via a client-server model through Ethernet connection and UDP protocol: the user (client) asks data or sets parameters to the server (DIDSON) that replays consistently.
In the client to server direction communication, parameters are set and data are asked.
Relevant parameters are:

- Frequency: 1 MHz or 1.8 MHz
- Window Start: distance of the closest acoustic return
- Window Length: range of the acoustic set of return for a single beam

Once asking for data the server replays to the client (server to client direction communication) with a set of data. The quantity of data depends on the frequency: a header of 256 bytes is followed by 24576 bytes of acoustic returns in low frequency or 49152 bytes in high frequency. The header contains a set of DIDSON information and checking flags that are listed hereafter:

```
unsigned short cmd;
unsigned short size;
unsigned short pkt_code;
unsigned short pkt_num;
unsigned int framenumber;
unsigned int frametime[2];
unsigned int version;
unsigned int status;
unsigned int year;
unsigned int month;
unsigned int day;
unsigned int hour;
unsigned int minute;
unsigned int second;
unsigned int hsecond;
unsigned int hi_res;
unsigned int window_start;
unsigned int window_length;
unsigned int threshold;
unsigned int intensity;
unsigned int gain;
unsigned int degC1;
unsigned int degC2;
unsigned int humid;
unsigned int focus;
unsigned int battery;
char string1[16];
char string2[16];
float velocity;
float depth;
float altitude;
```

```
float pitch;
float pitchrate;
float roll;
float rollrate;
float heading;
float headingrate;
float sonarpan;
float sonartilt;
float sonarroll;
double latitude;
double longitude;
float sonarposition;
unsigned int config_flags;
float beamtilt;
float targetrange;
float targetbearing;
unsigned int targetpresent;
unsigned int firmwarerevision;
unsigned int m_nFlags;
unsigned char rsvd[24];
unsigned char user[12];
```

Following the header, the acoustic data itself is stored in a byte array of dimensions equals to *sample x beam*, where *sample* ranges from 0 to 511 and *beam* ranges from 0 to 47 (in low frequency) or from 0 to 95 (in high frequency). The client-server module has been implemented in C++ in order to realize suitable interface driver for the DIDSON sensor integration within the SAUVIM xBus framework.
Such data are the raw polar information used to generate the DIDSON acoustic image. Each value corresponds to the amplitude of the acoustic beam return at a certain distance: so it refers to a volume of water as bigger as farer from the transducer it is (each beam is 12 degrees high and 0.3 degrees width). Moreover due to the beam high, two objects at the same distance from the sonar and one above the other are indiscernible because they belong to the same volume of water so they correspond to the same return value: the information about the 12 degree beam high is compressed in one return causing lack of information and uncertainty in the polar to Cartesian data processing. Another consideration that makes acoustic images different from optical images depends on the use of sound instead of light: the sonar must be oriented to project beams with a small angle of incidence to the object of interest rather than perpendicular as usual optic vision suggests. Such configuration guarantees the best and more informative acoustic returns and as result the object looks like it is seen from a perpendicular direction to the surface of the object with a shadow on the back. The same view with an optical camera is achieved by orienting the camera perpendicular to the surface: such orientation using an acoustic camera, instead, produces an image with a single line perpendicular to the center beam axis because each beam hits the surface at the range of the perpendicular surface in only a point.

These considerations bring to a deformation of object shape according to the angle of incidence of beams array; the dimension of the shape is, instead, free from the range on the contrary of optical vision where object are as smaller as farer the source of view is.
So, during the data processing phase these factors have to be considered in order to implement a suitable data visualization technique:

- Polar representation of the raw collected data
- 12° vertical high compressed to 2dimensional XY plan
- Beams angle of incidence
- Environmental acoustic noise

Figure IDUTI-3 shows an example of image acquisition by DIDSON (left) and the correspondent deformation of the insonified object (right).

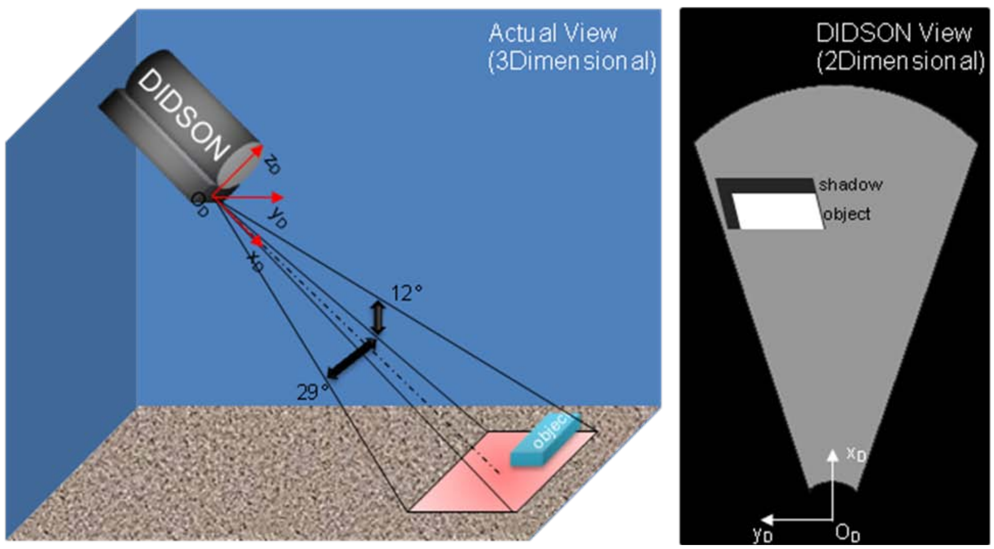


Figure IDUTI-3. Acquisition

Didson applications

The DIDSON is a very powerful device for underwater exploration in poor optical visibility conditions thanks to the acoustic transducers use [3]. Fine exploration and target identification are important requirement for the autonomous navigation and control of SAUVIM, therefore, by using such device two main applications have been realized:

- Fine middle-range exploration of the sea bottom
- Object identification and vehicle positioning

Fine middle-range exploration

Once the data from the DIDSON (we refer to this data as "polar pixel") is available via the ad-hoc interface driver, according to the consideration made in the previous section, the acoustic returns have to be processed in order to achieve a coherent representation of the sea bottom. The first step at this phase is the polar to Cartesian bi-dimensional conversion of the coordinates system following by image processing operation to rectify possible environmental noise.

The polar to Cartesian conversion is performed by a first dynamical estimation of the Cartesian image dimensions in pixels and the pixel dimension as well according to the DIDSON parameters: window start, window length, frequency (so number of beams) and samples (set to 512). Then each Cartesian pixel is associate to a polar pixel in order to deal with the dimension increase of the volume associated to a polar pixel when it moves away from the source: so, multiple Cartesian pixels correspond to the same polar pixel. Once the Cartesian image is made, standard image processing techniques are used in order to make the image clearer, to reduce the noise and to increase the contrast between actual objects and image background. Standard OpenCV library of programming functions are used at this phase. Figure IDUTI-4 shows an example of raw polar image (left), of raw Cartesian image (center) and of image processing result (right) on a standard set of DIDSON polar pixels (the image is as whiter as higher is the acoustic return).

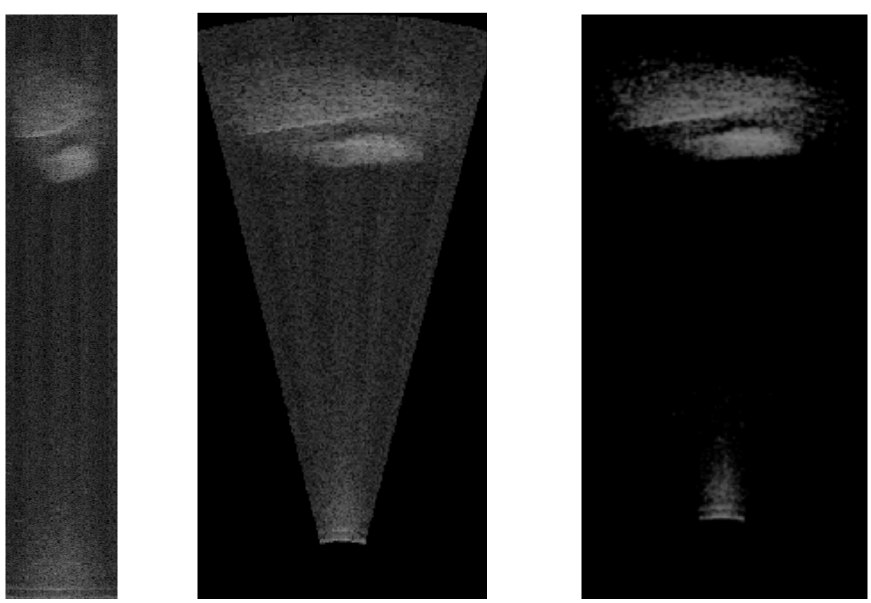


Figure IDUTI-4. Raw DIDSON polar image (left)
Raw DIDSON Cartesian image (center);
processed DIDSON Cartesian image (right)

The described procedure has also been integrated within SAUVIM main application (Figure IDUTI-5): this guarantees the DIDSON parameter control and data visualization in a user-friendly way together with the other SAUVIM sub-systems.

Figure IDUTI-5. DIDSON management panel of SAUVIM main application

Target identification and vehicle positioning

Together with the DIDSON data visualization, another important task is performed during SAUVIM vehicle navigation using DIDSON data: the identification and localization of known submerged objects ([2], [4]) for guiding the vehicle to approach such target. It consists in recognizing known submerged objects, in computing their absolute position and in using this information in the SAUVIM navigation control loop so the vehicle can autonomously moves to the detected target.
In order to use the DIDSON has a regular camera for bottom exploration and known objects identification, two main problems have to be considered:

- Object shape deformation due to the DIDSON beam features
- Environmental noise that affects acoustic signal propagation, so DIDSON acoustic return acquisition

To deal with the first problem, a recursive model estimator has been implemented: at a fixed frequency, a Cartesian model of the target is built according to object dimension (a-priori information) and DIDSON orientation (thanks to the inertial navigation system and the pan and tilt modules on board SAUVIM vehicle). So a fictitious DIDSON image is created: it is an estimation of the object Cartesian image by DIDSON view point. Maximum (white color) acoustic reflection from the object surface, no reflection (black color) from the object edge and average reflection (gray) from the background are the object model hypothesis.
Then, for the target identification, standard image processing edge detection techniques cannot be used due to the shape deformation and environmental acoustic noise: so statistical, bi-dimensional convolution based, approach via Intel Math Kernel Library (MKL), that guarantees high performance for real time application, has been implemented.
Figure IDUTI-6 displays the whole target identification process where the goal is to compute the target absolute position so its absolute transformation matrix which is the information to use then in the navigation system loop:

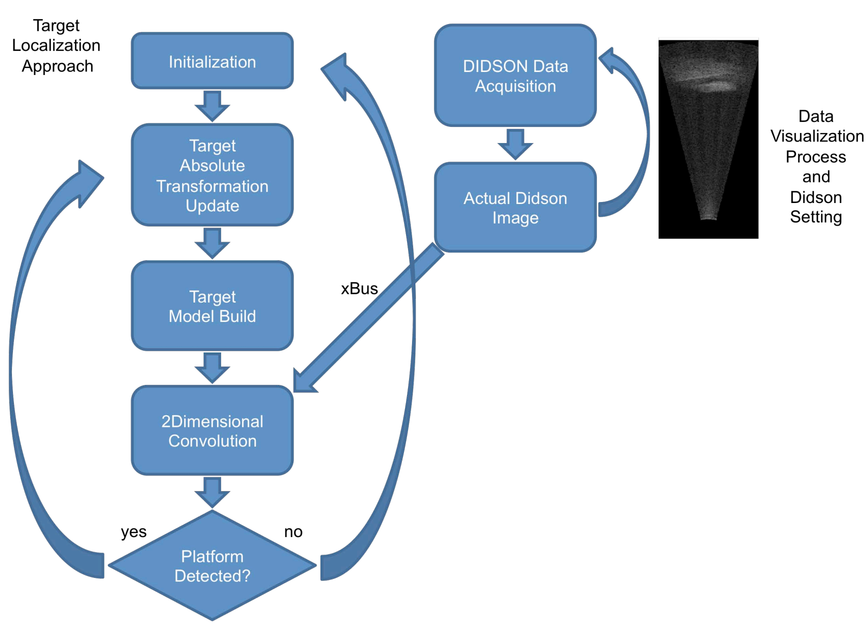


Figure IDUTI-6. Target localization approach

Figure IDUTI-6 shows two parallel processes running: DIDSON data visualization and target identification; in this section, the second procedure is described in detail. To have these two tasks separated is an important characteristic of the system. In fact, several missions require only exploring and mapping the sea bottom without any object detection that has different computational time: the exploration has a 15 frame/sec refresh frequency while the position of the target is updated each second due to the image processing and convolution operations.
The target localization is an iterative process that recursive refines the target position estimation using DIDSON acoustic returns; it can be divided into five steps:

0. Initialization: this phase is important to initialize variables and a-priori information of the system; in particular the initial hypothesis of object positioning in DIDSON image. Such information is necessary to estimate the Target Relative transformation matrix.
1. Target Absolute Position Update: according to the DIDSON Absolute transformation matrix and the Target Relative (to the DIDSON) transformation matrix, the Target Absolute transformation matrix is computed. This matrix identifies the global position of the target (the goal of the process). Figure IDUTI-7 graphically shows the meaning of absolute transformation matrix (O indicates the absolute coordinate system, P the target coordinate system)

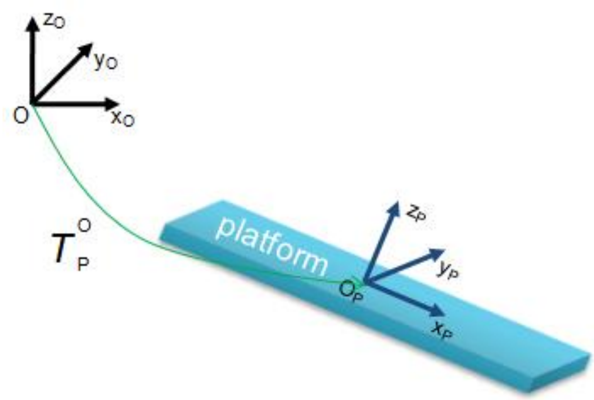


Figure IDUTI-7. Target Absolute Position

2. Target Model Build: the operations necessary to build a model of the target from the DIDSON view point are:
   - To build a tri-dimensional representation of the object surface in a Cartesian system by points (x, y, z) (see Figure IDUTI-9)
   - To convert the Cartesian points into spherical points (r, θ, φ)
   - To simulate the DIDSON volume compression by reconverting the polar points (missing the φ coordinate) into bi-dimensional Cartesian points (x, y) and then gray scaling the obtained clouds of bi-dimensional points as shown in Figure IDUTI-12

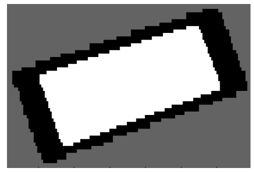


Figure IDUTI-12. Target Model example

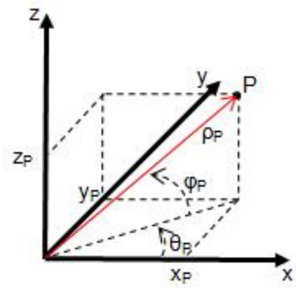


Figure IDUTI-9. Coordinate system

3. Bi-dimensional convolution: at this phase the current DIDSON Cartesian image (Figure IDUTI-4) is used and associated to the target model generated in the previous step by means of bi-dimensional convolution function (IDUTI-1). Bi-dimensional convolution is a very time consuming operation and often, according to the dimension of the image to process, is not applied to real time and on line tasks. Instead, the present implementation makes use of the Intel Math Kernel Library (MKL) that assures reliable result within 300 milliseconds (using images on the order of 300x600 pixels and 100x50 pixels). Figure IDUTI-14 graphically shows the result of bi-dimensional convolution operation between two images from real data, where the z coordinate represents the convolution value relative to a (*x*, *y*) position.

$$C(i,j) = \sum_{m=0}^{(M_a-1)} \sum_{n=0}^{(N_a-1)} A(m,n) \cdot B(i-m, j-n)$$

$$0 \leq i < M_a + M_b - 1 \qquad \text{(IDUTI-1)}$$

$$0 \leq j < N_a + N_b - 1$$

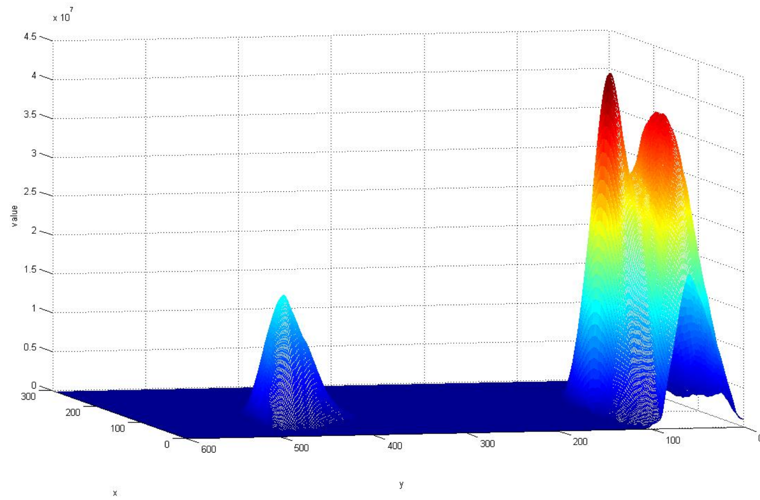


Figure IDUTI-14. Convolution result visualization

4. The result of the statistical convolution between two image indicates where the images have the better correlation, so where the two image are more similar. In the present application, the similarity means the presence of the object in the current DIDSON image: so the maximum of the convolution indicates where the probability of occupation of the object we are looking for is higher. However, since a maximum in the convolution result always exists, in order to determine if the maximum corresponds or not to the target, to use a criterion is necessary: the adopted criterion consists in estimating the maximum convolution result (it correspond to a perfect correspondence between actual image and model) and then set a percentage threshold above which the actual convolution maximum is assumed to correspond to the target.

   The result of the criterion determines the next step on the iterative process: if the target is found, the object absolute position is updated, so step 1 is performed. Otherwise, the initialization step takes place.

The described procedure is repeated recurrently during the target identification task in order to have the absolute target position constantly updated and guide the vehicle toward that direction using the navigation system.

The implementation of the data visualization and target identification algorithms has been realized in C++ programming language; moreover, MatLab has been used during test phase.

Didson experimental tests

In order to test the described procedures and algorithms, several experiments have been realized.

A first session of DIDSON tests in a structured environment was necessary in order to check and control the communication protocol, the sensor management and to collect reliable data. Then SAUVIM vehicle on board tests followed: this step required the hardware installation and connection of the DIDSON device on the vehicle as showed in Figure IDUTI-15.

The DIDSON control and data visualization panel of SAUVIM main application is displayed in Figure IDUTI-16 where the management of DIDSON parameters, the visualization of the acoustic returns and the result of the target localization process are accessible.

Figure IDUTI-15. DIDSON installation on SAUVIM

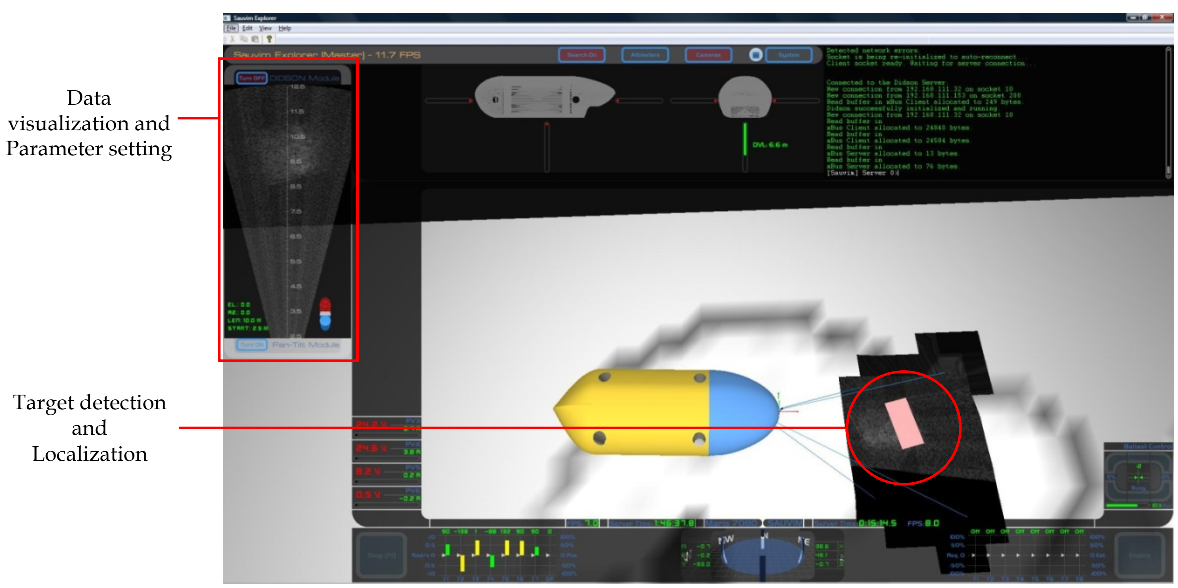
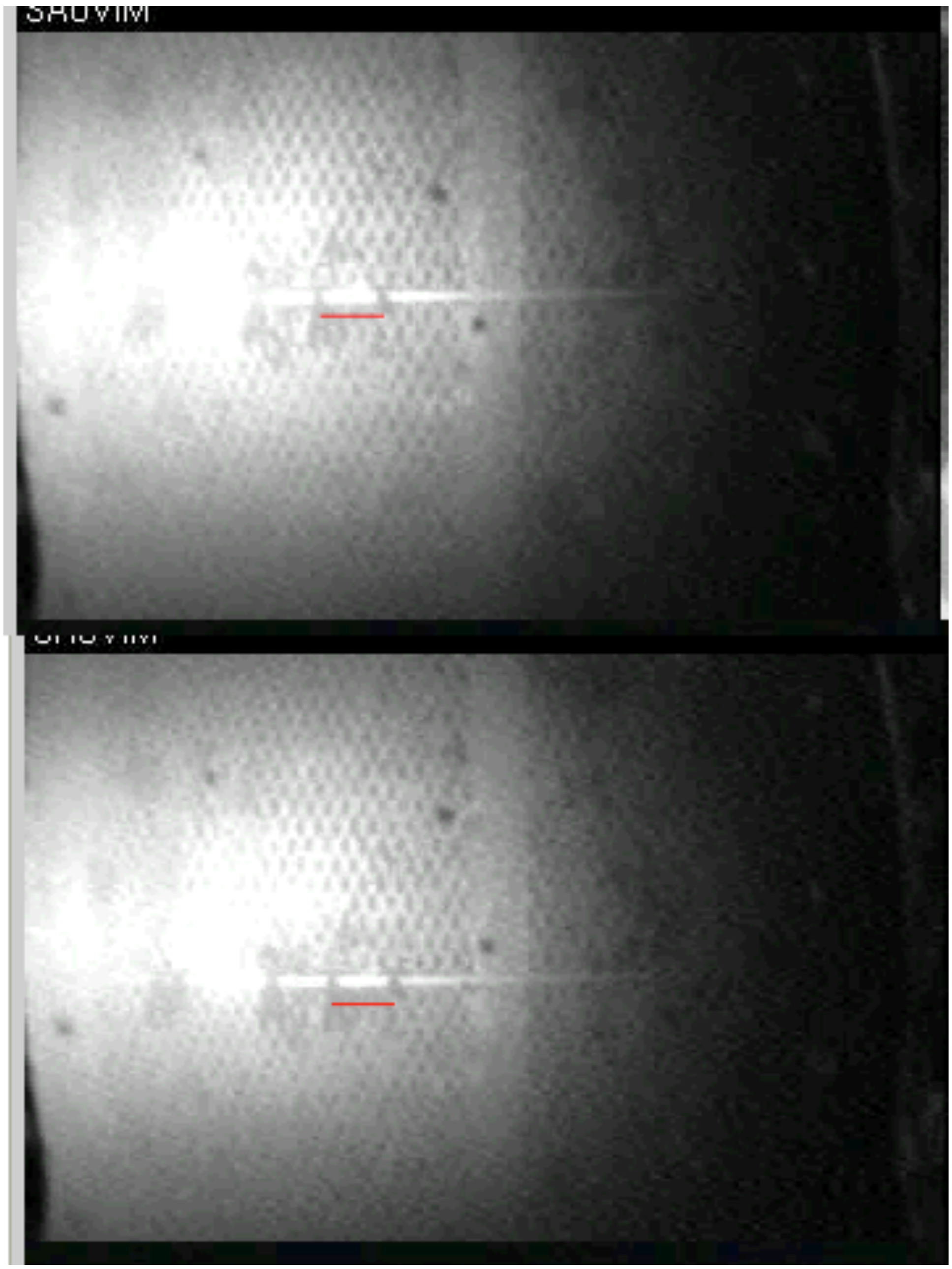


Figure IDUTI-16. SAUVIM application DIDSON modules

Validation

In order to practically quantify the standard deviation of the position error we repeated several times a pre-defined experiment, finalized to position the vehicle every time in the same hovering configuration above the platform. In this experiment, the relative cartesian coordinates of the platform with respect to the vehicle were computed using DIDSON imagery taken at a distance of 10 m from the target. The bottom facing video camera of SAUVIM was sending back images of a known dimension feature, visible in the figure below, where the reference red line is 75 mm in length.



