Marine Operations with the SWORDFISH Autonomous Surface Vehicle

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***Abstract*—This paper describes the design and development of the Swordfish Autonomous Surface Vehicle (ASV) system. The work focuses the sensors, actuators, communications and C4I of an unmanned vehicle for marine operations.**

SWORDFISH is an autonomous surface vehicle used as the central communications link between air, undersea, and terrestrial robotic vehicles of a network centric operation. It is used as a test bed platform for deployment and testing of advanced control and operational concepts for multi-vehicles systems.

This new unmanned marine vehicle was done in the context of the PISCIS project. The PISCIS project concerns the development, test and evaluation of new vehicles and new concepts of operation for networked vehicle systems in oceanographic data collection. The PISCIS system includes two autonomous underwater vehicles, the *Swordfish* ASV, an acoustic navigation system, acoustic and radio communications and a distributed command and control system.

I. Introduction

Autonomous vehicles have been used for several marine operations. The use of unmanned vehicles reduces the risks for humans in dangerous scenarios and provides the capability of several hours of on going work with high level human control and interface.

There are several research directions on autonomous marine vehicles. The major efforts concern Autonomous Underwater Vehicles (AUV) and Remote Operated Vehicles (ROV). The need of a low cost mobile link between underwater and surface world led to the developed of surface communication platforms [1] [2] [3].

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Fig. 1. The SWORDFISH Autonomous Surface Vehicle.

The idea of monitoring several miles of ocean water with AUVs and UAVs in constant communication led the development of the *Swordfish* ASV (See Figure 1) [4] [5] [6]. *Swordfish* acts as a testbed platform for relay communications between the surface and sub sea scenarios; it is also apt to work as a mobile robotic platform with oceanographic sensors and actuators for environmental monitoring and surveillance.

The research and development of *Swordfish* gain the experience and improvements from the ASV *ROAZ* (See Figure 2) [7].

Fig. 2. Roaz ASV and Isurus AUV joint mission at NATO Swordfish Naval exercise with the Portuguese Navy of War in May 2006.

Recent work at AUV vehicles and underwater communications research allowed vehicles to perform track following and rendezvous missions [8]. This innovation allows the ASV to carry out AUVs track following, and to aid the vehicles underwater navigation thru continuous global and acoustic position updates.

The *Swordfish* design builds on expertise, tools and technologies developed at the Underwater Systems and Technology Laboratory (USTL) from Porto University and at the Autonomous Systems Laboratory (ASL) from Porto Polytechnic Institute. Researchers at both the USTL and the ASL have been designing and building ocean and air going autonomous and remotely operated vehicles with the goal of deploying networked vehicle systems for oceanographic and environmental applications.

This work was done under the PISCIS project. The PISCIS project concerns the design and development of new vehicles and technologies for oceanic hydrographic operations. The PISCIS systems includes two AUVs, the *Swordfish* ASV, an acoustic navigation network, acoustic and radio communications and a distributed Command and Control Interface [9].

This paper is organized as follows: Section II describes the design and development of the *Swordfish* autonomous surface vehicle; witch is followed in section III by the C4I framework tools. At section IV it is presented early sea tests and results. Finally section V provides some conclusions and future work.

II. Vehicle Design

Swordfish has three major purposes: First it was designed to develop autonomous marine data capture; second to support the AUVs missions as a mobile gateway buoy for air-to-underwater communications; finally as a docking station for the AUV ISURUS (See Figure 2) [10].

A. Platform Design

The objective of developing a vehicle for marine operations led to the need of a robust, hydrodynamic and very stable platform. After surveying hull shapes and disposal of numerous marine boats solutions, the choice was of a catamaran shape (See Figure 3). This choice provides low hydrodynamic drag and high stability; it also has a large central structure with the capability for cargo and payload.

Swordfish ASV consists of two catamaran hulls in HDPE (High Density Polyethylene) connected by two transversal aluminum tubes with an attached central stainless steel platform. The vehicle weights 190 Kilograms (with 80 Kg from batteries) and has 4.5 meters long for 2.2 meters width and 0.5 meters height. Mission deployment ease and operational requirements led to the implementation of a simple and light central platform.

TABLE I
SWORDFISH Specifications

Symbol	Quantity
Length	4,5 meters
Width	2,2 meters
Height	0,5 meters
Weight (w/ batteries)	190 Kilograms
Weight (w/out batteries)	110 Kilograms
Speed – Cruise/Maximum	1,2 m/s / 2 m/s
Endurance	6 hours @ 1 m/s
Standard sensors	GPS, IMU, Compass
Payload	Sidescan sonar, Altimeter
Propulsion	Thrusters Seaeye SI-MCT01
Communications	Wifi, Freewave, Acoustic modem
Software	Dune, Neptus and Seaware
Operative System	Linux kernel 2.6
Power	48V / 2600W

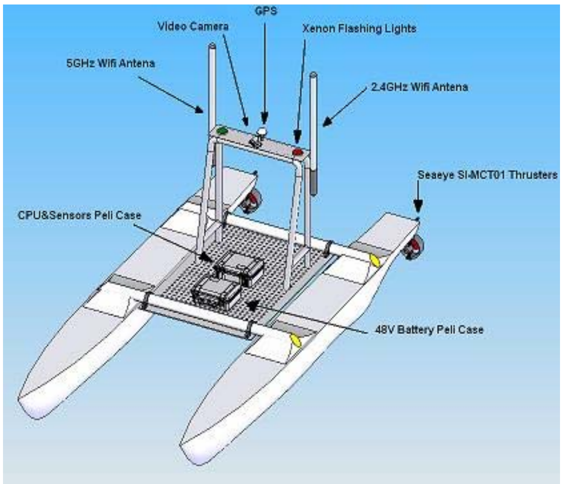

Fig. 3. The SWORDFISH multiple systems

At the central platform, the ASV has two robust *Peli* cases: one with power system and the other with the CPU and sensors system. The power case has four 12V AMG batteries to provide 48V power capability; on the other hand the CPU & Sensors case lodges the computational system and several sensors systems. The *Peli* cases assure the protection for hazardous and very rough conditions that the ASV vehicle will be exposed at sea operational missions. Connections between all subsystems are