The same figure shows two different final configurations, with only a small difference in the final hovering positions. Considering that the navigation from the area where the DIDSON images were taken to the hovering configuration was done in dead reckoning (thus introducing some extra errors), this experiment confirms an excellent repeatability and, with the successive trials, the global standard deviation of the position error has been confirmed of the order of few centimeters.

The information associated to the platform location is made available to the whole system, included the navigation controller and the main graphical interface (Sauvim Explorer) located in the ground mission control environment. Figure IDUTI-17 depicts a snapshot of the mission interface during a search test of the submerged platform. The red rectangle is the result, in real time, of the iteration process. In the SAUVIM missions, the platform represents a submerged docking area of the vehicle, and the precise knowledge of its location is fundamental to the autonomous landing procedure.

The Sauvim Explorer interface shows also the map of the DIDSON image overlapped to the terrain profile. In case of general imagery, since the The DIDSON does not disambiguate the elevation of the target, this operation may result approximate In our case, since we acquire elevation maps of the seafloor with other sensors, the sonar image can unambiguously mapped to the cartesian space.

References

[1] E. Belcher, W. Hanot and J. Brush, "Dual-Frequency Identification Sonar (DIDSON)", *2002 International Symposium on Underwater Technology*, pp.187-192, Tokyo, Japan, 2002.

[2] W. L. J. Fox, J. B. Hsieh, and C. Polwarth, “Segmentation of Images from an Acoustic Lens Sonar”, OCEANS'04, vol. 4, Kobe, Japan, 2004.

[3] J. A. Holmes, G. M. W. Cronkite, H. J. Enzenhofer, and T. J. Mulligan, “Accuracy and precision of fish-count data from a dual-frequency identification sonar (DIDSON) imaging system”, *ICES Journal of Marine Science: Journal du Conseil*, vol. 63, pp 543, 2006.

[4] S. C. Yu, T. W. and Kim, and G. Marani, and S. K. Choi, “Real-Time 3D Sonar Image Recognition for Underwater Vehicles”, *Symposium on Underwater Technology and Workshop on Scientific Use of Submarine Cables and Related Technologies*, Tokyo, Japan, 2007.

[5] http://www.soundmetrics.com/

Intelligent, Coordinated-Motion/Force Control (ICM/FC)

Project Leader(s): Dr. Giacomo Marani
Past Project Leader(s): Dr. Junku Yuh, Dr. Tae Won Kim, Dr. Song K. Choi, Dr. Kazuo Sugihara, Dr. Hyun Taek Choi, Mr. Michael West & Dr. Nilanjan Sarkar

The main technical development of the ICM/FC group is described in the following sections: Manipulator Control and Test Platform, Low-Level Control, Active Feedback Thruster System (AFTS), Localization and Navigation, and High-Level Control. The Manipulator Control and Test Platform is the combined sections of the previous Theoretical Modeling and Dry Test Design Set-Up. The Localization and Navigation is a separation from the Low-Level Control due to the vastness and complexity of the research area.

Manipulator Control and Test Platform (MCTP)

Project Leader(s): Dr. Giacomo Marani
Personnel: Ms. Allison Lyon, Mr. Kaikala Rosa
Past Project Leader(s): Dr. Song K. Choi, Dr. Tae Won Kim, Dr. Junku Yuh & Dr. Nilanjan Sarkar
Past Personnel: Mr. Tommaso Bozzo, Mr. Gang Cheng, Ms. Jing Nie, Mr. Mike Kobayakawa, Mr. Mark Fujita, Dr. Gyoung H. Kim, Mr. Tarun Podder, Mr. Jin Hyun Kim, Mr. Jong Ho Eun, Ms. Stacy L. Dees & Mr. Jangwon Lee

Objectives

During the Phase II of SAUVIM, one of the most important objectives for the manipulation platform was the first ocean test of the system. In order to achieve the above objective, extensive product engineering works have been necessary, other than several further developments of the hardware/software control system.
The final objectives included the following:

- Development of theoretical solutions for the arm control algorithm with extensive lab testing in order to verify the task-space controller performances.
- Development of a programming environment for manipulators, which include a low level software-emulated execution CPU, a high-level programming language and a program compiler.
- Development and testing of an ultrasonic-based tracking system for target localization.
- Development of an extended subset of routines for the arm programming environment, which include a set of calibration procedures for the joint offsets and the auto-calibration of the external position sensors.
- Development of the arm parking procedures
- Collision avoidance system.
- Integration of the manipulator on the vehicle
- Development and testing of a visual-based tracking system for close range target localization
- Development of an extended subset of routines for the arm programming environment which include a set of calibration procedures for the auto-calibration of the camera

The final step, after the above developments, was the first underwater manipulation experiment, as described previously.
These objectives have been successfully achieved, with good performances and stability. In particular, the theoretical solutions developed for prevent singularities showed an excellent performance and were published in several journal and conferences. Details on the overall development have been described on the previous report (Phase II-C, III-A and III-B).

Current Status (Tasks Completed)

The task has been completed in the previous phases. Refer to previous reports for its descriptions.

Low-Level Control (LLC)

Project Leader(s): Dr. Giacomo Marani
Personnel: Dr. Giacomo Marani
Past Project Leader(s): Dr. Side Zhao, Dr. Junku Yuh, Dr. Song K. Choi, Dr. Tae Won Kim & Dr. Hyun Taek Choi
Past Personnel: Ms. Jing Nie, Mr. Eric Kardash & Mr. Michael West

Objectives

- To design an advanced vehicle control for navigation and hovering, and coordinated motion/force control of the vehicle and manipulator during the intervention mode.
- To develop hybrid controllers that is robust to system uncertainties as well as external disturbances of the AUV dynamics.

Current Status (Tasks Completed during 10/25/2006 - 10/30/2009)

In all the SAUVIM Phases, most of the vehicle development has been focused in obtaining high performance in navigation and hovering. Before the past phase III-B the navigation and hovering techniques made use of the data from the on-board scan sonar, altimeter sonar, inertial navigation unit, Doppler Velocity Logger (DVL), and pressure sensors. The Ultra Short Base Line (USBL) and Global Positioning System (GPS) were added as a global vehicle position feedback sensor during underwater navigation and surface navigation, respectively.

However, at the end of the Phase III-A, it was evident how the accuracy and precision of this sensor system was insufficient, in particular conditions, during the manipulation tasks. Thus it was necessary, during the phase III-B, to introduce a more reliable Inertial Navigation System aimed to produce the position data with the reliability necessary to the autonomous intervention.

This important change, together with a complete re-design of the navigation controller, allowed the SAUVIM vehicle to successfully perform in compliance with the precision, accuracy and stability requirements of our manipulation task.

Another important upgrade of the Phase III-B, aimed to improve the coordinate motion between the arm and the vehicle, was the standardization of all the communication protocols. This was accomplished with the extension of the xBus protocol, once dedicate to the arm subsystem only, to the entire vehicle. xBus showed a great flexibility in handling every kind of communication (data, program code, messages..) and thus it was chosen as the SAUVIM standard.

During final phase (III-C) the navigation controller has been further upgraded with very important enhanced feature like on-line identification of the center of buoyancy. This is one of the most important capabilities of the system that allowed high hover stability during manipulation and optimized power consumption. The Extended Kalman Filter employed in the identification needs a relatively precise knowledge of the thrust force. This has been subject of another important research for mapping the thrusters actual inputs and status to the actual force developed.

Real-time center of buoyancy identification of underwater vehicles for optimal positioning in autonomous intervention

This research addresses the problem of optimal positioning for an intervention AUV, minimizing the energy consumption and improving the stability in orientation. During a generic intervention task, the vehicle is generally required to maintain a hovering configuration, thus requiring a 6 DOF control of the vehicle positioning. The choice of roll and pitch, if done arbitrarily, can severely impact the power efficiency of the vehicle, especially in heavy systems, since the center of buoyancy may not be necessarily aligned over the center of mass. This approach uses an Extended Kalman Filter to identify the location of the center of buoyancy w.r.t. the center of mass, thus allowing to compute the working orientation that maintains the COB vertically aligned above the COM. The EKF is implemented online and hence is able to detect movement of the COB due for example to ballast operations. This algorithm has been firstly implemented in simulation and then successfully validated with the SAUVIM autonomous underwater vehicle. With its weight of about 4 tons, this testbed is an optimal platform for validating the precision of the filter, since a very small variation of the target pitch and roll results in a large restoring torque.

Introduction

Underwater intervention operations are ordinarily executed using manned submersibles or Remotely Operated Vehicles in tele-operation mode. Autonomous Underwater Vehicles are generally employed in survey missions, and only few AUVs are today equipped with manipulators. In fact, the low bandwidth and significant time delay inherent in acoustic subsea communications represent a considerable obstacle to remotely operate a manipulation system, making it impossible for remote controllers to react to problems in a timely manner.

Nevertheless, robots for autonomous underwater intervention would pave the way for a different range of new operations, such as deep-ocean and under-ice exploration, tasks in hazardous areas, in natural or man-made disastrous regions, automated searches, surveillance missions, to name a few.

The key technology in underwater intervention performed with autonomous vehicles is autonomous manipulation. This is a challenging technology milestone, which refers to the capability of a robot system that performs intervention tasks requiring physical contacts with unstructured environments without continuous human supervision. Autonomous manipulation systems, unlike teleoperated manipulation systems that are controlled by human operators with the aid of visual and other sensory feedback, must be capable of assessing a situation, including self-calibration based on sensory information, and executing or revising a course of manipulating action without continuous human intervention.

During a generic autonomous manipulation task the vehicle controller has the main responsibility of maintaining the vehicle in the necessary configuration. For example, often the vehicle has to be actively stabilized in a hovering configuration, while the manipulator performs its task. Among the hydrodynamic effects acting on a rigid body moving in a fluid, the restoring generalized forces (gravity plus buoyancy) and the ocean current are of major concern in designing a motion control law for intervention AUVs. In literature, several works have been presented in order to assess the problem of 6 DOF control of AUVs (see for example [1], [2], [3], [4], [5], [6]). An analysis of the capacity of the above works to compensate for the persistent dynamic effects, e.g., the restoring forces and the ocean current, has been presented in [7].

In general, one of the main problem is the lack of knowledge of the restoring-related dynamic parameters, especially in case of heavy vehicles. In particular, the location of the center of buoyancy with respect to the center of mass plays a fundamental role in the performance of the dynamic control. The importance of its knowledge is also related to the problem of power optimization, since very often a working orientation of the vehicle does not have strict constrains, being the manipulator more capable of realizing specific orientation than the vehicle. Thus a working vehicle orientation could be simply chosen as the one that aligns the COB above the COM, minimizing the power requirement for maintaining the vehicle in hovering.

In this research we present a methodology for identifying the relative position of the COB with respect to the center of mass. This approach is based on the use of an extended Kalman filter and, being suitable of real-time implementation, it can easily adapt to any change in the vehicle configuration (i.e. ballast operations or manipulator dynamics).

The algorithm has been successfully tested firstly in a simulation environment and then with the SAUVIM underwater vehicle, in both cases with a model-based dynamic control. Results here presented have been proven to be extremely accurate, and thus allowing to optimize the hovering of the SAUVIM vehicle during its manipulation tasks.

DYNAMICS OF THE UNDERWATER VEHICLE-MANIPULATOR SYSTEM

In our study the dynamics has been modeled with particular care to the further extension of the global vehicle-manipulator system dynamics. We used the Lagrange equation for quasi-coordinates, since this approach allows an easy generalization of multibody systems with joints not limited to be only one degree of freedom. With this choice, the UVM system becomes a linear chain of simple joints with the first one being of 6 DOF (free body). In this paper we are not considering the dynamics of the manipulator, since we assume that it is in its parked position and part of the vehicle dynamics. With this assumption, the Lagrange equation for the quasi-coordinates becomes ([11], [12], [13]):

$$A(\mathbf{q})\dot{\mathbf{p}} + B(\mathbf{q},\mathbf{p})\mathbf{p} = V^T \mu^e \tag{1.1}$$

where, in general:

- [$\mathbf{q}$] is the system configuration vector $\left[q_1,..,q_6\right]^T = \left[roll \quad pitch \quad yaw \quad x_{Cm} \quad y_{Cm} \quad z_{Cm}\right]^T$;
- [$\mathbf{p}$] is the system quasivelocity vector $\left[Cm\omega_x \quad Cm\omega_y \quad Cm\omega_z \quad Cmv_x \quad Cmv_y \quad Cmv_z\right]^T$;
- [$A(\mathbf{q})$] is the inertia matrix of the structure (comprehensive of the added mass and added inertia);
- [B] is the is the matrix of Coriolis and centrifugal forces (also comprehensive of the added mass and added inertia);
- [$V(\mathbf{q})$] is the transformation matrix between the $\mathbf{p}$ space and the $\dot{\mathbf{q}}$ space, such as $\dot{\mathbf{q}} = V\mathbf{p}$;
- [$V^T\mu^e$] is the projection in the space of the joint velocities (i.e. body axis in our case) of the external generalized forces.

Let $J(\mathbf{q},P)$ be the jacobian of the structure, such as:

$$\dot{X} = J(\mathbf{q},P)\mathbf{p} \tag{1.2}$$

where $\dot{X}$ is the generalized velocity (in the main frame) of the point P. With this assumption, the projection in the space of the joint velocities of a generalized extern action $W_P = \left[M_P \quad F_P\right]$ is given by:

$$\mu_{\mathbf{P}} = J^T(\mathbf{q},P)W \tag{1.3}$$

In modeling our vehicle, since we consider the vehicle stationary in a hovering configuration, the extern action is composed of the restoring torque, linear dumping actions and thruster forces. This lead to the final form of the (1.1):

$$A(\mathbf{q})\dot{\mathbf{p}} + B(\mathbf{q},\mathbf{p})\mathbf{p} = D\cdot\mathbf{p} + TCM\cdot\tau + \theta_{\mathbf{r}} \tag{1.4}$$

where D is a diagonal matrix associated with the linear damping term of the drag force, TCM is the thruster control matrix and θ_r is the generalized restoring action, given by:

$$\theta_r = J^T(\mathbf{q},CB)\begin{bmatrix}0\\0\\0\\0\\0\\g\cdot f_b\end{bmatrix} + J^T(\mathbf{q},CM)\begin{bmatrix}0\\0\\0\\0\\0\\g\cdot m_S\end{bmatrix} \tag{1.5}$$

COB identification with Extended Kalman Filter

Equation (1.4) implicitly describes the evolution of the state vector through time. It can be solved with respect to the derivative of the quasivelocity vector as:

$$\dot{\mathbf{p}} = A^{-1}\left(-B\mathbf{p} + D\mathbf{p} + \mathbf{TCM}\cdot\tau + \theta_{\mathbf{r}}\right) \tag{1.6}$$

Then, in order to complete the state space equations of the Kalman filter, we can add 4 more equations describing the evolution of the three coordinates of the center of buoyancy and the buoyancy force. Since the ballast movements are supposed much slower than the dynamics of the vehicle, their evolution is simply given by:

$$\begin{cases} \dot{c}_{bx} = 0 \\ \dot{c}_{by} = 0 \\ \dot{c}_{bz} = 0 \\ \dot{F}_b = 0 \end{cases} \tag{1.7}$$

being c_{bx}, c_{by} and c_{bz} the coordinates of the center of buoyancy with respect to the center of mass, and F_b the resultant of the buoyancy force (applied to the COB).
We also need to add the evolution of the generalized position of the vehicle. This is easily done by integrating the rotation matrix:

$${}^{0}_{Cm}\dot{R} = {}^{0}_{Cm}R \begin{bmatrix} 0 & -p3 & p2 \\ p3 & 0 & -p1 \\ -p2 & p1 & 0 \end{bmatrix} \tag{1.8}$$

and the linear acceleration:

$${}^{0}\dot{c}_m = {}^{0}_{Cm}R\begin{bmatrix} p_4 & p_5 & p_6 \end{bmatrix}^T \tag{1.9}$$

Process

The complete non-linear process can be described putting together Eqs. (1.6), (1.7), (1.8) and (1.9), and adding the opportune noise. Since several parameters are known approximatively, we can consider adding a noise variable w_i to each one of them. In our case we have added noise in the following terms:

Added mass:

$$\overline{m}_t = m_t + w_m t$$

Added inertia:

$$\overline{I}_t = I_t + \begin{bmatrix} w_{i11} & w_{i12} & w_{i13} \\ w_{i12} & w_{i22} & w_{i23} \\ w_{i13} & w_{i23} & w_{i33} \end{bmatrix}$$

Center of mass location (for the computation of the *TCM*:

$$\overline{c}_m = c_m + \left[w_{cmx}, w_{cmy}, w_{cmz} \right]^T$$

Thrust vector (considering that our vehicle has 8 thrusters):

$$\overline{\boldsymbol{\tau}} = \boldsymbol{\tau} + \left[w_{t1}, ., w_{t8} \right]^T$$

Damping coefficients:

$$\overline{D} = diag\left(k_d + w_{kd}\right)$$

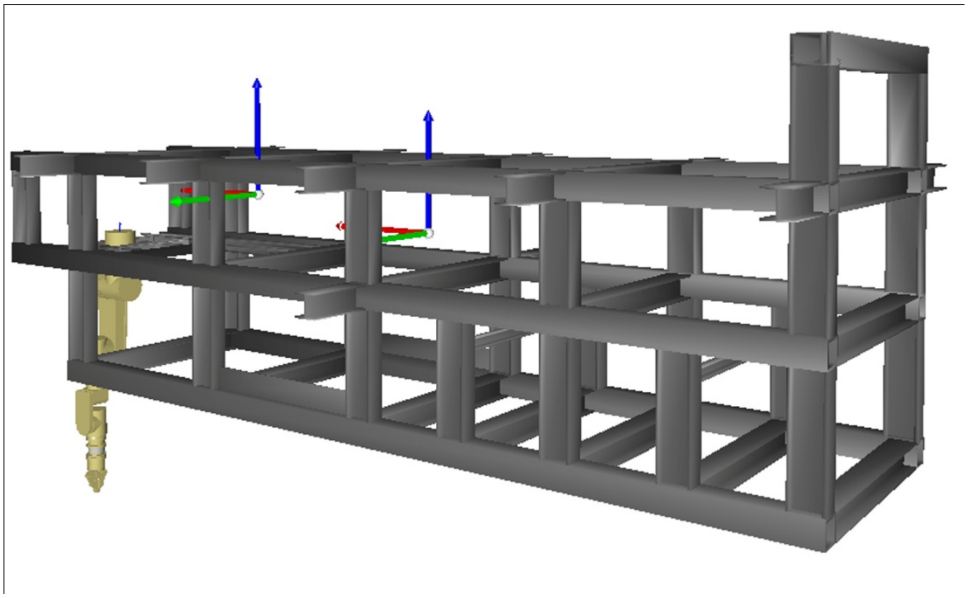
With this assumptions, after discretizing the system equations (1.6) and, (1.7) the non-linear stochastic difference equation of our extended Kalman filter becomes:

$$\mathbf{x}_k = \begin{bmatrix} \mathbf{p}_k \\ (\mathbf{c}_b)_k \\ (F_b)_k \\ \left({}^{0}_{Cm}R\right)_k \\ (\mathbf{c}_m)_k \end{bmatrix} = \begin{bmatrix} \mathbf{p}_{k-1} + \overline{A}^{-1}\left(-\overline{B}\mathbf{p}_{k-1} + \overline{D}\mathbf{p}_{k-1} + \overline{TCM}\overline{\tau} + \theta_{\mathbf{r}}\right)\Delta T \\ (\mathbf{c}_b)_{k-1} + (\mathbf{w}_{cb})_{k-1} \\ (F_b)_{k-1} + (w_{Fb})_{k-1} \\ \left({}^{0}_{Cm}R\right)_{k-1} + \left({}^{0}_{Cm}R\right)_{k-1} \begin{bmatrix} 0 & -p_3 & p_2 \\ p_3 & 0 & -p_1 \\ -p_2 & p_1 & 0 \end{bmatrix}_{k-1} \Delta T \\ (\mathbf{c}_m)_k + \left({}^{0}_{Cm}R\right)_{k-1} \left(\begin{bmatrix} p_4 & p_5 & p_6 \end{bmatrix}^T\right)_{k-1} \Delta T \end{bmatrix} \qquad (1.10)$$

where ΔT is the sample time. Note that many noise variables are encapsulated within $\overline{A}$, $\overline{B}$, $\overline{TCM}$ and $\overline{\tau}$. The last, vector of the thrust forces, is the process input. The dimension on the state vector is thus 22.

Measure

The equations of the measure, in our system, are way more complicated than the process evolution. This is due to the fact that the Inertial Navigation system (PHINS) is physically mounted with an offset (in translation and rotation) w.r.t. the center of mass (see Figure).



The PHINS is basically composed by another extended Kalman filter which fuses together sensor data from fiber optical gyroscope, accelerometers, velocity sensor (DVL), position sensor (GPS) and a depth probe. It provides in output the following information:

The PHINS is basically composed by another extended Kalman filter which fuses together sensor data from fiber optical gyroscope, accelerometers, velocity sensor (DVL), position sensor (GPS) and a depth probe. It provides in output the following information:

The PHINS is basically composed by another extended Kalman filter which fuses together sensor data from fiber optical gyroscope, accelerometers, velocity sensor (DVL), position sensor (GPS) and a depth probe. It provides in output the following information:

The PHINS is basically composed by another extended Kalman filter which fuses together sensor data from fiber optical gyroscope, accelerometers, velocity sensor (DVL), position sensor (GPS) and a depth probe. It provides in output the following information:

- $^{0}_{P}T$ generalized position of the PHINS w.r.t. the main frame <*0*>;
- $^{0}v_{Ph}$ is the linear velocity of the PHINS projected the main frame <0>;
- $^{P}\omega_{Ph}$ is the angular velocity of the PHINS projected the PHINS frame <Ph>;
- $^{P}a_{Ph}$ is the linear acceleration the PHINS projected the PHINS frame <Ph>;

The above outputs represent our measure. In order to integrate them in our EKF it is necessary to express the quasivelicity vector and its derivative in term of the PHINS outputs.

The *transformation matrix* ${}^{0}_{P}T$ of the PHINS frame w.r.t. the main frame can be easily expressed in function of the transformation matrix of the center of mass:

$$ {}^{0}_{P}T = {}^{0}_{Cm}T \cdot {}^{Cm}_{P}T \tag{1.11} $$

which is function of the state variables ${}^{0}_{Cm}R$, $\mathbf{c}_m$ and of the known generalized offset ${}^{Cm}_{P}T$ (see previous Figure). The reorganization of the transformation matrix ${}^{0}_{P}T$ into a 12 element vector represents the first set of measure equations.

The *linear velocity* of the PHINS, projected the main frame <0>, can be computed from the quasivelocity vectors making use of the linear part of the jacobian (i.e. the bottom-half of the matrix) of Eq.(1.2):

$$ {}^{0}v_P = {}^{0}J_{Lin}\left(\mathbf{q}, \mathbf{r}_P\right)\mathbf{p} \tag{1.12} $$

where $\mathbf{r}_P$ is the location of the origin PHINS frame <Ph> w.r.t. the main frame <0>. Details on the computation of the Jacobian here used can be found in [11].

The *angular velocity* of the PHINS, projected the main frame <0>, is simply given by:

$$ {}^{Ph}\omega_{Ph} = {}^{Ph}_{Cm}R\,{}^{Cm}\omega_{Cm} = {}^{Ph}_{Cm}R\begin{bmatrix} p_1 & p_2 & p_3 \end{bmatrix}^T \tag{1.13} $$

Finally, it is necessary to express the *linear acceleration* of the PHINS in term of derivative of the quasivelocity vector. This can be done considering the relation between the derivative of the configuration vector $\mathbf{q}$ and the quasivelocity $\mathbf{p}$:

$$ \frac{d}{dt}\left(\frac{d\mathbf{q}}{dt}\right) = \frac{d}{dt}\left(V\mathbf{p}\right) = \frac{dV}{dt}\mathbf{p} + V\frac{d\mathbf{p}}{dt} = \left(\sum_{i=1}^{6}\frac{\partial V}{\partial q}\left[V\mathbf{p}\right]_i\right)\mathbf{p} + V\frac{d\mathbf{p}}{dt} \tag{1.14} $$

The last three elements of the vector (1.14) represent the linear acceleration ${}^{0}\mathbf{a}_{Cm}$ of the center of mass projected in the main frame <0>. This is related to the linear acceleration ${}^{0}\mathbf{a}_{Ph}$ of the PHINS frame, projected in the main frame, by the following relation:

$$ {}^{0}\mathbf{a}_{Ph} = {}^{0}\mathbf{a}_{Cm} + {}^{0}\mathbf{v}_{Cm} \wedge {}^{0}\mathbf{r}_p + {}^{0}_{Cm}R\begin{bmatrix} \dot{p}_1 & \dot{p}_2 & \dot{p}_3 \end{bmatrix}^T \wedge {}^{0}\mathbf{r}_p \tag{1.15} $$

Note that the quantity $\frac{d\mathbf{p}}{dt}$ can be easily computed from the first 6 state equations (1.6).

Finally, combining together equations (1.11), (1.12), (1.13) and (1.15) we obtain a set of 21 equations which represent the measure equations of the extended Kalman filter:

$$ \mathbf{z}_k = \begin{bmatrix} \left({}^{Ph}_{0}RT\right)_k + \nu_{RTk} & \left(0\mathbf{v}_{Ph}\right)_k + \nu_{vk} & \left(Ph\omega_{Ph}\right)_k + \nu_{\omega k} & \left(0\mathbf{a}_{Ph}\right)_k + \nu_{ak} \end{bmatrix} \tag{1.16} $$

The 4 vectors ν represent the measure noise, associated with the PHINS unit.

Optimal configuration for hovering

The importance of the knowledge of the center of buoyancy is also related to the problem of power optimization. During an autonomous manipulation task, the working orientation of the vehicle does not have strict constrains, being the manipulator more capable of realizing specific orientation than the vehicle. Thus a working vehicle orientation could be simply chosen as the one which aligns the COB above the COM, minimizing the power requirement for maintaining the vehicle in hovering. The equilibrium target rotation is thus computed with the following considerations.

Let the rotation matrix of the equilibrium configuration be

$$ {}_E^0R = \begin{bmatrix} {}^0\mathbf{i}_e & {}^0\mathbf{j}_e & {}^0\mathbf{k}_e \end{bmatrix} \tag{1.17} $$

To reach our goal, the axis ${}^0\mathbf{k}_e$ is chosen to be the parallel to the COM-COB segment:

$$ {}^0\mathbf{k}_e = \frac{{}^0\mathbf{c}_b}{\left|{}^0\mathbf{c}_b\right|} \tag{1.18} $$

The axis ${}^0\mathbf{i}_e$ is instead chosen as the one orthogonal to the plane formed by ${}^0\mathbf{k}_e$ and the axis $\begin{bmatrix} 0 & 1 & 0 \end{bmatrix}^T$:

$$ {}^0\mathbf{i}_e = \frac{\begin{bmatrix} 0 & 1 & 0 \end{bmatrix}^T \wedge {}^0\mathbf{k}_e}{\left|\begin{bmatrix} 0 & 1 & 0 \end{bmatrix}^T \wedge {}^0\mathbf{k}_e\right|} \tag{1.19} $$

Finally, the ${}^0\mathbf{j}_e$ axis is simply computed as the cross product:

$$ {}^0\mathbf{j}_e = {}^0\mathbf{k}_e \wedge {}^0\mathbf{i}_e \tag{1.20} $$

The matrix (1.17) so formed is then transformed in roll, pitch and yaw angles and the first two replace the ones target orientation for the navigation controller.

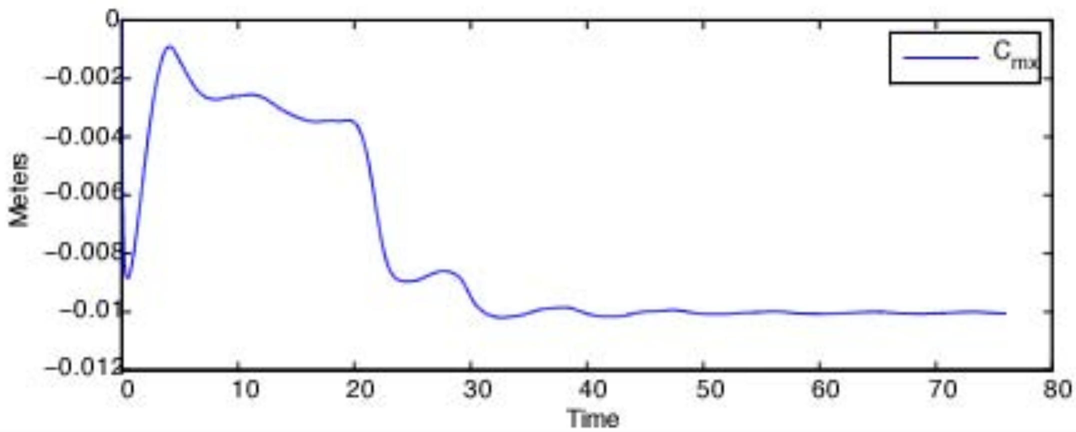
Implementation

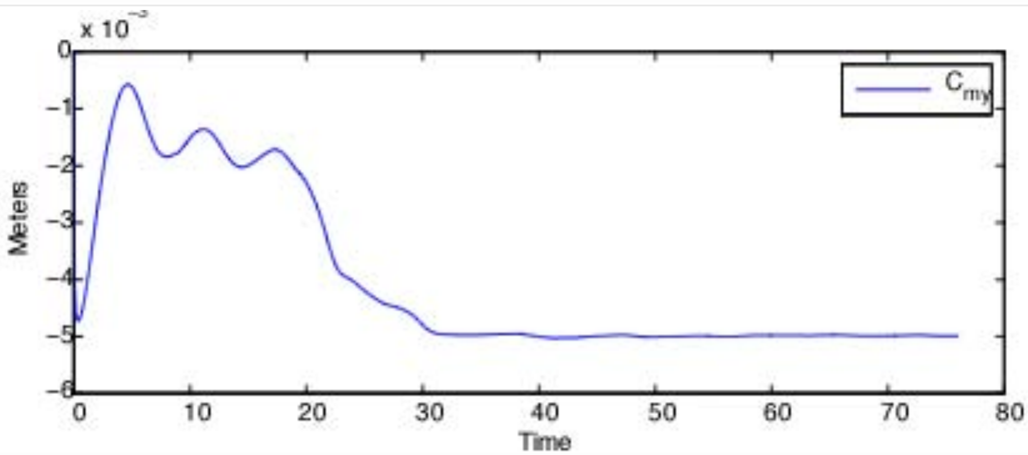
The complex nature of our EKF has been the main obstacle to its practical implementation. In SAUVIM, this has been overcome by means of automated tools for code generation. The computation of the partial derivatives of the process measure, necessary to the implementation of the extended Kalman filter, has been done using symbolic computation

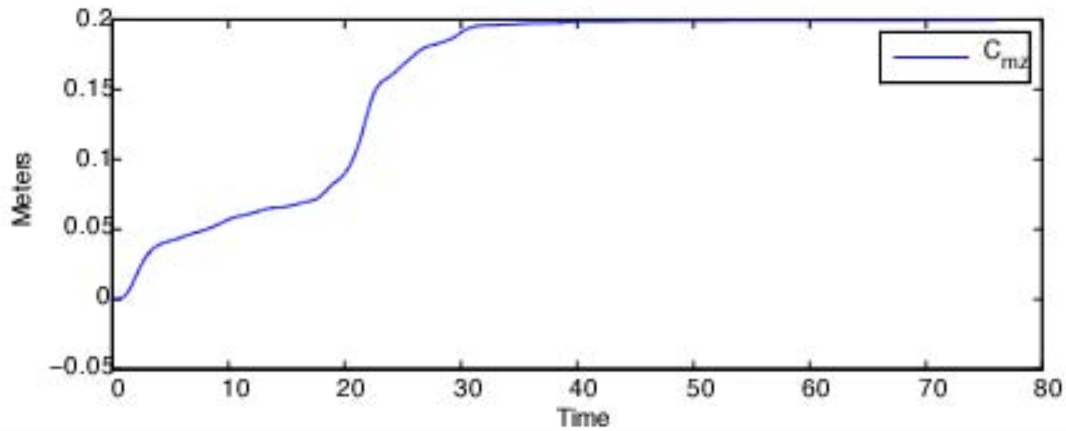
packages. The symbolic processor has then been used for generating the 5,000+ lines of C++ code necessary to import the EKF in our hardware system.
Despite the complexity and length, with the optimization introduced by the code generation process, the release version of our EKF is able to run with a sample time of about 50ms, hence perfectly suitable to an online implementation in the vast majority of navigation controllers.

Simulative results
The first results of the EKF for COB identification have been validated using the SAUVIM simulator. The simulator implements the Lagrange equation for quasicoordinates (1.4), inclusive of the drag, restoring force and added mass.

The first experiment consisted in performing simple open-loop oscillation around the three center of mass axis, in order to assess the performance of the EKF. Results are shown in the following figures.





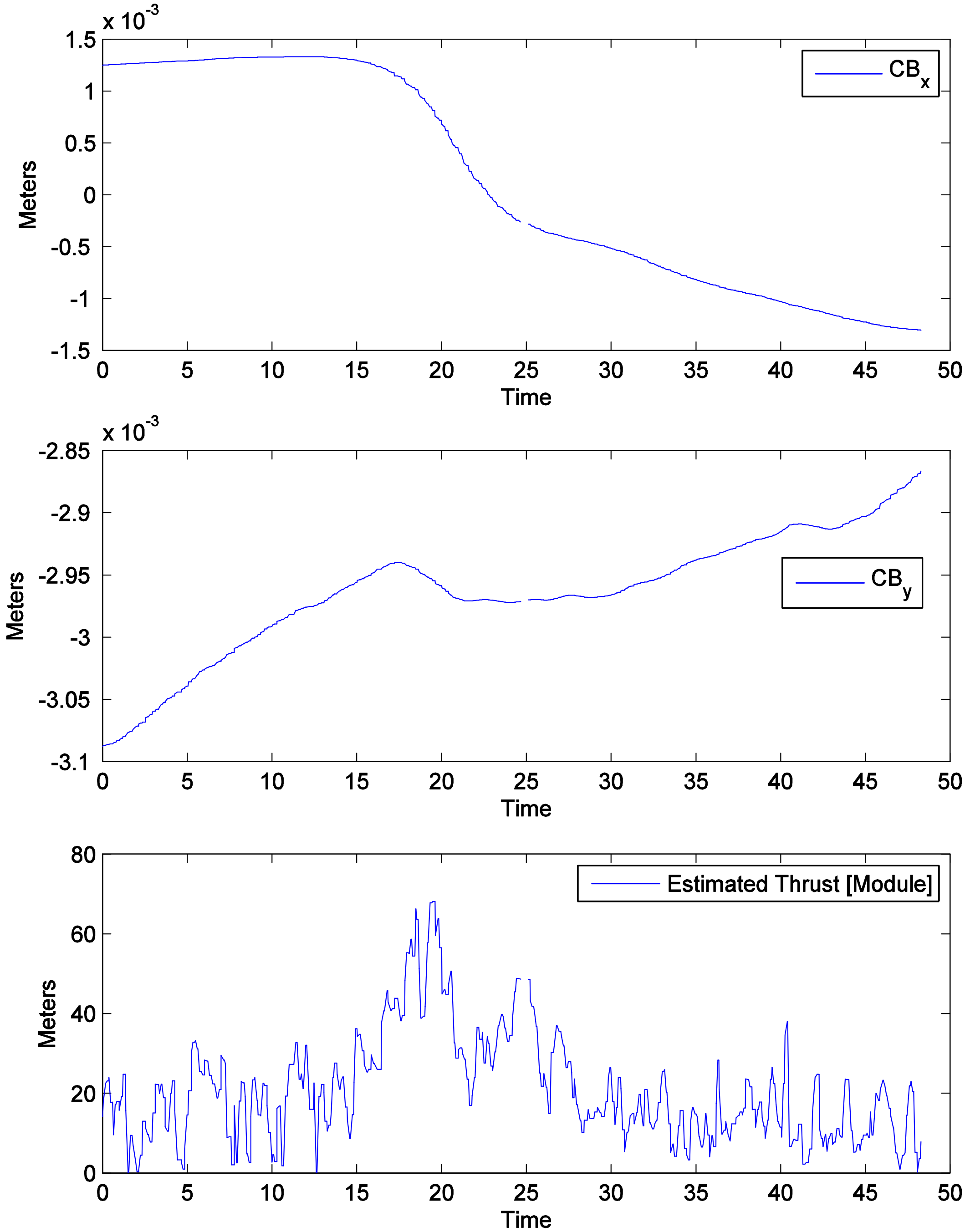


Output of the EKF during random navigation over 70 sec.

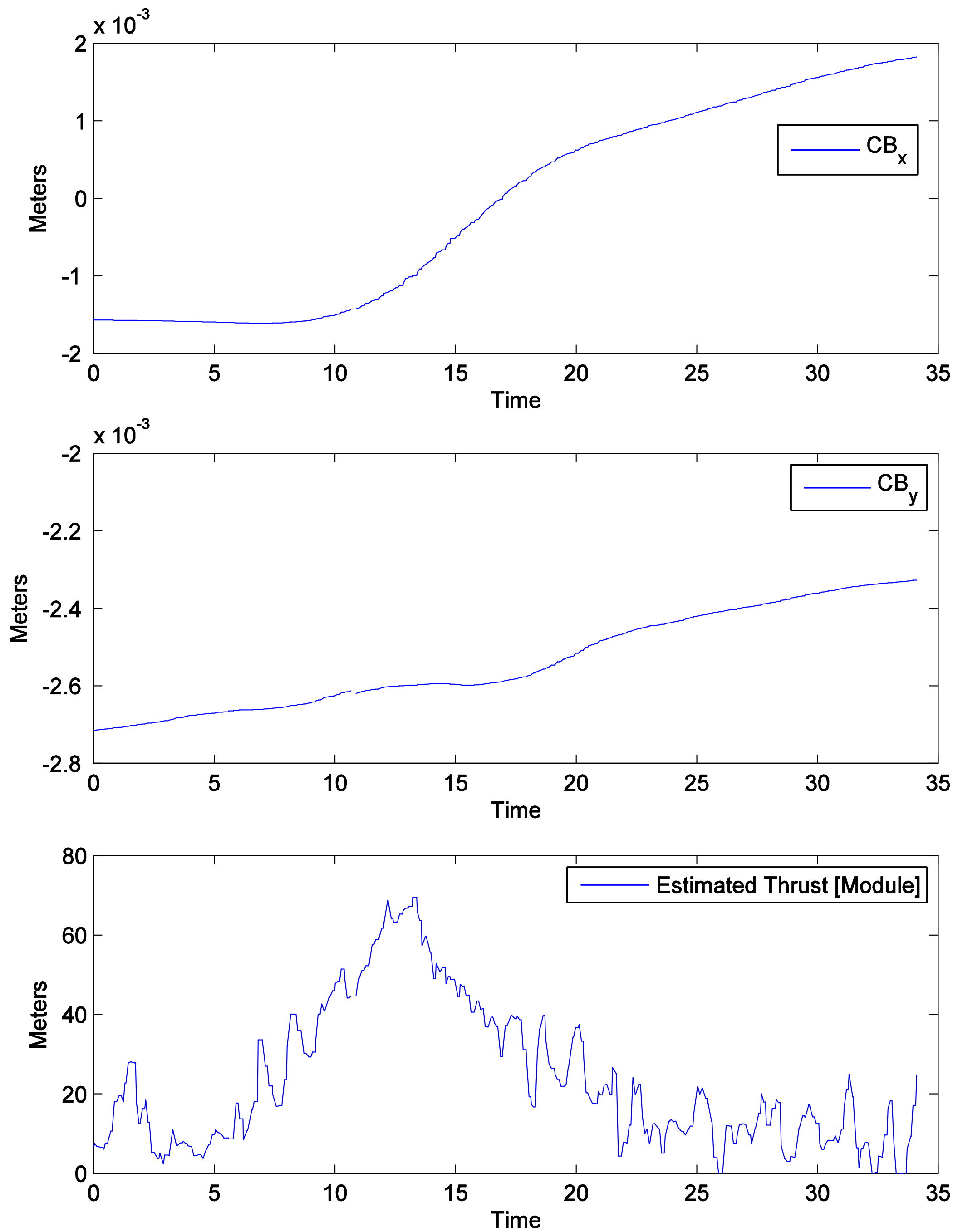
Here, the three coordinates of the center of buoyancy successfully converge toward the simulated values of the COB (respectively -10mm, -5mm and 200mm). The accuracy, in this simulative case, is in the order of fraction of millimeter.

Experimental results

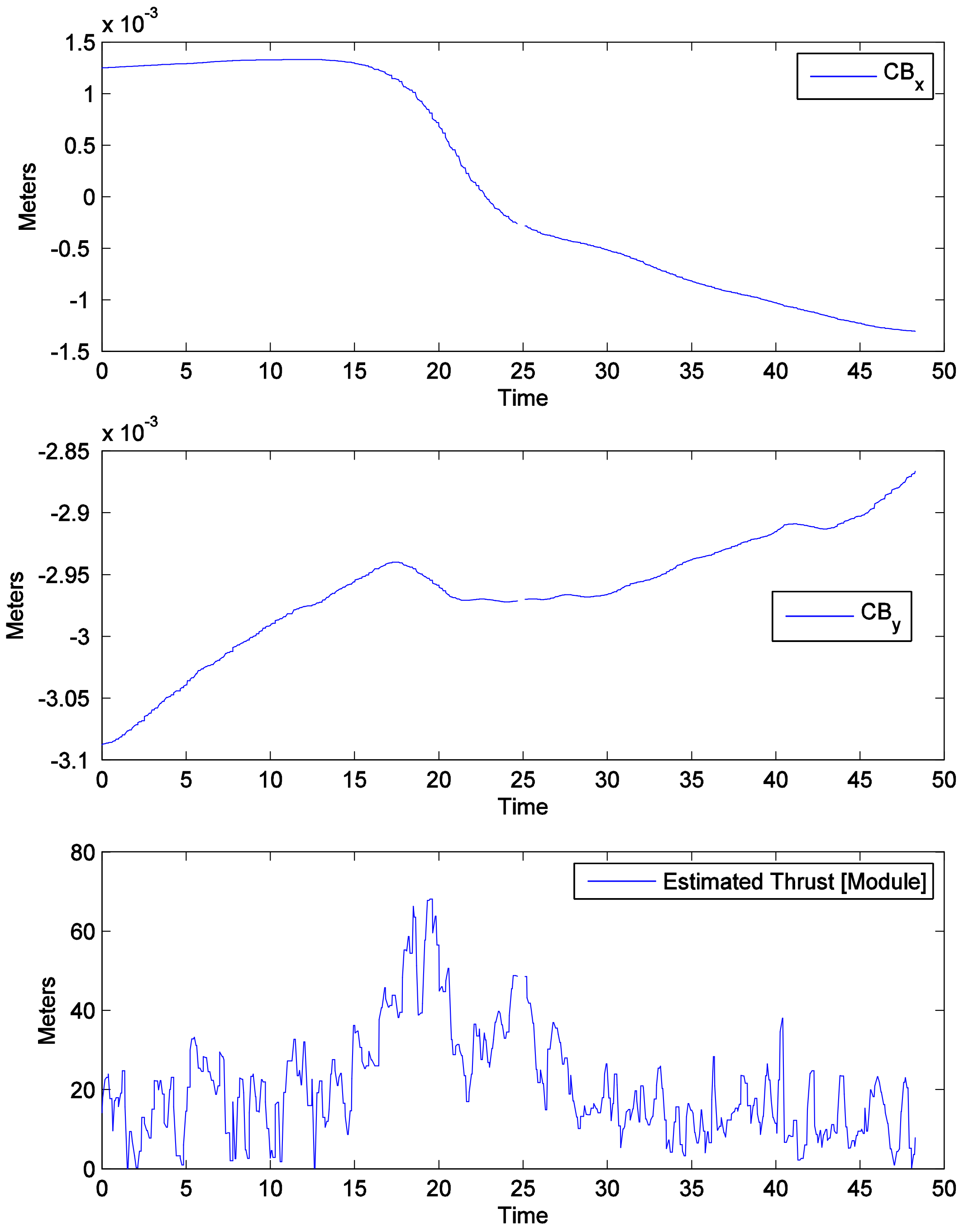
The previous results were experimentally confirmed with the SAUVIM vehicle. In this case the vehicle is set to maintain an hovering position, with the roll and pitch chosen in order to align the center of buoyancy over the center of mass. In this experiment the controller is a 6 DOF model-based [7], re-adapted to the quasivelocity formulation ([11], [13]).
The following plots show the output of the Kalman filter subsequent to three different changes of the COB position, obtained by re-distributing the air in the ballasts.


x 10-3
1.5
1
0.5
0
-0.5
-1
-1.5
Meters
CBx
0 5 10 15 20 25 30 35 40 45 50
Time
x 10-3
-2.85
-2.9
-2.95
-3
-3.05
-3.1
Meters
CBy
0 5 10 15 20 25 30 35 40 45 50
Time
80
60
40
20
0
Meters
Estimated Thrust [Module]
0 5 10 15 20 25 30 35 40 45 50
Time

Case 1

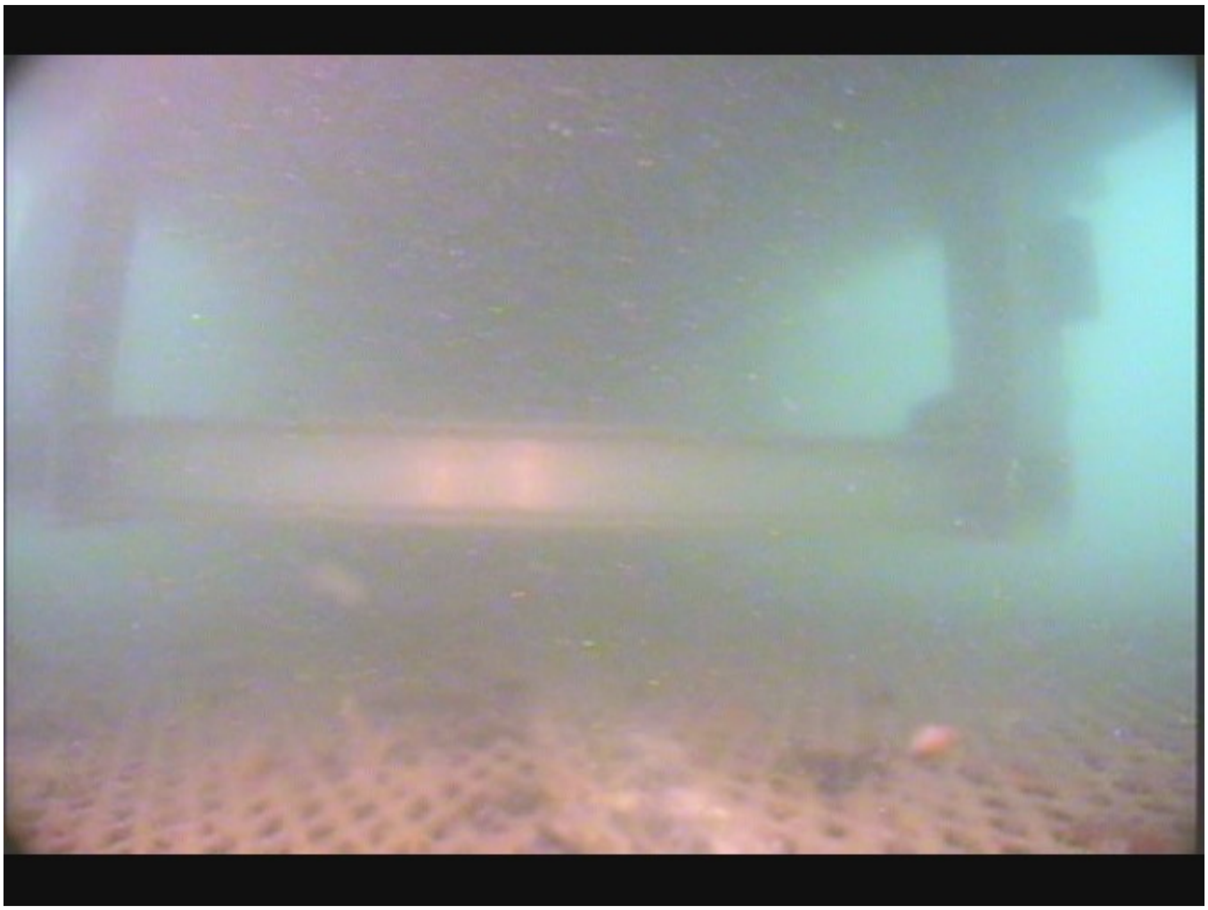

x 10^-3
Meters
Time
CBx
x 10^-3
Meters
Time
CBy
Meters
Time
Estimated Thrust [Module]

Case 2


x 10^-3
1.5
1
0.5
0
-0.5
-1
-1.5
Meters
CB_x
0 5 10 15 20 25 30 35 40 45 50
Time
x 10^-3
-2.85
-2.9
-2.95
-3
-3.05
-3.1
Meters
CB_y
0 5 10 15 20 25 30 35 40 45 50
Time
80
60
40
20
0
Meters
Estimated Thrust [Module]
0 5 10 15 20 25 30 35 40 45 50
Time

Case 3

The proof that the COB lies above the COM is that the global module of the thrust vector converges toward zero (see figure). As a matter of fact, even a small fraction of degree in the target orientation would generate a compensation thrust of several kilograms, given the mass of 3,660kg and 90mm of distance between the COB and COM of the vehicle.
The condition, in this experiment, were the same of the simulative case, and the model based controller was set to maintain a hovering position over a submerged reference target. The global buoyancy of SAUVIM, in this case, was set to neutral.



In particular, right after the initialization, the estimated value of the COB was done with a larger error and the thrusters had to compensate the restoring force in order to maintain the hovering position. Successively, the EKF converges toward the COB location with a sub-millimeter accuracy, proven by the convergence toward zero of the thrust force.

REFERENCES

[1] G. Antonelli, F. Caccavle, S. Chiaverini, and G. Fusco, "A novel adaptive control law for autonomous underwater vehicles," in Robotics and Automation, 2001. Proceedings 2001 ICRA. IEEE International Conference on, vol. 1, 2001, pp. 447–452 vol.1.

[2] O.-E. Fjellstad and T. Fossen, "Singularity-free tracking of unmanned underwater vehicles in 6 dof," in Decision and Control, 1994., Proceedings of the 33rd IEEE Conference on, vol. 2, Dec 1994, pp. 1128–1133 vol.2.

[3] — —, "Position and attitude tracking of auv's: a quaternion feedback approach," Oceanic Engineering, IEEE Journal of, vol. 19, no. 4, pp. 512 – 518, October 1994.

[4] T. Fossen and J. Balchen, "The nerov autonomous underwater vehicle," in OCEANS '91. 'Ocean Technologies and Opportunities in the Pacific for the 90's'. Proceedings., Oct 1991, pp. 1414–1420.

[5] Y. Sunand C. Cheah, "Adaptive setpoint control for autonomous underwater vehicles," in Decision and Control, 2003. Proceedings. 42nd IEEE Conference on, vol. 2, Dec. 2003, pp. 1262–1267 Vol.2.

[6] J. Yuh, J. Nie, and C. Lee, "Experimental study on adaptive control of underwater robots," in Robotics and Automation, 1999. Proceedings. 1999 IEEE International Conference on, vol. 1, 1999, pp. 393–398 vol.1.

[7] G. Antonelli, Underwater Robots, 2nd ed. Springer, February 2006. [8] G. Marani, S. K. Choi, and J. Yuh, "Underwater autonomous manipulation for intervention missions auvs," Ocean Engineering, vol. 36, no. 1, pp. 15 – 23, 2009, aUV. [Online]. Available: http://www.sciencedirect.com/science/article/B6V4F-4T7F5PD-1/2/ce310fd84710cc86d5ffd871b95edd70

[9] J. Yuh, S. Choi, C. Ikehara, G. Kim, G. McMurty, M. Ghasemi-Nejhad, N. Sarkar, and K. Sugihara, "Design of a semi-autonomous underwater vehicle for intervention missions (sauvim)," Apr 1998, pp. 63–68.

[10] J. Yuh and S. K. Choi, "Semi-autonomous underwater vehicle for intervention mission: An auv that does more than just swim," Sea Technology, vol. 40, no. 10, pp. 37–42, 1999.

[11] G. Marani, "Robosim: a program for simulating mechanical systems in robotics," Master's thesis, University of Pisa, 1997.

[12] — —, "Symbolic computation in system modelling, identification and control," Ph.D. dissertation, University of Pisa, 2000. [13] H. Kwatny and G. Blankenship, "Symbolic construction of models for multibody dynamics," Robotics and Automation, IEEE Transactions on, vol. 11, no. 2, pp. 271 – 281, April 1995.

Active Feedback Thruster System (AFTS)

Project Leader(s): Mr. Aaron Hanai
Personnel: Mr. Kaikala Rosa

Objectives

Since one of the primary goals for the vehicle is underwater manipulation, the thruster subsystem must be accurate enough to maintain robust hovering of the vehicle. This has required experimental analysis and tuning of the hardware and engineering design into the performance of the software feedback control scheme. The objectives of this system include:

- An energy efficient distribution of forces among the 8 vehicle thrusters using an analytical approach (as opposed to heuristics).
- A closed-loop thruster control design based on feedback from the motor controllers.
- A software supervisor to prevent errors when the reference thrust exceeds the physical limits of the hardware due to voltage sag in the source batteries.
- A model-based thrust estimator that is robust to unfavorable water conditions in which cavitation may occur.

Current Status (Tasks Completed during 10/25/2006 - 10/30/2009)

1. Thruster force allocation:
    - Definition of a variable thruster configuration matrix mapping between the thruster forces and the body-fixed vehicle forces/torques
    - Solution of the thruster configuration matrix via weighted pseudoinverse

2. Saturation Guard:
    - Separation and isolation of the linear and angular thrust errors
    - Modeling of thrust loss due to battery voltage sag

3. Thruster modeling:
    - Experimental analysis of the functional relationships between thruster input reference voltage, measured current, measured velocity, and output thrust
    - Development of model-based thrust approximation functions

4. Cavitation tolerance:
    - Experimental observation of the effects of cavitation on thruster performance
    - Development of a model-based fault tolerant thrust estimation function (robust to cavitation)
    - Development of a fault accommodating thruster system that scales the thruster configuration matrix based on the error estimation

Automatic Fault-Accommodating Thrust Redistribution for a Redundant AUV

This research reports on the development of an automatic thrust redistribution algorithm for a redundant autonomous underwater vehicle (AUV) in the case of thruster faults. Under favorable conditions, the transformation of the thruster force vector to the generalized body-fixed force vector can be computed in a least-squares manner, which provides the minimum norm solution. In the case of some type of thruster fault, the redundancy in the system allows for seamless redistribution of the thruster forces while maintaining the desired vehicle motion. An accurate, fault-detecting thrust estimator has been previously developed that is robust to changes in source power and propeller ventilation. Such an estimator is necessary in order to quantify the health of the thrusters, which can then be used to weigh the contribution of each thruster to the vehicle motion in a continuous manner. An example of the thruster health index in its simplest form is the approximated thrust divided by the reference thrust, passed through a moving average filter, and normalized over all thrusters. This index can effectively scale back the contribution of any faulty thruster to the body-fixed, vehicle force vector solution.

1. Introduction

The primary motivation of this paper is to evolve the station-keeping ability of an AUV for the purpose of autonomous manipulation, as implemented for intervention tasks. Fine motion control of the vehicle is necessary since its motion is translated to the end-effector. Furthermore, the unpredictable nature of subsea conditions during a mission requires a fault-accommodating system design that is robust to unfavorable water conditions or internal subsystem failures. For example, the propellers may become entangled or damaged, ventilation may occur near the water surface, or there may be a reduction in source power to the thrusters.

To design an appropriate thrust estimator, the propeller physics may be considered in order to develop a set of single or multiple state mathematical models for the thrusters [1-5]. However, since the servo motor controllers associated with the thrusters may provide velocity and motor current draw as feedback, the data may be compared to measured thrust values (by load cell) in order to develop a set of easily and practically derived thruster models [6]. This was the method employed to derive the existing thruster models, although due to the lack of measurement equipment, the ambient water flow velocity [7-8] was not considered, which would have theoretically improved the accuracy of the models.

A fault-tolerant thruster system design can be divided into the areas of fault detection, fault isolation, and fault accommodation [9]. Examples of fault detection and isolation include a statistical method [10], a trained diagnostic observer [11], or a practically derived, model based approach [12]. Provided a successful thruster fault detection method, the desired vehicle body-force reference can be achieved by distributing the thruster forces by means of a weighted least-norm [13], or bounded infinity-norm solution [14].

This paper focuses on the details of innovative fault accommodation in particular. The difference between a thruster's reference value and its corresponding estimate can generate a type of quantified health index. This value can subsequently be used to scale back the contribution of a particular thruster to the overall vehicle motion by adjusting the weights in the mappings between the vehicle-space and thruster-space configurations. Furthermore, this can be implemented in a continuous manner, as opposed to a thruster that is discretely deemed either on or off.

Fig. 1 SAUVIM

2. Thrust Distribution

The basic thrust distribution algorithm is a component of an active feedback thruster system that is implemented and tested on the Semi-Autonomous Underwater Vehicle for Intervention Missions (SAUVIM) [15], shown in Fig. 1. Development is a collaborative project between Marine Autonomous Systems Engineering, Inc. (MASE, Inc.), the Autonomous Systems Laboratory of the University of Hawaii's College of Engineering, and the Naval Undersea Warfare Center, Rhode Island. The vehicle is outfitted with a seven degree-of-freedom electromechanical robotic manipulator, and as a unified system is designed for intervention tasks. This requires fine motion control for hovering and is therefore equipped with eight brushless DC thrusters for geometric redundancy.
Vehicle sensors feed kinematic information to the navigation controller, which develops a body-fixed reference force vector τ, which is derived from the input of the vehicle equation of motion [16]:

$$M(q)\dot{p} + D(q,p)p + g(q) = \tau \qquad (1)$$

where p is the linear and angular velocities in the body-fixed frame and q is the vehicle position and orientation vector in the earth-fixed frame. M is the inertia matrix, including both rigid body and added mass terms. D is the matrix of dissipative terms including Coriolis and centripetal effects, as well as hydrodynamic damping. The vector g describes the gravitational and buoyant restoring forces.
As applied to SAUVIM, its navigation controller solves this equation of motion in order to generate a 6-DOF reference vector τ_{ref} from the kinematic values measured by the sensors. This vector must be transformed to a thruster reference vector $T = [T_1 \cdots T_8]$ according to the geometry in Figs. 5 and 6, where thrusters 1 through 4 are oriented vertically, 5 and 6 are longitudinal, and thrusters 7 and 8 are laterally aligned.
Defining the positions and orientations x_i and r_i of thruster i respectively, as well as the vehicle center of mass $C = [C_x, C_y, C_z]$, then by geometry,

$$\boldsymbol{\tau} = KT \qquad (2)$$

according to the transformation matrix

$$K = \begin{bmatrix} r_1 & \cdots & r_8 \\ (x_1 - C) \times r_1 & \cdots & (x_8 - C) \times r_8 \end{bmatrix} \qquad (3)$$

At this point, (2) can be inverted such that

$$T = K^{\#}\boldsymbol{\tau} \qquad (4)$$

according to the generalized inverse [17]

$$K^{\#} = W^{-1}K^{T}\left(KW^{-1}K^{T}\right)^{-1} \quad (5)$$

which minimizes the error norm $||\tau - KT||$ of (2). Consistent with the method outlined in [13], the diagonal weight matrix *W* can be defined such that

$$W^{-1} = \begin{bmatrix} w_1 & 0 & 0 \\ 0 & \ddots & 0 \\ 0 & 0 & w_8 \end{bmatrix} \qquad (6)$$

where the coefficients ($0 \le w_i \le 1$) can each be set to some value based on the reliability of the corresponding thruster. In this case ($w_i = 1$) represents complete functionality, and ($w_i = 0$) represents complete thruster failure.

3. Thrust Estimation

To develop the thrust estimators, experiments were performed to measure the relationship between the control input voltage, feedback current, feedback velocity, and output thrust (measured via load cell). These relative measurements are displayed versus time in Fig. 2. Two independent, single-input thrust approximation functions were developed with respect to the measured electric current draw, and the measured propeller shaft velocity. The purpose for the two separate functions is apparent when subsea conditions become unfavorable. When ventilation occurs, which is common if the vehicle is at the surface, the two thrust approximations deviate from each other. This difference can quantify the state of thruster fault. The first half of the time interval in Fig. 3 represents favorable subsea conditions, such that the test thruster is a sufficient distance below the surface of the water. In this case, the measured thrust follows the reference, and the two thrust approximations agree with the measured value. However, in the second half of Fig. 3, the thruster is purposely positioned near the water surface in order to promote propeller ventilation. In this case, the measured thrust no longer follows the reference, and the velocity-based thrust approximation is overestimated relative to the measured value, while the current-based approximation is also overestimated, but to a lesser extent. This relationship was exploited in order to develop a new thrust approximation that accounts for ventilation by considering both current and velocity feedback measurements [12]. The experiment performed as plotted in Fig. 4 is identical to that in Fig. 3, except that the new thrust approximation function is robust to ventilation effects.

4. Thruster Fault Accommodation

4.1 Thruster Weights

In its simplest application, the thrust estimate T_{est} based on the feedback current I and feedback velocity Ω can be combined with the reference thrust T_{ref} to generate a quantified health index value per thruster according to

$$w = \left| \frac{T_{est}(I, \Omega)}{T_{ref}} \right| , \quad |T_{ref}| > 0 , \quad w(t = 0) = 1 \quad (7)$$

Note that the values for w are initialized to 1 at the start of a mission, where time $t = 0$. Also, if $T_{ref} = 0$ for a particular time step, then w does not need to be updated, but rather maintains its previous computed value (zero-order hold). During favorable conditions, the value for w is unity, and scales down toward zero as the thrust approximation deviates from the reference due to some form of internal fault or external environmental effect. The health indices defined in (7) can be input as the coefficients of the weight matrix from (6). Effectively, the contribution of any thruster that is experiencing ventilation or any other fault condition will be scaled down relative to the other components of the thrust vector in a continuous manner.

4.2 Thruster Weight Smoothing

In order to smooth the action of the thruster weights, a basic signal processing filter was employed. The *simple moving average* for the thruster weight w_t at time sample t is

$$\overline{w}(t) = \frac{1}{n} \sum_{k=0}^{n-1} w_{t-k} , \quad \overline{w}(t = 0) = 1 \quad (8)$$

which provides the unweighted mean of the previous n data points. Experiments with SAUVIM thrusters have proven successful with a value of n that yields about a 10 second moving average data window.

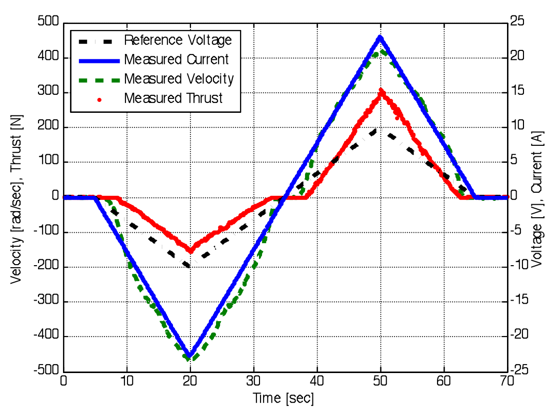


Fig. 2 Control input voltage, feedback current, feedback propeller velocity, and measured thrust versus time

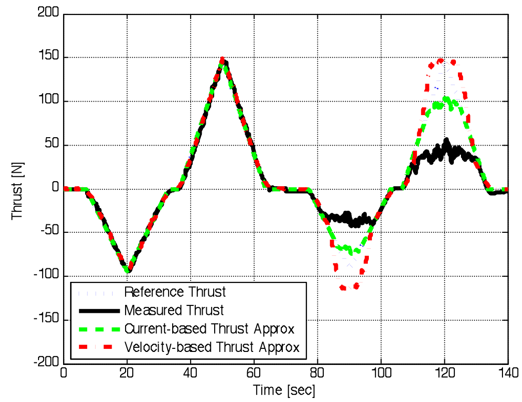


Fig. 3. Thrust versus time with unfavorable conditions (ventilation occurs) during second half of experiment.

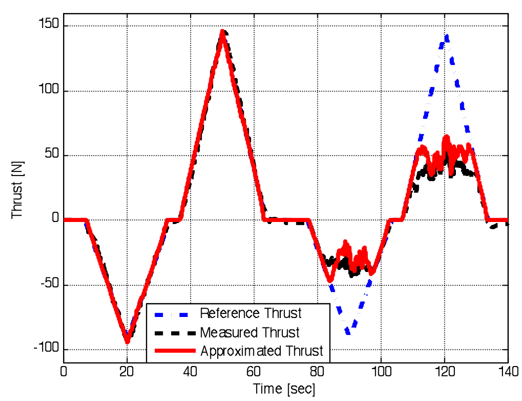


Fig. 4 Reference, measured, and ventilation-robust thrust approximation during unfavorable conditions

From the definition of the weight matrix in (6), the values of the time averaged coefficients must be constrained so that

$$0 \le \overline{w}(t) \le 1 \qquad (9)$$

However, any instantaneous measure of the thruster health index w_t is allowed to exceed unity

$$0 \le w_t \le w_{max} \,,\ w_{max} > 1 \qquad (10)$$

which occurs when the estimated thrust is greater than the reference, and indicates that the thruster has recovered from its fault condition. This can happen when thruster ventilation initially occurs at the water surface, but then the vehicle submerges to a depth sufficient to halt the ventilation. Conversely, if the instantaneous measure w_t is not allowed to exceed unity, then the time averaged value recovers its weight slowly because of the interval of the moving average, and furthermore would be unable to fully recover to complete functionality where $\overline{w}(t) = 1$.

It is also necessary that the time averaged thruster health index remain strictly above zero

$$0 < w_{min} \le \overline{w}(t) \le 1 \qquad (11)$$

This is important because once a weight value w goes to zero, then its corresponding thruster reference also goes to zero. The consequence is that the coefficient w would no longer get updated, and the thruster reference would subsequently be trapped at zero.

4.3 Thruster Weight Normalization

Furthermore, it is necessary to normalize the time averaged thruster health indices so that the weight matrix receives a relative indication of the thruster faults instead of an absolute measure. Collecting the time averaged health indices at time *t* for all *n* thrusters into a single vector, then the normalization yields

$$\left[\overline{w}_1(t) \quad \cdots \quad \overline{w}_n(t)\right] / \left[\overline{w}_{max}(t)\right] \quad (12)$$

This ensures that at least one thruster weight is equal to 1. It has been observed on SAUVIM that it is possible for all eight of the thrusters to experience some form of estimated inaccuracy. In this case, without the implementation of the thruster weight normalization, all *n* of the weight coefficients may be reduced, and the reference vector T_{ref} will have a large component in the nullspace of the weighted pseudoinverse solution from (4) and (5). This translates empirically to a waste of thruster energy.

5. Testing

In order to illustrate the function of the automatic thrust redistribution algorithm, a simple planar simulation was analyzed. The reference thrust input is set as a pure surge motion, linearly ramped up to 200N over 10 seconds.

$$\tau_{ref} \triangleq \left[surge \quad sway \quad yaw\right] = \left[x(t) \quad 0 \quad 0\right]$$

$$x(t) = \begin{cases} 20t\ , & t \le 10 \\ 200\ , & t > 10 \end{cases} \quad (13)$$

The starboard longitudinal thruster is purposely limited to an output of 30N to simulate a reduction in its health index. Figs. 5 and 6 illustrate snapshots of the thruster outputs at $t = 7$ and $t = 50$ seconds into the simulation respectively. The larger arrow outlines represent the reference thrust values T_{ref} computed from the weighted pseudoinverse solution of the τ_{ref} input from above. The smaller arrows within the outlines represent the estimated thrust values. Fig. 7 plots the reference inputs and estimated outputs for the thrusters, Figs. 8 and 9 show the thruster errors and body force errors respectively, and Fig. 10 plots the thruster weights.

During the first 3 seconds of the test, the thrust estimates track the reference (Fig. 7), but the simulated fault for thruster 6 limits its output. This results in an error in its output (Fig. 8), leading to its time averaged reduction in weight (Fig. 10). Due to its decreasing weight index, the reference for thruster 6 continues to reduce until its error stabilizes its weight. At this point, all of the thruster errors (Fig. 8) are reduced, and therefore, so are the body force errors (Fig. 9). A direct comparison of Figs. 5 and 6 should clearly illustrate the effect of the thrust redistribution. The former case shows a minimum-norm reference that is unable to be realized due to a thruster fault. The latter case includes the addition of a homogeneous solution reference derived from the weighted pseudoinverse solution, which uses more overall thruster power, but automatically accommodates the fault condition.

6. Conclusion

An automatic fault-accommodating thrust redistribution algorithm has been successfully implemented by quantifying the health of the thrusters, and using the resulting values to continuously scale the contribution of each thruster to the overall vehicle motion by means of a weighted pseudoinverse solution. The thruster weights are smoothed by means of a simple moving average, and then normalized. This procedure, combined with the careful consideration of the upper and lower limits of the weights, ensures that the thruster references are continuous and can recover from fault conditions. The result is a thrust distribution that automatically reconfigures itself as an encapsulated subsystem, at a lower level than the navigation controller.

References

[1] L. L. Whitcomb, and D. R. Yoerger, "Development, comparison, and preliminary experimental validation of nonlinear dynamic thruster models", *IEEE Journal of Oceanic Engineering*, Vol 24, No 4, pp 481 – 494, 1999.

[2] L. L. Whitcomb, and D. R. Yoerger, "Preliminary experiments in model-based thruster control for underwater vehicle positioning", *IEEE Journal of Oceanic Engineering*, Vol 24, No 4, pp 495 - 506, 1999.

[3] T. I. Fossen, and M. Blanke, "Nonlinear output feedback control of underwater vehicle propellers using feedback from estimated axial flow velocity", *IEEE Journal of Oceanic Engineering*, Vol 25, No 2, pp 241 – 255, 2000.

[4] R. Bachmayer, L. L. Whitcomb, and M. A. Grosenbaugh, "An accurate four-quadrant nonlinear dynamical model for marine thrusters: theory and experimental validation", *IEEE Journal of Oceanic Engineering*, Vol 25, No 1, pp 146 – 159, 2000.

[5] R. Bachmayer, and L. L. Whitcomb, "An open loop nonlinear model based thrust controller for marine thrusters", in *Proc. IEEE/RSJ International Conference on Intelligent Robots and Systems*, Vol 4, 2001, pp 1817 – 1823.

[6] A. Hanai, C. McLeod, K. Rosa, G. Marani, and S. K. Choi, "A practical approach to the development of thruster models for underwater robots", in *Proc. Eighteenth International Offshore and Polar Engineering Conference*, Vol 2, 2008, pp 382 – 388.

[7] J. Kim, J. Han, W. K. Chung, and J. Yuh, "Accurate thruster modeling with non-parallel ambient flow for underwater vehicles", in *Proc. IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2005, pp 978 – 983.

[8] J. Kim, J. Han, W. K. Chung, J. Yuh, and P. M. Lee, "Accurate and practical thruster modeling for underwater vehicles", in *Proc. IEEE International Conference on Robotics and Automation*, 2005, pp 175 – 180.

[9] K. Yang, J. Yuh, and S. K. Choi, "Experimental study of fault-tolerant system design for underwater robots", in *Proc. IEEE International Conference on Robotics and Automation*, 1998, pp 1051 – 1056.

[10] N. Miskovic, and M. Barisic, "Fault detection and localization on underwater vehicle propulsion systems using Principal Component Analysis", in *Proc. IEEE International Symposium on Industrial Electronics*, 2005, Vol 4, pp 1721 – 1728.

[11] G. Antonelli, F. Caccavale, C. Sansone, L. Villani, "Fault diagnosis for AUVs using support vector machines", in *Proc. IEEE International Conference on Robotics and Automation*, 2004, Vol 5, pp 4486 – 4491.

[12] A. Hanai, S. K. Choi, G. Marani, K. Rosa, "Experimental validation of model-based thruster fault detection for underwater vehicles", in *Proc. IEEE International Conference on Robotics and Automation*, 2009, pp 194 – 199.

[13] N. Sarkar, T. K. Podder, and G. Antonelli, "Fault-accommodating thruster force allocation of an AUV considering thruster redundancy and saturation", *IEEE Transactions on Robotics and Automation*, Vol 18, No 2, pp 223 – 233, 2002.

[14] S. Soylu, B. J. Buckham, and R.P. Podhorodeski, "Robust control of underwater vehicles with fault-tolerant infinity-norm thruster force allocation", in *Proc. MTS/IEEE Oceans 2007*, Vancouver, BC, Canada, 2007.

[15] J. Yuh, and S. K. Choi, "Semi-Autonomous Underwater Vehicle for Intervention Missions (SAUVIM)", *Sea Technology*, 1999.

[16] T. Fossen, "Guidance and Control of Ocean Vehicles", John Wiley & Sons, Chichester, 1994.

[17] Y. Nakamura, "Advanced Robotics: Redundancy and Optimization", Addison-Wesley Longman Publishing Co., Inc., Boston, 1999.

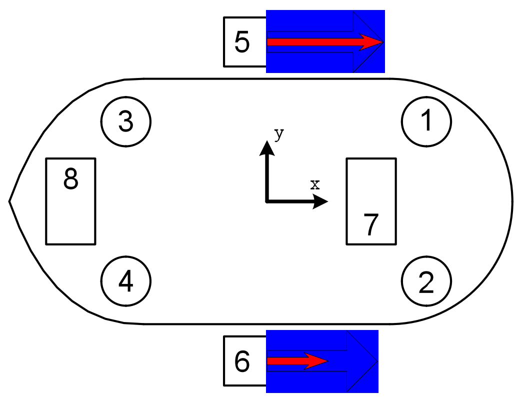


Fig. 5 Pure surge along positive x-axis, with reduced output on thruster 6, and no thrust redistribution

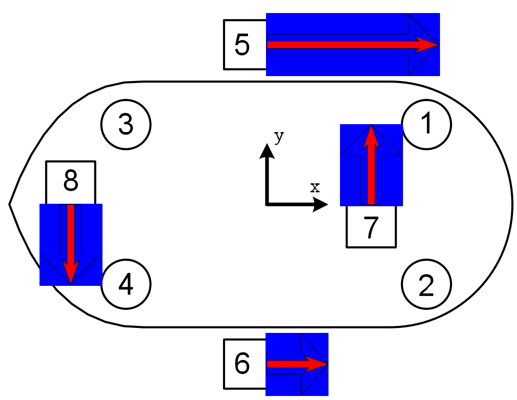


Fig. 6 Pure surge along positive x-axis, with reduced output on thruster 6, and active thrust redistribution

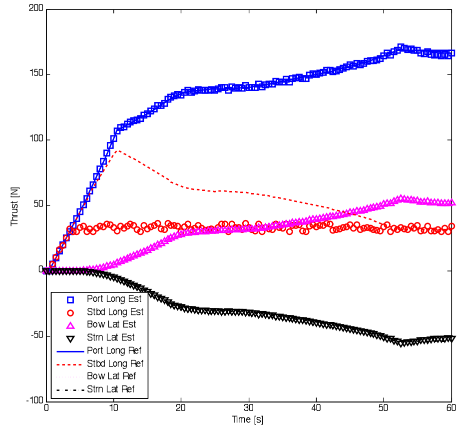


Fig. 7 Simulation: Reference inputs and estimated outputs for SAUVIM longitudinal and lateral thrusters

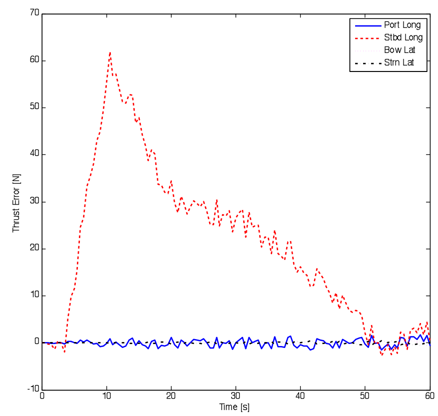


Fig. 8 Thruster errors

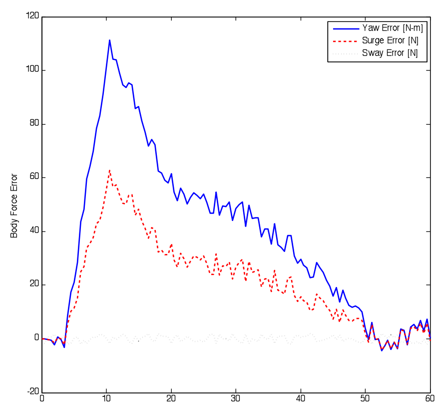


Fig. 9 Body force errors

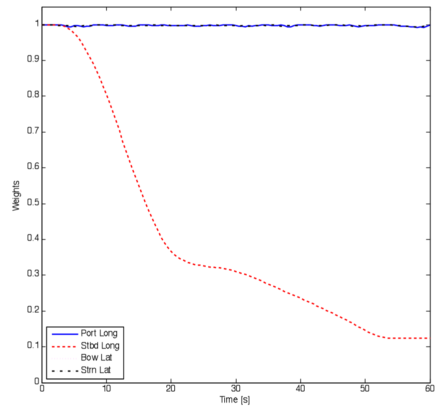


Fig. 10 Thruster weights

Localization and Navigation (LN)

Project Leader(s): Dr. Giacomo Marani
Personnel: Dr. Son-Cheol Yu, Dr. Giacomo Marani
Past Project Leader(s): Dr. Son-Cheol Yu, Dr. Junku Yuh, Dr. Tae Won Kim, Dr. Song K. Choi & Mr. Michael West
Past Personnel: Mr. Kaikala H. Rosa, Mr. Scott A. Menor, Mr. Daniel Shnidman & Mr. Mike Hall

Objectives

Global Localization of SAUVIM in all the different condition (on the surface and underwater).

Current Status (Tasks Completed)

The task has been completed in the previous phases. Refer to previous reports for its descriptions.

High-Level Control (HLC)

Project Leader(s): Dr. Giacomo Marani
Personnel: Dr. Giacomo Marani
Past Project Leader(s): Dr. Tae Won Kim , Dr. Junku Yuh, Dr. Kazuo Sugihara & Dr. Song K. Choi
Past Personnel: Mr. Side Zhao, Ms. Jing Nie & Mr. Zhi Yao

Objectives

HLC's objective is to develop a supervisory control module that will minimize human involvement in the control of the underwater vehicle and its manipulation tasks.

Current Status (Tasks Completed)

The task has been completed in the previous phases. Refer to previous reports for its descriptions.

Virtual Environment (VE)

Project Leader(s): Dr. Giacomo Marani
Personnel: Dr. Giacomo Marani
Past Project Leader(s): Dr. Song K. Choi, Dr. Kazuo Sugihara, Dr. Stephen Itoga & Mr. Scott Menor
Past Personnel: Mr. Alexander Nip, Mr. Zhenyu Yang, Mr. Jiwen Liu, Mr. Steve Timcho, Ms. Lori Yokota, Ms. Jennifer Saito, Mr. Brandon Higa, Mr. Xiandong Su, Mr. Alberto Brunete, Ms. Tammy Yamauchi & Mr. Jeffery P. Yee

Objectives

The VE is aimed at developing a supervisory monitoring system for SAUVIM to smoothly and realistically integrate mapping data with on-line sensory information even in the case of low bandwidth. It is the evolution of the old idea of the Predictive Virtual Environment, described in the previous reports of SAUVIM, into a more advanced system collecting also the virtual manipulator and the SAUVIM control interface through direct interaction with the virtual environment.

Current Status (Tasks Completed)

MarisGL was, during the Phase II, the preliminary version of the virtual environment targeted to the MARIS 7080 Manipulator and making use of a standard OpenGL PC video accelerator. During the Phase III-A the application was extended in order to introduce the vehicle model, mainly for collision avoidance verification. But the most important transition toward the global virtual environment happened in the current Phase III-B.

Here, the name of the application, once targeted to visualize only the configuration of the arm, has been changed to Sauvim Explorer (Figure VE-1). Sauvim Explorer collects in a unified application the data from all the sensors of SAUVIM, including data from the DIDSON that can be overlaid over the graphical reconstruction of the floor.

In the final phase III-C we added the important capability of data recording and playback, thus allowing an easy analysis and post-process of all the mission data.

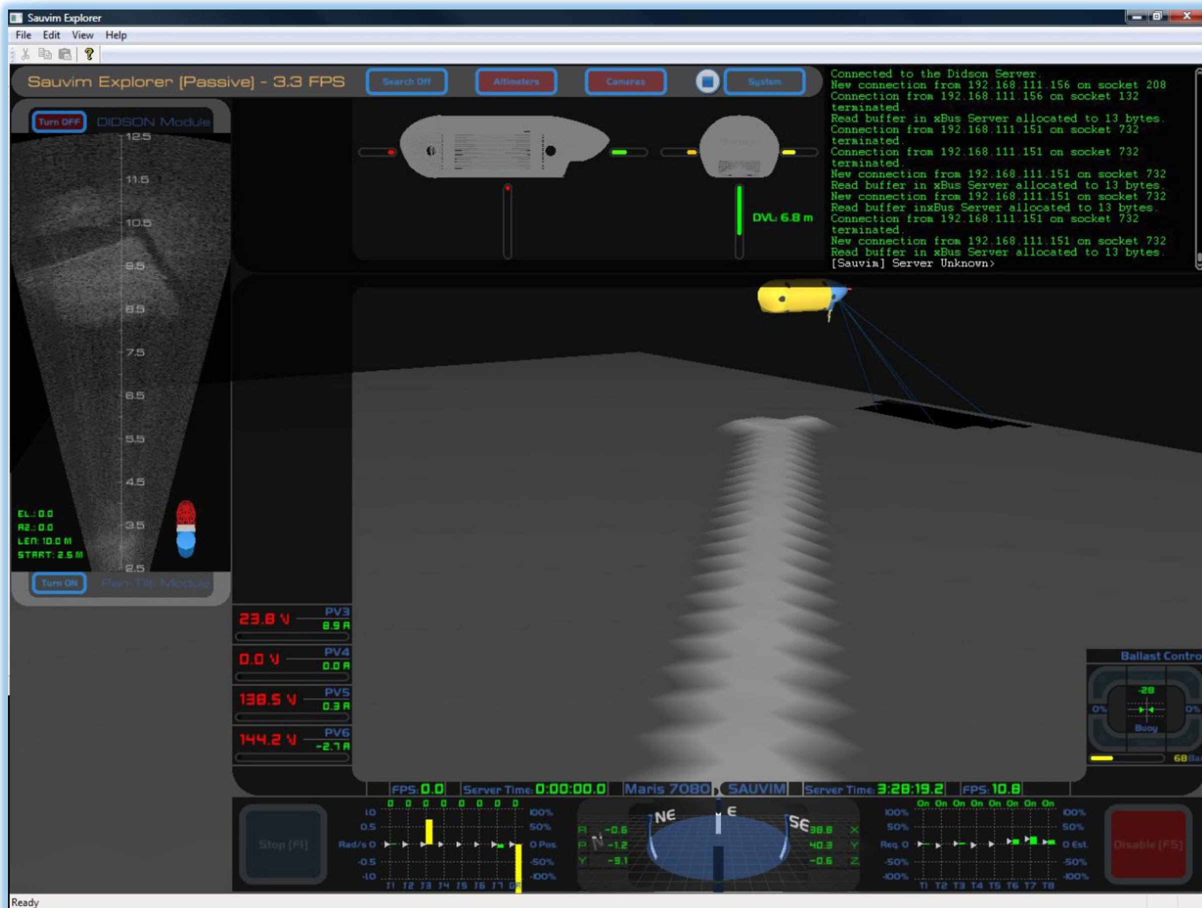


Figure VE-1: Sauvim Explorer

It also hosts the remote console clients for both the Arm Programming Language and the Sauvim Programming Language servers, and may act as remote control (ROV mode) when a sufficient bandwidth channel is present. At this aim Sauvim Explorer contains software interface with several input device hardware, including 6 DOF space controllers.

This represents an enormous step forward toward the unification of the whole system, since it required a huge effort on the standardization of the communication protocol between every module of SAUVIM (sensors, actuators, controllers…). With this modular approach it is now extremely easy to add further sensor modules to SAUVIM and add their input and outputs to the SE application with a minimal effort.

The following is the summary of the major key points:

- Unified interface for SAUVIM and MARIS Manipulator
- Support for SPL (Sauvim Programming Language) and APL (Arm Programming Language) clients in the same console

- Integration of the DIDSON interface
- Integration of the altimeters
- Integration of the pan-tilt control

Following some screenshots of the actual Virtual Reality interface.

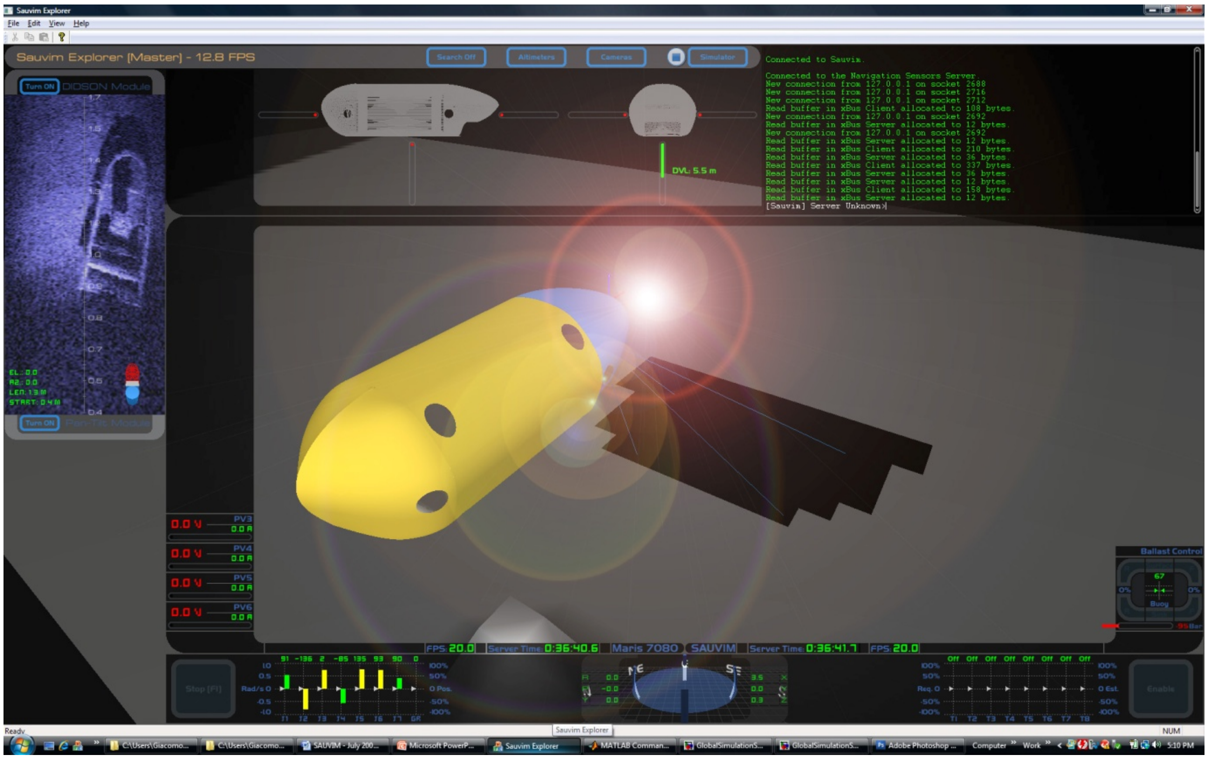


Figure VE-2: General Interface

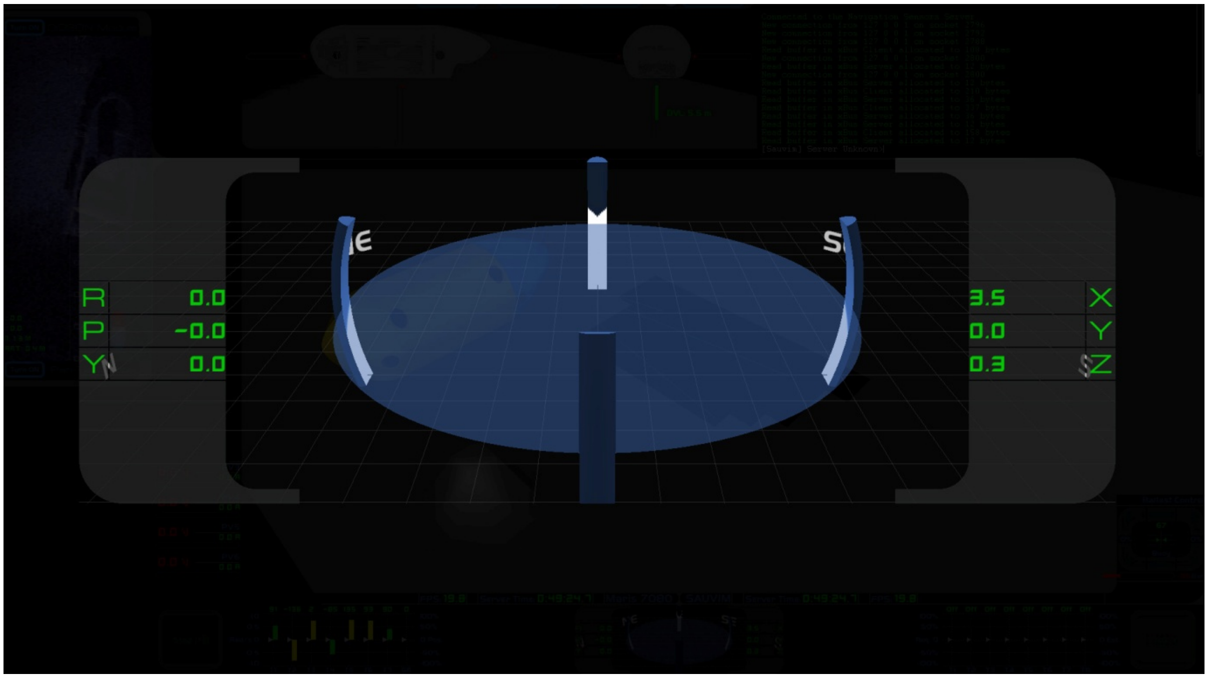


Figure VE-3: The Generalized Position display

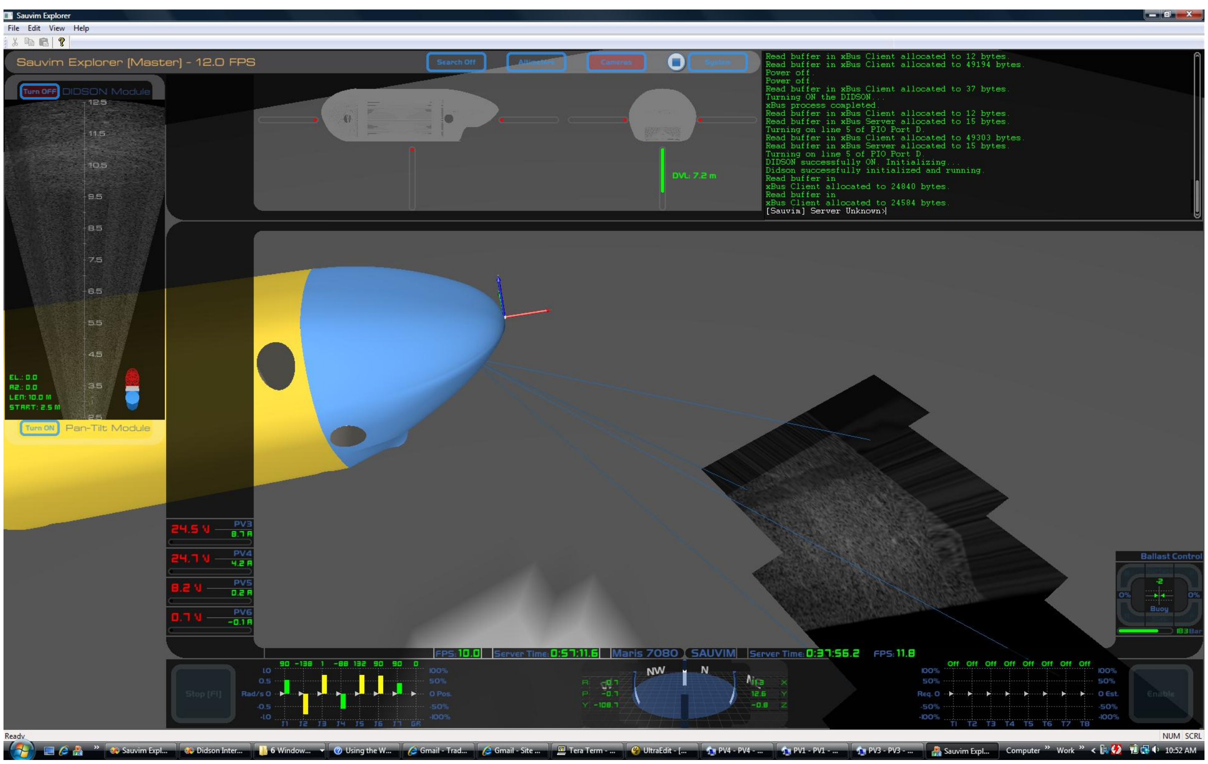


Figure VE-4: Real-time terrain generator (height mapping) for the virtual reconstruction of the ocean floor, with real-time overlay of the DIDSON image

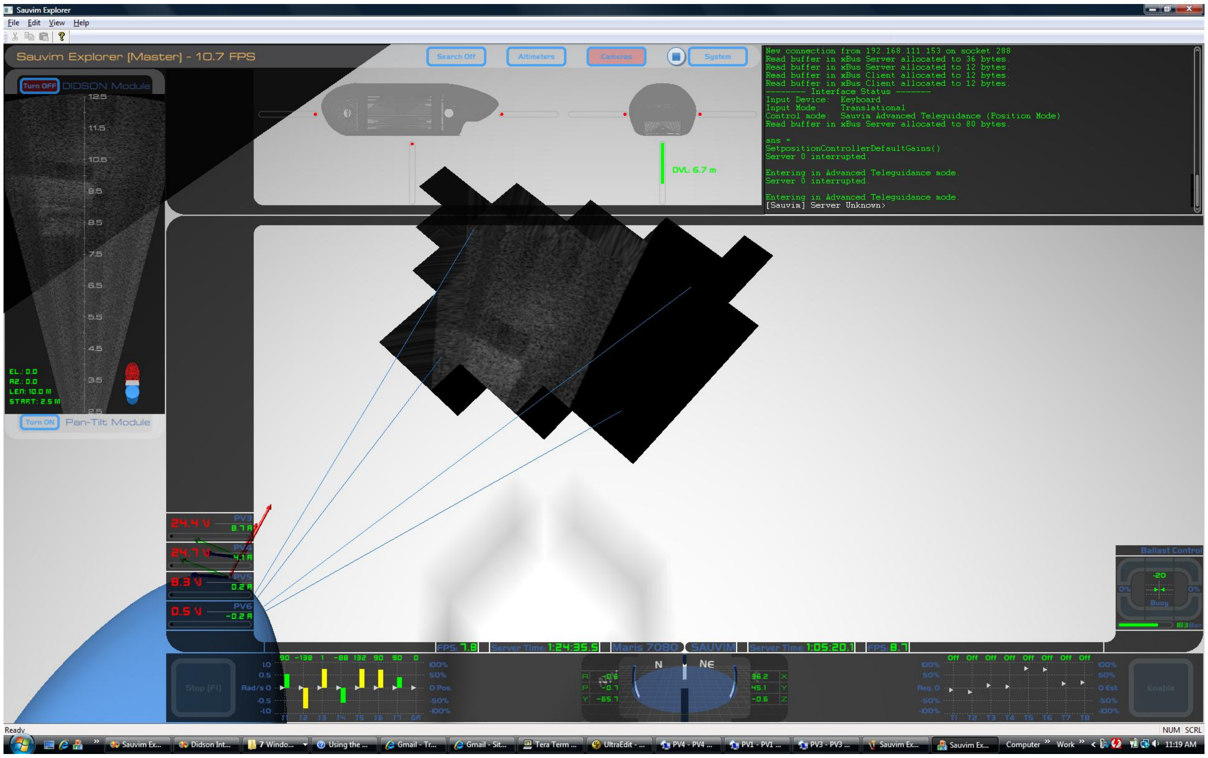


Figure VE-5: Support for 6 DOF motion controller devices, for an alternate driving solution for both the vehicle and manipulator (in case of teleoperation/teleguidance)

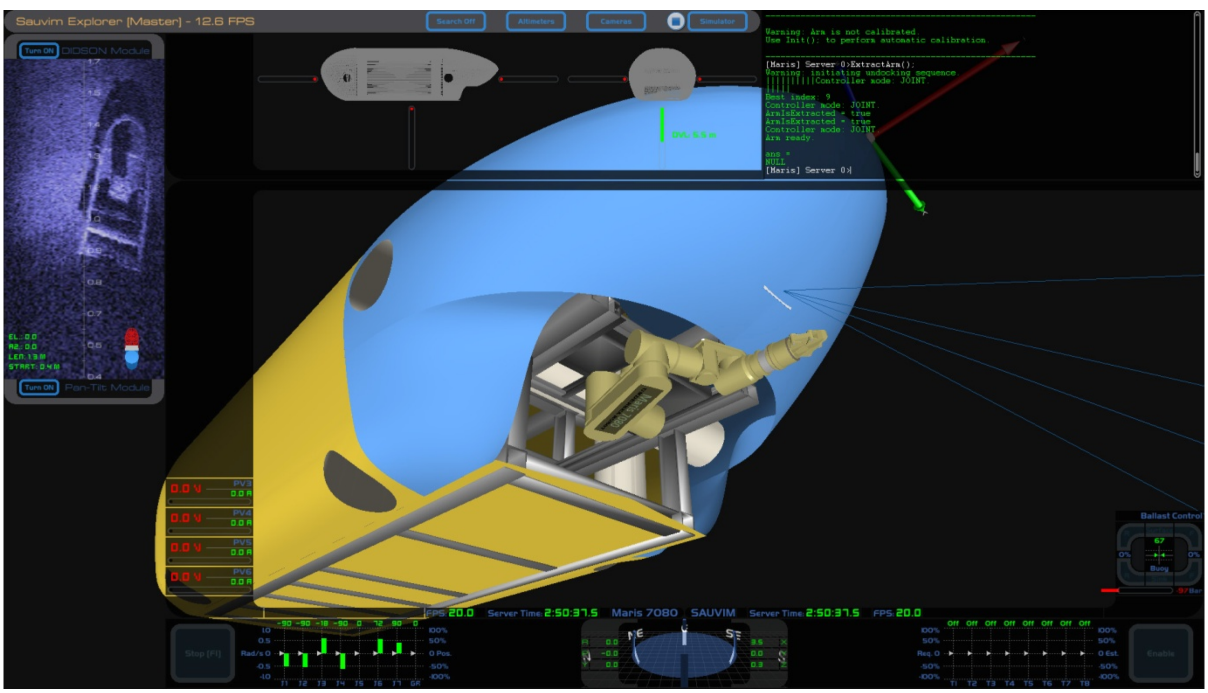


Figure VE-6: Real-time link with the Arm subsystem

SAUVIM Design (SD)

Project Leader(s): Dr. Giacomo Marani, Dr. Song K. Choi
Past Project Leader(s): Dr. Curtis S. Ikehara, Dr. Junku Yuh, Dr. Mehrdad Ghasemi Nejhad, Dr. Gary McMurtry, Dr. Pan-Mook Lee, Dr. Farzad Masheyekhi, Dr. Gyoung H. Kim, Mr. Gus Coutsourakis, Mr. Oliver T. Easterday & Mr. Michael E. West

The main technical development of the SD group is described in the following sections: Reliable, Distributed Control, Mission Sensor Package, Hydrodynamic Drag Coefficient Analysis, Mechanical Analysis & Fabrication and Mechanical-Electrical Design. Many of the developments relative to the SD group have been competed in the previous phases. However the Phase III-B has seen substantial changes in the Reliable, Distributed Control, here described.

Reliable Distributed Control (RDC)

Project Leader(s): Dr. Giacomo Marani
Personnel: Dr. Giacomo Marani
Past Project Leader(s): Dr. Tae Won Kim, Dr. Pan-Mook Lee, Dr. Curtis S. Ikehara, Dr. Song K. Choi & Dr. Gyoung H. Kim
Past Personnel: Mr. Jang-Won Lee, Mr. Michael West, Mr. Tuan M. Hyunh, Dr. Hyun Taek Choi, Mr. Alberto Brunete & Mr. Alexander Nip

Objectives

The objective is to develop a reliable & efficient computing architecture for signal and algorithmic processes of the entire SAUVIM system.

Current Status (Tasks Completed)

The task has been completed in the previous phases. Refer to previous reports for its descriptions.

Mission Package Sensors (MSP)

Project Leader(s): - none -
Personnel: - none -
Past Project Leader(s): Dr. Gary McMurtry, Dr. Song K. Choi & Mr. Oliver T. Easterday
Past Personnel: Mr. Yann Douyere, Mr. Alan Parsa & Mr. Max D. Cremer

Objectives

The SAUVIM Mission Sensor Package for Phase 1 is designed to provide semi-continuous records of AUV water depth (pressure), water temperature, conductivity, computed salinity, dissolved oxygen, pH and turbidity for at least eight hours. These parameters as well as the magnetic signature of the seafloor can be acquired by the SAUVIM in survey mode. In intervention mode, the Mission Sensor Package will provide AUV water depth (pressure) and the water temperature and compositional parameters at a selected seafloor target, including pumped samples from submarine seeps or vents.

Current Status (Tasks Completed)

The task has been completed in the previous phases. Refer to previous reports for its descriptions.

Hydrodynamic Drag Coefficient Analysis (HDCA)

Project Leader(s): - none -
Personnel: - none -
Past Project Leader(s): Dr. Song K. Choi, Dr. Farzad Masheyekhi, Dr. Junku Yuh, Dr. Curtis S. Ikehara & Mr. Oliver T. Easterday
Past Personnel: Mr. Brian S.C. Lau

Objectives

- Determination of the hydrodynamic coefficient via numerical solution of full Navier-Stokes equations using commercial CFD code, PHOENICS.
- Provide design recommendations for the vehicle fairing from the hydrodynamic results.
- Perform experiments to verify and confirm the CFD results.

Current Status (Tasks Completed)

The task has been completed in the previous phases. Refer to previous reports for its descriptions.

Mechanical Analysis and Fabrication (MAF)

Project Leader(s): Dr. Song K. Choi
Personnel: - none -
Past Project Leader(s): Dr. Mehrdad Ghasemi Nejhad & Mr. Oliver T. Easterday
Past Personnel: Dr. Ali Yousefpour, Mr. Eric Sung, Mr. Bruce Flegal, Mr. Robert Ng, Mr. Mark Uyema, Mr. Saeid Pourjalali, Ms. Melanie Yamauchi & Mr. Reid Takaiya

Objectives

Mechanical Analysis and Fabrication (MAF) group is responsible for designing, analyzing, manufacturing, and testing of pressure vessels and flooded fairing as well as analyzing the metallic frame of the vehicle.

Current Status (Tasks Completed)

The task has been completed in the previous phases. Refer to previous reports for its descriptions.

Mechanical-Electrical Design (MED)

Project Leader(s):	Dr. Song K. Choi, Dr. Giacomo Marani
Personnel:	Mr. Kaikala Rosa, Mr. Aaron Hanai, Mr. Christopher A. McLeod, Mr. Edgar Gongora, Mr. Scott Weatherwax, Mr. Patrick Simmons, Mr. Greg Tamasahi.
Past Project Leader(s):	Dr. Curtis S. Ikehara, Dr. Junku Yuh, Mr. Gus Coutsourakis, Mr. Oliver T. Easterday & Mr. Michael E. West
Past Personnel:	Mr. Ismael Medrano, Mr. Dante Julian, Mr. Stacy Hanson, Mr. Lawrence Wong, Mr. Mark Fujita, Mr. Dicson Aggabao, Mr. Szu-Min Chang, Ms. Colleen Kaku, Mr. Mike Hall, Mr. Tai Blechta, Mr. Scott Sufak, Mr. Keith Sunderlin, Mr. Clyde Campos, Mr. Richard Antunes, Mr. John Lee, Mr. Scott Sufak, Mr. Daniel Shnidman, Mr. Weston Fujii, Mr. John Lemmond & Ms. Elizabeth Shim

Objectives

Integrate mechanical and electrical components of the SAUVIM vehicle and provide vehicle infrastructure in terms of structure and power to support research aspects of SAUVIM AUV. One of the most relevant progress in the Phase III-B was the Thruster power system upgrade.

Current Status

The task has been completed in the previous phases. Refer to previous reports for its descriptions.

References

[Aerotech92] Aerotech, "Operation & Technical Manual", 1992.

[Akiba00] Akiba T and Kakui Yoshimi, "Design and Testing of an Underwater Microscope and Image Processing System for the Study of Zooplankton Distribution", IEEE Journal of Oceanic Engineering, vol. 25, no 1, page 97-104 (2000)

[Aloimonos97] Aloimonos, Y., Visual Navigation: From Biological Systems to Unmanned Ground Vehicles, Mahwah, NJ, Lawrence Erlbaum Associates, 1997.

[ANSYS94] ANSYS User's Manual (Version 5.2), Ansys, Inc., Houston, TX, USA, 1994.

[ANSYS99] ANSYS User's Manual, ANSYS, Inc., Canonsburg, PA, 1999.

[Antonelli98] Antonelli, G., and S. Chiaverini, "Task-Priority Redundancy Resolution for Underwater Vehicle-Manipulator Systems", in Proceedings of the 1998 IEEE International Conference on Robotics & Automation, pp.756-761, Leuven, Belgium, 1998.

[Archibald93] Archibald C and Petriu E, "Robot Skills Development Using a Laser Ranger Finder", IEEE 0-7803-1229-5, page 448-452 (1993)

[Ashby80] Ashby, M. F., and D. R. H., Jones, "Engineering Materials 1: An Introduction to their Properties and Applications", New York: Pergamon Press, 1980.

[Askeland84] Askeland, D. R., "The Science and Engineering of Materials" California: Wadsworth, Inc., 1984

[Atari97] Atari A and Dodds G, "Practical Stereo Vision and Multi-Laser Scanning in Object Face Detection and Orientation Determination", IEEE 0-7803-4119-8, page 746-751 (1997)

[Atari99] Atari A and Dodds G, "Integration of a Stereo Multiple-laser Ranger System and Force Sensor in a Virtual Robotic Environment", IEEE/RSJ Int. Conference on Intelligent Robots and Systems, page 1519-1524 (1999)

[Auran95] Auran, P.G. and O. Silven, "Ideas for Underwater 3D Sonar Range Sensing and Environmental Modeling", Proceeding of CAMS'95, pp. 284-290, 1995.

[AUV96] Proceedings of the 1996 Symposium on Autonomous Underwater Vehicle Technology, Monterey, California, 1996.

[Avallone87] Avallone, E.A, and Baumeister, T., Mark's Standard Handbook for Mechanical Engineers - Ninth Edition, McGraw-Hill Book Co., 1987.

[Ayache91] Ayache, N., Artificial Vision for Mobile Robots : Stereo Vision and Multisensory Perception, MIT Press, 1991.

[Beckwith90] Beckwith, T.G., and Maranogoni, R.D., Mechanical Measurements, Addison-Wesley Publishing Company, 1990.

[Ben07] Benjamin, M. R., 2007. Software Architecture and Strategic Plans for Undersea Cooperative Cueing and Intervention. White paper, NAVSEA-DIVNPT, Code 2501

[Bollinger89] Bollinger, J.G. and N.A. Duffie, Computer Control of Machines and Processes, Reading, MA, Addison-Wesley Publishing Company, 1989.

[Borland92] Borland C++ User's Guide, Borland International, Inc., 1992.

[Brush75] Brush, D.O. and B.O. Almroth, Buckling of Bars, Plates, and Shells, New York: McGraw-Hill, Inc., 1975.

[Brutzman92] Brutzman, D.P., Y. Kanayama & M.J. Zyda, "Integrated Simulation for Rapid Development of Autonomous Underwater Vehicles," Proceedings of the IEEE Oceanic Engineering Society Autonomous Underwater Vehicle 92 Conference, Jun. 1992.

[Bushnell85] Bushnell, D., "Computerized Buckling Analysis of Shells", Dordrecht: Martinus Nijhoff Publishers, 1985

[Caimi95] Caimi, F, "Technical Challenges and Recent Developments in Underwater Imaging", Micro-Optics/Micromechanics and Laser Scanning and Shapining, M. Edward Motamedi, Leo Beiser, Editors, Proceedings of SPIE Vol. 2383, 408-418 (1995)

[Caimi99] Caimi F and Kocak D and Colquitt C, "Design and performances characterization of Simultaneous Reflectance and Surface Mapping laser Scanner for Application in Underwater inspection", in Optical Scanning: Design and Application, Leo Beiser, Stephen F. Sagan, Gerald F. Marshall, Editors, SPIE Vol. 3787, 228-239 (1999).

[Callister91] Callister, W.D., Materials Science and Engineering, John Wiley and Sons, Inc., 1991.

[Casalino00] Casalino, G., D.Angeletti, G.Cannata, G. Marani: On the Function and Algorithmic Control Architecture of the AMADEUS Dual Arm Robotic Workcell, SURT 2000, Wailea, Hawaii, June 2000.

[Chan95] Chan, T.F. and R.V. Dubey, "A Weighted Least-Norm Solution Based Scheme for Avoiding Joint Limits for Redundant Joint Manipulators", IEEE Transaction on Robotics and Automation, vol.11, no.2, pp.286-292, 1995.

[Chappell99] Chappell, S.C., R.J. Komerska, L. Peng & Y. Lu, "Cooperative AUV Development Concept (CADCON) - An Environment for High-Level Multiple AUV Simulation," Proceedings of the 11th International Symposium on Unmanned Untethered Submersible Technology, Aug. 1999.

[Chiaverini93] Chiaverini, S. and L. Sciavicco, "The Parallel Approach to Force/Position Control of Robotic Manipulators," IEEE Transaction on Robotics and Automation, vol. 9, pp. 361-373, 1993.

[Chiaverini97] Chiaverini, S., "Singularity-Robust Task-Priority Redundancy Resolution for Real-Time Kinematic Control of Robot Manipulators," IEEE Transaction on Robotic and Automation, vol. 13, 398-410, 1997.

[Choi95a] Choi, S.K., J. Yuh, and G.Y. Takashige, "Design of an Omni-Directional Intelligent Navigator, Underwater Robotic Vehicles: Design and Control, TSI Press, pp. 277-297, 1995.

[Choi95b] Choi, S.K. and J. Yuh, "Development of an Omni-Directional Intelligent Navigator", IEEE Robotics and Automation Magazine, 1995.

[Choi95c] Choi, S.K., G.Y. Takashige & J. Yuh, "Development of an Omni-Directional Intelligent Navigator," IEEE Robotics and Automation Magazine on Mobile Robots, Mar. 1995.

[Choi96] Choi, S.K., and J. Yuh, "Experimental Study on a Learning Control System with Bound Estimation for Underwater Robots", International Journal of Autonomous Robots, 3 (2 & 3), pp. 187-194, 1996.

[Clayton82] Clayton, B.R. and Bishop, R.E.D., Mechanics of Marine Vehicles, E. & F.N. Spon Ltd., 1982.

[Comstock67] Comstock, J.P., Principles of Naval Architecture, Society of Naval Architects and Marine Engineers, 1967.

[Coz74] Cox, A.W., Sonar and Underwater Sound, Lexington Books, 1974.

[Craig86] Craig, J.J, Introduction to Robotics: Mechanics and Control, Reading, MA, Addison-Wesley, 1986.

[Crawford98] Crawford A and Hay A, "A Simple System for Laser-Illuminated Video Imaging of Sediment Suspension and Bed Topography", IEEE Journal of Oceanic Engineering, vol. 23, no 1, page 12-19 (1998)

[Cristi96] Cristi, R., M. Caccia, G. Veruggio and A.J. Healey, "A Sonar Based Approach to AUV Localization", Proceeding of CAMS'95, pp. 291-298, 1996.

[Cunha95] Cunha, J.P., R.R. Costa, and L. Hsu, "Design of a High Performance Variable Structure Position Control of ROV's," IEEE Journal of Oceanic Engineering, vol. 20, no. 1, pp.42-55, 1995.

[D'egoulange94] D'egoulange, E. and P. Dauchez, P., "External Force Control of an Industrial PUMA 560 Robot," journal of Robotic Systems, vol. 11, pp. 523-540, 1994.

[de Wit96] Candus de Wit, C., B. Siciliano, and G. Bastin (Editors), Theory of Robot Control, Springer-Verlag, Berlin, Germany, 1996.

[DeBitetto94] DeBitetto, P.A., "Fuzzy Logic for Depth Control of Unmanned Undersea Vehicles," Proceedings of the Symposium of Autonomous Underwater Vehicle Technology, pp. 233-241, 1994.

[Deepsea90] UnderPressure Software Manual, DeepSea Power and Light Co., 1990.

[Doebelin75] Doebelin, E.O., Measurement Systems: Application and Design, New York, McGraw-Hill Book Company, 1975.

[Dote90] Dote, Y., Servo Motor and Motion Control Using Digital Signal Processors, Englewood Cliffs, NJ, Prentice-Hall Publishing, 1990.

[Dougherty90] Dougherty, F. and G. Woolweaver, "At-Sea Testing of an Unmanned Underwater Vehicle Flight Control System," Proceedings of the Symposium of Autonomous Underwater Vehicle Technology, pp. 65-73, 1990.

[Dunningan96] Dunningan, M.W., D.M. Lane, A.C. Clegg, and I. Edwards, "Hybrid Position/Force Control of a Hydraulic Underwater Manipulator," IEEE Proceedings Control Theory and Application, vol. 143, no. 2, pp. 145-151, March 1996.

[Englemann95] Engelmann, W.H., Handbook of Electric Motors, M. Dekker, 1995.

[Evans96] Evans, A.J., Basic Digital Electronics - Digital System Circuits and Their Functions, Master Publishing Inc., 1996.

[Evans03] Evans, J., Redmond, P., Plakas, C., Hamilton, K., Lane, D., 2003. Autonomous docking for Intervention-AUVs using sonar and video-based real-time 3D pose estimation. OCEANS 2003. Proceedings, 22-26 Sept., Vol. 4, pp.2201-2210.

[Ferrerri97] Ferrerri, G., G. magnani, and P. Rocco, "Toward the Implementation of Hybrid Position/Force Control in Industrial Robots," IEEE Transaction on Robotics and Automation, vol. 16, pp. 838-845, 1997.

[Fox88] Fox J, "Structured light imaging in turbid water", Underwater Imaging, Douglas J. Holloway, Editor, SPIE vol. 980, page 66-71 (1988).

[Fox92] Fox, R.W. and McDonald, A.T., Introduction to Fluid Mechanics, John Wiley amd Sons, Inc., 1992.

[Gere90] Gere, J.M. and Timoshenko, S.P., Mechanics of Materials, PWS-Kent Publishing Co., 1990.

[Geyer77] Geyer, R. A., Submersibles and Their Use in Oceanography and Ocean Engineering, Amsterdam, Elsevier Scientific Pub. Co., 1977.

[Gill85] Gill, R., Electrical Engineering Handbook, Siemens Co., 1985.

[Goheen98] Goheen, K.R., and R.E. Jeffery, "Multivariable Self-Tuning Autopilots for Autonomous and Remotely Operated underwater Vehicles", IEEE Journal of Oceanic Engineering, vol. 15, pp.144-151, 1990.

[Goldberg89] Goldberg, D. E., Genetic Algorithms in Search, Optimization, and Machine Learning, Addison-Wesley, 1989.

[Harding97] Harding, K.G. and D.J. Svetkoff (chairs/editors), Three-dimensional Imaging and Laser-based Systems for Metrology and Inspection III (Pittsburgh, PA), International Society for Optical Engineering, Bellingham, Washington, 1997.

[Healy92] Healy, A.J. and D.B. Macro, "Slow Speed Flight Control of Autonomous Underwater Vehicles: Experimental Results with NPS AUV II", Proc. of ISOPE, pp. 523-532, 1992.

[Healy93] Healy, A.J. and D. Lienard, "Multi-variable Sliding Mode Control for Autonomous Diving and Steering of Unmanned Underwater Vehicles," IEEE Journal of Oceanic Engineering, vol. 18, no. 3, pp. 327-339, 1993.

[Hibbeler92] Hibbeler, R.C., Engineering Mechanics, Macmillian Publishing Co., 1992.

[Hill70] Hill, P.G. and Peterson, C.R., Mechanics and Thermodynamics of Propulsion, Addison Wesley Publishing Co., 1970.

[Hoerner65] Hoerner, S.F., Fluid Dynamic Drag: Practical Information on Aerodynamic and Hydrodynamic Resistance, American Institute of Aeronautics and Astronautics, 1965.

[Hollerback87] Hollerbach, J.M. and K.C. Suh, "Redundancy Resolution of Manipulator Through Torque Optimization", IEEE Journal of Robotics and Automation, vol RA-3, No.4, pp. 308-316, 1987.

[Holman89] Holman, J.P. and W.J. Gajda, Jr., Experimental Methods for Engineers, New York, McGraw-Hill Book Company, 1989.

[Howard86] Howard, G.. Automobile Aerodynamics: Theory and Practice for Road and Track, Motorbooks International, 1986.

[Hsu94] Hsu, L., R. Costa, and F. Lizarralde, "Underwater Vehicle Dynamic Positioning Based on a Passive Arm Measurement System", International Advanced Robotics Programme, pp. 23-32, 1994.

[Hudson99] Hudson, J. and Luecke J., Basic Commincations Electronics, Master Publsihing, Inc., 1999.

[Hueber95] Huebner, K. H., E. A., Thornton, and T. G., Byrom, "The Finite Element Method for Engineers," New York: John Wiley & Sons, Inc., 1995.

[Hughes94] Hughes, A., Electric Motors and Drives - Fundamentals, Types and Applications, BH Newnes, 1994.

[Hull83] Hull, D., "Axial Crusing of Fibre Reinforced Composite Tubes," Structural Crashworthiness, Eds. N. Jones and T. Wierzbicki, Butterworth., pp. 118-135, 1983.

[Hyer88] Hyer, M. W., "Respond of Thick Laminate Cylinders to External Hydrostatic Pressure," Journal of Reinforced Plastics and Composites, vol. 7, pp. 321-340, 1988.

[ICI Thermoplastic Composite92] ICI Thermoplastic Composite, "Thermoplastic Composite Handbook," 1992.

[Incropera85] Incropera, F.P. and DeWitt, D.P., Introduction to Heat Transfer, John Wiley and Sons, 1985.

[Ishii94] Ishii, K., T. Fujii, and T. Ura, “A Quick Adaptation Method in Neural Network Based Control System for AUVs,” Proceedings of the Symposium of Autonomous Underwater Vehicle Technology, pp.269-274, 1994.

[Jones92] Jones, D. A., “Principle and Prevention of Corrosion,” New York: Macmillian Publishing Company, 1992.

[Kajita97] Kajita, H. and K. Kosuge, “Force Control of Robot Floating on the Water Utilizing Vehicle Restoring Force,” Proceedings of the 1997 IEEE/RSJ International Conference on Intelligent Robot and Systems, vol.1, pp. 162-167, 1997.

[Kato93] Kato, N., Y. Ito, K. Asakawa, and Y. Shirasaki, "Guidance and Control of Autonomous Underwater Vehicle AQUA Explorer 1000 for Inspection of Underwater Cables", Proc. 8th Int. Symposium on Unmanned, Untethered Submersible Technology, Sept. 1993.

[Kawaguchi96] Kawaguchi, K., C. Ikehara, S.K. Choi, M. Fujita, and J. Yuh, “Design of an Autonomous Underwater Robot: ODIN II,” World Automation Congress, Montpellier, France, May 1996.

[Kernighan78] Kernighan, B.W. and D.M. Ritchie, The C Programming Language, Englewood Cliffs, NJ, Prentice-Hall, Inc., 1978.

[Klafter83] Klafter, R. D., Robotic Engineering: an Integrated Approach, Prentice Hall, 1989.

[Klein83] Klein, C.A. and C.S. Huang, "Review of Pseudoinverse Control for Use with Kinematically Redundant Manipulators," IEEE Trans. on System, Man, and Cybernetics, vol. SMC-13, pp. 245-250, 1983.

[Kocak99] Kocak D and Lobo N and Widder E, “Computer Vision Techniques for Quantifying, Tracking, and Identifying Bioluminescent Plankton”, IEEE Journal of Oceanic Engineering, vol. 24, no 1, page 81-95 (1999)

[Kochin65] Kochin, N.E., I.A. Kibel, and N.V. Rose, Theoretical Hydrodynamics, John Wiley & Sons, 1965.

[Krar67] Krar, S.F., and Amand, J.E., Machine Shop Training, McGraw-Hill Co., 1967.

[Kuroda95] Kuroda, Y., K. Aramaki, T. Fujii & T. Ura, "A Hybrid Environment for the Development of Underwater Mechatronic Systems," Proceedings of the 1995 IEEE 21st International Conference on Industrial Electronics, Control, and Instrumentation, Nov. 1995.

[Lamb45] Lamb, H., Hydrodynamics, Dover, 1945.

[Lander87] Lander, C.W., Power Electronics, McGraw-Hill, 1987.

[Lane99] Lane D and Davies: and Robinson G and O’Brien D and Sneddon J and Seaton E and Elfstrom Anders, “The AMADEUS Dextrous Subsea Hand: Design, Modeling, and Sensor Processing”, IEEE Journal of Oceanic Engineering, vol. 24, no 1, page 96-111 (1999)

[Lawry90] Lawry, M.H., I-DEAS Student Guide, Structural Dynamics Research Corp., 1990.

[Leon95] Leon, G. F. and J. C. Hall, “Case Study-Design and Testing of the Brunswick Graphite Epoxy Composite Ring-Stiffened Thermo set Cylinder,” Journal of Thermoplastic Composite Materials, vol. 8., 1995.

[Lewis84] Lewis, D.J., J.M. Lipscomb, and P.G. Thompson, "The simulation of Remotely Operated Underwater Vehicle", Proceeding of ROV 1984, pp. 245-252, 1984.

[Lewis89] Lewis, E.V., Principles of Naval Architecture, Jersey City, NJ, Society of Naval Architects and Marine Engineers, 1988-1989.

[Liegeois77] Liegeois, A., "Automatic Supervisory Control of the Configuration and Behavior of Multibody Mechanisms," IEEE Trans. on Systems, Man, and Cybernetics, vol. SMC-7, No.2, pp.868-871, 1977.

[Lines97] Lines, D., Building Power Supplies - Useful Designs for Hobbyists and Technicians, Jerry Leucke Master Publishing Inc., 1997.

[LS-DYNA99] LS-DYNA User's Manual, Livermore Software Technology Corporation, Livermore, CA, 1999.

[Luanglat97] Luanglat, C. S., and M. N Ghasemi Nejhad., "A Crash Simulation Study of Composite Materials and Structures for Electric and Hybrid Vehicles," 14th International Electric Vehicle Symposium, Proceedings, pp. 14-17, 1997.

[Lundgren99} Lundgren, J., and P. Gudmundson, " Moisture Absorption in Glass-Fiber/Epoxy Laminates with Transverse Matrix Cracks," Composites Science and Technology, vol. 59, no. 13, pp. 1983-1991, 1999.

[Mahesh91] Mahesh, H., J. Yuh, and R. Lakshmi, "A Coordinated Control of an Underwater Vehicle and Robot Manipulator", Journal of Robotic Systems, Vol.8, No.3, pp.339-370, 1991.

[Mallick93] Mallick, P. K., "Fiber-reinforced Composites: Materials, Manufacturing, and Design," New York: Marcel Dekker, Inc., 1993.

[Marani05] Marani, G., Medrano, I., Choi, S.K., Yuh, J., 2005. A client-server oriented programming language for autonomous underwater manipulation. The Proceedings of The Fifteenth (2005) International Offshore and Polar Engineering Conference, Seoul, Korea, June 19-24.

[Marco96] Marco, D.B., Autonomous Control of Underwater Vehicles and Local Area Maneuvering, Ph.D. Dissertation, Naval Postgraduate School, 1996.

[Martini84] Martini, L.J., Practical Seal Design, Marcel Dekker, Inc., 1984.

[Mattsson89] Mattsson, E., Basic Corrosion Technology for Scientists and Engineers, Ellis Horwood Ltd., 1989.

[McLain96] McLain, T.W., S.M. Rock, and M.J. Lee, "Experiments in the Coordinated Control of an Underwater Arm/Vehicle System", Autonomous Robots 3, pp. 213-232, Kluwer Academic Publisher, Netherlands, 1996.

[McMillan95] McMillan, D.O., and R. McGhee, "Efficient Dynamic Simulation of an Underwater Vehicle with a Robotic Manipulator," IEEE Trans. on Systems, Man, and Cybernetics, Vol.25, No.8, pp.1194-1206, August, 1995.

[Microsoft88a] Microsoft QuickBASIC - Learning to Use Microsoft QuickBASIC, Microsoft Corp., 1988.

[Microsoft88b] Microsoft QuickC - Learning to Use Microsoft QuickC, Microsoft Corp., 1988.

[Milne-Thomson68] Milne-Thomson, L., Theoretical Hydrodynamics, Macmillan, 1968.

[Mims98] Mims, F., Getting Started in Electronics, Radioshack Co., 1998.

[Mullen99] Mullen L and Contarino M and Laux A and Concannon: and Davis J and Strand M and Coles B, "Moduladet Laser Line Scanner for Enhanced Underwater Imaging", Airborne and In-water Underwater Imaging, Gary D. Gilbert, Editor, SPIE vol. 3761, page 2-9 (1999).

[Nakamura85] Nakamura, Y., and H. Hanafusa, "Task Priority based Redundancy Control of Robot Manipulators", Robotics Research: The Second International Symposium, Cambridge, MA: MIT Press, pp.155-162, 1985.

[Needler85] Needler, M.A. and Baker Don E., Digital and Analog Controls, Reston Pub. Co., 1985.

[Negahdaripour90] Negahdaripour S and Yu C. H. and Shokrollahi A, "Recovering Shape and Motion From Undersea Images", IEEE Journal of Oceanic Engineering, vol 15, no 3, page 189-198 (1990)

[Nejhad91a] Ghasemi Nejhad, M. N., R. D. Cope, and S. I. Guceri, "Thermal Analysis of In-Situ Thermoplastic-Matrix Composite Filament Winding," ASME Journal of Heat Transfer, vol. 113, no. 2, pp. 304-313, 1991.

[Nejhad91b] Ghasemi Nejhad, M. N., R. D. Cope, and S. I. Guceri, "Thermal Analysis of In-Situ Thermoplastic-Matrix Composite Tape Laying," Journal of Thermoplastic Composite Materials, vol. 4, no. 1, pp. 29-45, 1991.

[Nejhad92a] Ghasemi Nejhad, M. N., J. W., Jr., Gillespie, and R. D., Cope, "Prediction of Process-Induced Stresses for In-situ Thermoplastic Filament Winding of Cylinder," Proceedings of Third International Conference CADCOMP, Computer Aided Design in Composite Material Technology, pp. 225-253, 1992.

[Nejhad92b] Ghasemi Nejhad, M. N., J. W., Jr., Gillespie, and R. D., Cope, "Processing Stresses for In-situ Thermoplastic Filament Winding Using the Divergence Method," Proceedings of ASME Winter Annual Meeting 1992, Heat Transfer Effects in Materials Processing, Guceri, S. I., and Alam M. K., Eds., HTD-vol. 233, pp. 33-43, 1992.

[Nejhad93] Ghasemi Nejhad, M. N., "Issues Related to Processability during the Manufacture of Thermoplastic Composite Using On-line Consolidation Technique," Journal of Thermoplastic Composite Materials, vol. 6, pp. 130-145, 1993.

[Nejhad94] Ghasemi Nejhad, M. N., J. W., Jr., Gillespie, and R. D., Cope, "Effects of Processing Parameter on Material Responses during In-situ Filament Winding of Thermoplastic Composites," International Journal of Materials and Product Technology, Concurrent Engineering of Advanced Materials-Integration of Mechanics and Manufacturing, vol. 9, no. 1/2/3, pp. 183-214, 1994.

[Nejhad97] Ghasemi Nejhad, M. N., "Thermal Analysis for Thermoplastic Composite Tow/Tape Preheating and Pultrusion," Journal of Thermoplastic Composite Materials, vol. 10, no. 4, pp. 504-523, 1997.

[Ng00a] Ng, R., A., Yousefpour, M., Uyema, and M. N., Ghasemi Nejhad, "Design, Analysis, Manufacture, and Test of Shallow Water Pressure Vessels using E-Glass/Epoxy Woven Composite Material for a Semi-Autonomous Underwater Vehicle, submitted to the Journal of Composite Materials, in review, 2000.

[Ng00b] Ng, R., M., Uyema, A., Yousefpour, M. N., Ghasemi Nejhad, B., Flegal, and E., Sung, "Manufacturing and Testing of Shallow Water Composite Pressure Vessels for Semi-Autonomous Underwater Vehicle," World Automation Congress 2000 (WAC 2000), in press, June 2000.

[Nie98] Nie, J., J. Yuh, E. Kardash, and T.I. Fossen, "On-Board Sensor-Based Adaptive Control of Small UUVs in Very Shallow Water", IFAC Symposium on Control Applications for Marine Systems, 1998.

[Nie99] Nie, J., J. Yuh, E. Kardash, and T.I. Fossen, "On-Board Sensor-Based Adaptive Control of Small UUVs in Very Shallow Water", International Journal of Adaptive Control and Signal Processing, vol. 13, 1999.

[Nygards98] Nygards J and Wernersson A, "On Covariances for fusing Laser Ranger and Vison with Sensors Onboard a Moving Robot", IEEE/RSJ Int. Conference on Intelligent Robots and Systems, page 1053-1059 (1998)

[Ogata87] Ogata, K., Discrete-time Control Systems, Prentice-Hall, New Jersey, 1987.

[Omura95] Omura, G., Mastering AutoCAD 13 for Windows95, Windows3.1, and WindowsNT, Sybex, 1995.

[Parrish73] Parrish, A., Mechanical Engineer's Reference Book, Butterworths, 1973.

[Pascol93] Pascoal, A., M. J. Rendas, V. Barroso, C. Silvestre, P. Oliveria and I. Lourtie, "Simulation Study of an Integrated Guidance System for an Autonomous Underwater Vehicle", Acoustic Signal Processing for Ocean Exploration (Eds. J.M.F. Moura and I.M.G. Lourtie), pp. 587-592, 1993.

[Pickering97] Pickering, E. R., "Welding Aluminum," Journal of Advance Materials & Processing, pp. 29-30, 1997.

[Porter67] Porter, H.W., Machine Shop Operations and Setups, American Technical Society, 1967.

[Pugh70] Pugh, H., Mechanical Behavior of Materials Under Pressure, Elsevier Publishing Co., 1970.

[Raibert81] Raibert, M.H. and J.J. Craig, "Hybrid Position/Force Control of Manipulators," Transactions of the ASME Journal of Dynamic Systems, Measurement, and Control, vol. 12, pp. 126-133, 1981.

[Reynolds89] Product and Data Catalog - Reynolds Aluminum Supply Company, Reynolds Aluminum Supply Company, 1989.

[ROV91] Intervention/ROV'91 Conference & Exposition, Hollywood, Florida, Sponsored by the ROV Committee and the South Florida Section of the Marine Technology Society, 1991.

[Sagatun92] Sagatun, S.I. Modeling and Control of Underwater Vehicles: Lagrangian Approach, Dr. Ing Thesis, Norwegian Institute of Technology, 1992.

[Sayers99] Sayers, C., Remote Control Robotics, Springer, 1999.

[Scheck84] Scheck, L.A.. and Edmondson, G.C., Practical Welding, Glencoe Publishing Co., 1984.

[Schlichting79] Schlichting, H., Boundry-Layer Theory, McGraw-Hill, Inc., 1979.

[Schwartz84] Schwartz, M.M., Composite Materials Handbook, McGraw-Hill, 1984.

[Schweitzer83] Schweitzer, P.A., Corrosion and Corrosion Protection Handbook, M. Dekker, 1983.

[Serway89] Serway, R.A. and Faughn, J.S., College Physics, Saunders College Publishing, 1989.

[Shahinpour87] Shahinpoor, M., A Robot Engineering Textbook, New York, Harper & Row Publishers, 1987.

[Shames89] Shames, I.H, Introduction to Solid Mechanics, Prentice-Hall, Inc., 1989.

[Shen81] Shen, C., and G. S. Springer, "Environmental Effects in the Elastic Moduli of Composite Materials," Environmental Effects on Composite Material, Ed. G. S. Springer, Westport: Technomic Publishing Company, Inc., 1981.

[Shigley89] Shigley, J.E. and Mischke, C.R., Mechanical Engineering Design, McGraw-Hill, Inc., 1989.

[Smith90] Smith, C.S., Design of Marine Structures In Composite Materials, Elsevier Applied Science, 1990.

[Smith96] Smith, J. and K. Sugihara, “GA toolkit on the Web”, Proc. of the First Online Workshop on Soft Computing (WSC1), pp.93-98, 1996.

[Sonmez97] Sonmez, F.O. and H.T. Hahn, "Analysis of the On-line Consolidation Process in the Thermoplastic Composite Tape Placement", Journal of Thermoplastic Composite Materials, v. 10, pp. 543-572, 1997.

[Sprong89] Sprong, M.W. and M. Vidyasagar, Robot Dynamics and Control, New York, John Wiley & Sons, 1989.

[SubTech85] Submersible Technology: Proceedings of an International Conference (Subtech '85), Aberdeen, UK, pp. 29-31, 1985.

[Sugihara97] Sugihara, K. and Yuh, J., “GA-based motion planning for underwater robotic vehicle,” Proc. 10th Int’l Symp. on Unmanned Untethered Submersible Technology (UUST-10), Durham, NH, 1997, pp.406-415.

[Sugihara98a] Sugihara, K., “GA-based on-line path planning for SAUVIM,” Proc. 11th Int’l Conf. on Industrial and Engineering Applications of Artificial Intelligence and Expert Systems (IEA-98-AIE), Castellon, Spain, 1998, pp.329-338.

[Sugihara98b] Sugihara, K. and J. Smith, Genetic Algorithms for Adaptive Planning of Path and Trajectory of a Mobile Robot in 2D Terrain, IEICE Trans. on Information and Systems, to appear 1998 .

[Sugihara98c] Sugihara, K. and J. Yuh, “GA-based Motion Planning for Underwater Robotic Vehicles”, Proc. 10th Int’l Symp. On Unmanned Untethered Submersible Technology (UUST-10), pp.406-415, 1998.

[Sugihara99] Sugihara, K. and Smith, J., “Genetic algorithms for adaptive planning of path and trajectory of a mobile robot in 2D terrain,” IEICE Trans. Information and Systems, Vol. E82-D, No. 1, pp.309-317, January 1999.

[Svensoon99] Svensson S. and Lexander J. and Ericson B, “OBSERVATION AND INSPECTION IN SWEDISH WATERS”, Underwater Imaging, Douglas J. Holloway, Editor, SPIE vol. 980, page 75-81 (1988).

[Swartz91] Swartz: and Cummings J, “Laser range-gated underwater imaging including polarization discrimination”, Underwater Imaging, Photography, and Visibility, Richard W. Spinard, SPIE vol. 1537, page 42-56 (1991).

[Tai99] Tsai, L.W., Robot Analysis: The Mechanics of Parallel and Serial Manipulators, John Wiley and Sons, 1999.

[Takashi91] Takashi, K., Electric Motors and their Controls: An Introduction, Oxford University Press, 1991.

[Tarn96] Tarn, T.J., G.A., Shoultsand, and S.P. Yang, "A Dynamic Model of an Underwater Vehicle with a Robotic Manipulator using Kane's Method", Autonomous Robots 3, pp. 269-283, Kluwer Academic Publisher, Netherlands, 1996.

[TI92] Linear Circuits Operational Amplifiers Data Book, Texas Instruments, 1992.

[Tsai99] Tsai, L.W., Robot Analysis - The Mechanics of Parallel and Serial Manipulators, John Wiley and Sons, Inc. 1999.

[Tupper96] Tupper, E.C., Introduction to Naval Architecture, Oxford, Butterworth-Heinemann Publishing, 1996.

[Ullman92] Ullman, D.G., The Mechanical Design Process, McGraw-Hill Inc., 1992.

[Unimate81] Unimate PUMA Robot: Volume 1 – Technical Manual 398H1, Unimation Inc., Condec Company, Danbury CT, 1981.

[Unimate84] Unimate PUMA Mark II Robot: 500 Series, Volume 1 – Equipment Manual, Unimation, Westinghouse Corporation, Danbury CT, 1984.

[Unimate86] Unimate Industrial Robot: Programming Manual, User's Guide to VAL II Version 2.0 (398AG1), Unimation, Westinghouse Corporation, Danbury CT, 1986.

[Unimate97] Unimate – Supplement to the User's Guide to VAL II: VAL II-IVM PC Supervisor Interface (397W1), Unimation, Westinghouse Corporation, Danbury CT, 1987.

[Valentine98] Valentine, R., Motor Control Electronics Handbook, McGraw-Hill, 1998.

[Vieville97] Vieville, T., A Few Steps Towards Active 3D Vision, Springer-Verlag, 1997.

[Vinson87] Vinson, J.R., and R.L. Sierakowski, The Behavior of Structures Composed of Composite Materials, Netherlands, Kluwer Academic Publishers, 1987.

[Wang95] Wang, H.H., Rock, S.M., Lees, M.J., 1995. Experiments in automatic retrieval of underwater objects with an AUV. OCEANS '95. MTS/IEEE. Challenges of Our Changing Global Environment. Conference Proceedings, vol.1, pp.366-373, October 9-12.

[Weast81] Weast, R.C. and Astle, M.J., CRC Handbook of Chemistry and Physics - 61st Edition, CRC Press, Inc. 1981.

[Wedermann89] Werdermann, C., K. Friedrich, M. Cirino, and R. B. Pipes, "Design and Fabrication an On-Line Consolidation Facility for Thermoplastic Composites," Journal of Thermoplastic Composite Materials, vol. 2, pp. 293-306, 1989.

[Wells91] Wells W, "Indirect illumination to reduce veiling luminance in seawater", Underwater Imaging, Photography, and Visibility, Richard W. Spinard, SPIE vol. 1537, page 2 (1991).

[Werdermann89] Werdermann, C., K. Friedrich, M. Cirino, and R.B. Pipes, "Design and Fabrication an On-line Consolidation Facility for Thermoplastic Composites", Journal of Thermoplastic Composite Materials, vol. 2, pp. 293-306, 1989.

[Whitney87] Whitney, D.E., "Historical Perspective and State of the Art in Robot Force Control," International Journal of Robotic Research, vol. 6, no.1, pp. 3-14, 1987.

[Wilson92] Wilson, P.A., International Conference on Manoeuvring and Control of Marine Craft, Proceedings of the Second International Conference, 1992.

[Wit98] Wit, C.C.D., E.O. Diaz, and M. Perrier, "Robust Nonlinear Control of an Underwater Vehicle/ Manipulator System with Composite Dynamics", Proc. IEEE Conf. on Robotics and Automation, pp.452-457, 1998.

[Yang98a] Yang, K.C., J. Yuh, and S.K. Choi, "Experimental Study of Fault-tolerant System Design for Underwater Robots", Proc. IEEE Conf. on Robotics and Automation, pp. 1051-1056, 1998a.

[Yang98b] Yang, K.C., J. Yuh, and S.K. Choi, "Experimental Study of Fault-tolerant System Design for Underwater Robots", Journal of System Sciences, 1998b.

[Yousefpour00a] Yousefpour, A., and M. N. Ghasemi Nejhad, "Effects of Geometric Optimization of Tapered End-caps on Thick Thermoplastic Composite Pressure Vessels for Deep Ocean Applications," Journal of Thermoplastic Composite Materials, submitted for publication, 2000.

[Yousefpour00b] Yousefpour, A., and M. N. Ghasemi Nejhad, "Experimental and Computational Study of APC-2/AS4 Thermoplastic Composite C-Rings," Journal of Thermoplastic Composite Materials, in press, 2000b.

[Yousefpour00c] Yousefpour, A., R., Ng, M., Uyema, M. N., and Ghasemi Nejhad, "Design and Finite Element Analysis of Shallow Water Composite Pressure Vessels for Semi-Autonomous Underwater Vehicle," World Automation Congress 2000 (WAC 2000), in press, June 2000c.

[Yousefpour99] Yousefpour, A., and M. N. Ghasemi Nejhad, "Testing and Finite Element Modeling of APC-2/AS4 Thermoplastic Composite C-rings," 31st International SAMPE Technical Conference: Advanced Materials & Processes Preparing for the New Millennium, vol. 31, pp. 643-654, Chicago, IL, 1999.

[Yuh92] Yuh, J., V. Adivi & S.K. Choi, "Development of a 3D Graphic Test Platform for Underwater Robotic Vehicles," Proceedings of the 2nd International Offshore and Polar Engineering Conference, Jun. 1992.

[Yuh94a] Yuh, J., "Learning Control for Underwater Robotic Vehicles", IEEE Control System Magazine, vol.15, No.2, pp.39-46, 1994.

[Yuh94b] Yuh, J., Underwater Robotic Vehicles: Design and Control, Workshop on Future Research Directions in Underwater Robotics, TSI Press, p. 361, 1994.

[Yuh95] Yuh, J., Underwater Robotic Vehicles: Design and Control, TSI Press, 1995.

[Yuh96] Yuh, J., "An Adaptive and Learning Control System for Underwater Robots", 13th World Congress International Federation of Automatic Control, A, pp. 145-150, 1996.

[Yuh98a] Yuh, J., S.K. Choi, C. Ikehara, G.H. Kim, G. McMurtry, M. Ghasemi Nejhad, N. Sarkar, and K. Sugihara, "Design of a Semi-Autonomous Underwater Vehicle for Intervention Missions (SAUVIM)," Proceeding of the Underwater Technology '98, 1998.

[Yuh98b] Yuh, J., J. Nie, and W.C. Lee, "Adaptive Control of Robot Manipulators Using Bound Estimation", IEEE International Conference on Intelligent Robots and Systems, 1998.

[Yuh99] Yuh, J. and J. Nie, "Experimental Study on Adaptive Control of Underwater Robots," Proceedings of the IEEE International Conference of Robotics and Automation, Detroit, MI, May 1999.

[Zege91] Zege E and Ivanov A and Katsev I, "Image Transfer Through a Scattering Medium" Springer-Verlag, Berlin, page 277-305 (1991)

[Zuech88] Zuech, N., Applying Machine Vision, John Wiley and Sons, Inc., 1988.

Publications

Choi, S.K., Easterday, O., Ikehara, C., Coutsourakis, C., & Yuh, J., "Development of SAUVIM," The Proceedings of the *Symposium of Underwater Robotic Technologies* (*SURT*), Maui, HI, Jun. 2000.

Choi, S.K., Sugihara, K., Menor, S., Nip, A., & Yang, Z., "A Predictive Virtual Environment Monitor for SAUVIM," The Proceedings of the *Symposium of Underwater Robotic Technologies* (*SURT*), Maui, HI, Jun. 2000.

Choi, S.K., Menor, S. & Yuh, J., "Distributed Virtual Environment Collaborative Simulator for Underwater Robots" The Proceedings of the *International Conference on Intelligent Robots and Systems* (*IROS* '00), Takamatsu, JAPAN, Nov. 2000

Choi, S.K. & Easterday, O.T., "The Development of an Underwater Vehicle Monitoring System and Its Sensor Systems," The Proceedings of the *International Symposium on Experimental Robotics* (*ISER*), Honolulu, HI, Dec. 2000.

Choi, S.K. and Yuh, J., "A Virtual Collaborative World Simulator for Underwater Robots using Multi-Dimensional, Synthetic Environment," The Proceedings of the *IEEE International Conference on Robotics and Automation* (*ICRA* '01), Seoul, KOREA, May 2001. dfsdfs

Hanai, A., McLeod, C., Rosa, K., Marani, G., Choi, S. K., A Practical Approach to the Development of Thruster Models for Underwater Robots, The 18th International Offshore (Ocean) and Polar Engineering Conference & Exhibition, Vancouver, British Columbia, Canada, July 6-11, 2008

Kim, J., G. Marani, W. K. Chung, J. Yuh, "Kinematic Singularity Avoidance for Autonomous Manipulation in Underwater," The Fifth *ISOPE Pacific/Asia Offshore Mechanics Symposium*, Daejeon, Korea, November 17-20, 2002.

Kim, J., G. Marani, W. K. Chung, J. Yuh: *Task Reconstruction Method for Real-Time Singularity Avoidance for Robotic Manipulators*, Advanced Robotics, Vol. 20, No. 4, pp. 391-498, 2006

Kim, T.W., Choi, S.K., Lee, J.W., West, M.E., & Yuh, J., "A Real-Time Distributed Control Architecture for AUVs," The Proceedings of the *Symposium of Underwater Robotic Technologies* (*SURT*), Maui, HI, Jun. 2000.

Kim, T.W. and J. Yuh, "A Novel Neuro-Fuzzy Controller for Autonomous Underwater Vehicles, " Proc. of *IEEE International Conference on Robotics and Automation (ICRA 2001)*, pp.2350-2355, May 2001 (Seoul, Korea).

Kim, T.W. and J. Yuh, "Task Description Language for Underwater Robots," Proc. of *IEEE International Conference on Intelligent Robots and Systems* (*IROS* '03), Vol.1, pp.565-570, Oct. 2003 (Las Vegas, NV, USA).

Kim, T.W. and J. Yuh, "Application of On-line Neuro-Fuzzy Controller to AUVs," *Journal of Information Sciences*, Vol.145, No.1, pp.169-182, Aug. 2002

Kim, T.W., J. Yuh, and S. Choi, "Real-Time Control Architecture," *IFAC Workshop on Guidance and Control of Underwater Vehicle* (*GCUV* '03), South Wales, UK, April 2003

Kim, T.W. and J. Yuh, "Development of real-time control architecture for a semi-autonomous underwater vehicle for intervention missions," *Journal of Control Engineering Practice*, Vol.12/12, pp.1521-1530, Sep. 2004

Marani, G., Bozzo, T., & Choi, S.K., "A Fast Prototyping Approach for Designing the Maris Manipulator Control," The Proceedings of the *Symposium of Underwater Robotic Technologies* (*SURT*), Maui, HI, Jun. 2000.

Marani, G., “Development of a Dexterous Redundant Manipulator for Automation of Machine Tools,” 2002 International Intensive Short Course on Machine Tools and new Machining Technology, Changwon, Korea, Nov. 7-9, 2002.

Marani, G., J. Kim, J. Yuh, W. K. Chung, “Algorithmic singularities avoidance in task-priority based controller for redundant manipulators,” *IEEE/RSJ International Conference on Intelligent Robots and Systems* (*IROS* ’03), Las Vegas, October 27-31, 2003

Marani, G., J. Yuh, S. K. Choi, “Autonomous manipulation for an intervention AUV,” in *Guidance and Control of Unmanned Marine Vehicles* (G. Roberts and B. Sutton, Eds.), IEE's Control Engineering Series, 2004.

Marani, G, I. Medrano, S. K. Choi, J. Yuh: *A client-server oriented programming language for autonomous underwater manipulation*, The Proceedings of The Fifteenth (2005) International Offshore and Polar Engineering Conference, Seoul, Korea, June 19-24, 2005.

Marani, G., Choi, S.K., Yuh, J.: *Experimental Study on Autonomous Manipulation for Underwater Intervention Vehicles*, ISOPE 2007: Proceedings of the 17th International Offshore and Polar engineering Conference, Libon, Portugal, July 1-6 2007.

Ng, R., Uyema, M., Yousefpour, A., Ghasemi Nejhad, M.N., Flegal, B., and Sung, E., "Manufacturing and Testing of Shallow Water Composite Pressure Vessels for Semi-Autonomous Underwater Vehicle," *World Automation Congress* (WAC 2000), June 2000.

Sugihara, K. and Yuh, J., “GA-based motion planning for underwater robotic vehicle,” Proc. 10th *Int’l Symp. on Unmanned Untethered Submersible Technology* (*UUST*-10), Durham, NH, 1997, pp.406-415.

Sugihara, K., “GA-based on-line path planning for SAUVIM,” Proc. 11th Int’l Conf. on *Industrial and Engineering Applications of Artificial Intelligence and Expert Systems* (IEA-98-AIE), Castellon, Spain, 1998, pp.329-338.

Sugihara, K. and Smith, J., “Genetic algorithms for adaptive planning of path and trajectory of a mobile robot in 2D terrain,” *IEICE Trans. Information and Systems*, Vol. E82-D, No. 1, pp.309-317, January 1999.

Sugihara, K. and Yuh, J., “Adaptive, intelligent motion planning system for AUV’s,” The Proceedings of the *Symposium of Underwater Robotic Technologies* (*SURT*), Maui, HI, Jun. 2000.

Yousefpour, A., and Ghasemi Nejhad, M. N., "Testing and Finite Element Modeling of APC-2/AS4 Thermoplastic Composite C-rings," 31st *International SAMPE* (*Society for the Advancement of Material and Process Engineering*) *Technical Conference*, vol. 31, pp. 643-654, Chicago, IL, October 1999.

Yousefpour, A., Ng, R., Uyema, M., and Ghasemi Nejhad, M.N., "Design and Finite Element Analysis of Shallow Water Composite Pressure Vessels for Semi-Autonomous Underwater Vehicle," *World Automation Congress* 2000 (*WAC* 2000), June 2000.

Yousefpour, A. and M. N., Ghasemi Nejhad "Experimental and Computational Study of APC-2/AS4 Thermoplastic Composite C-Rings," *Journal of Thermoplastic Composite Materials*, 2000.

Yousefpour, A., and M. N. Ghasemi Nejhad, “Effects of Geometric Optimization of Tapered End-caps on Thick Thermoplastic Composite Pressure Vessels for Deep Ocean Applications,” *Journal of Thermoplastic Composite Materials*, 2000.

Yu, Son-Cheol; Tae-Won Kim; Marani, G.; Choi, S.K., "Real-Time 3D Sonar Image Recognition for Underwater Vehicles," *Underwater Technology and Workshop on*

Scientific Use of Submarine Cables and Related Technologies, 2007. Symposium on , vol., no., pp.142-146, 17-20 April 2007

Yu, Son-Cheol, Tae Won Kim, G. Marani, S. K. Choi, "*High resolution acoustic camera model based object recognition for AUVs*", International Symposium on Unmanned Untethered Submersible Technology, Aug. 2007 (Durham, NH)

Yuh, J, Choi, S.K., Ikehara, C., Kim, G.H., McMurtry, G., Nejhad, M., Sarkar, N., & Sugihara, K., "Design of a Semi-Autonomous Underwater Vehicle for Intervention Missions (SAUVIM)," The Proceedings of the *IEEE Oceanic Engineering Society Underwater Technology* '98, Tokyo, JAPAN, Apr. 1998.

Yuh, J. and Choi, S.K., "Semi-Autonomous Underwater Vehicle for Intervention Missions (SAUVIM)," *Sea Technology*, Oct. 1999.

Yuh, J., S. Zhao, "Application of Adaptive Disturbance Observer Control to an Underwater Manipulator," *IEEE International Conference on Robotics and Automation* (*ICRA* '01), Seoul, May 21-26, 2001

Zhao, S., J. Yuh, "Experimental Study on Advanced Underwater Robot Control," *IEEE Transactions on Robotics*, Vol. 21, No. 4, August 2005.

Zhao, S., J. Yuh, S. Choi, "Adaptive DOB Control for AUVs: Experiment," *IEEE International Conference on Robotics and Automation* (*ICRA* '04), New Orleans, LA, USA, April 26-30 2004

Zhao, S., J. Yuh, "Adaptive DOB Control of Underwater Robots," *IEEE International Conference on Intelligent Robots and Systems* (*IROS* '03), Las Vegas, Nevada, October 27-31, 2003

Zhao, S., J. Yuh, "Adaptive DOB Control of Underwater Robotic Vehicles," *IEEE/MTS Oceans Conference*, 2001, Honolulu, Hawaii, Nov. 5-8, 2001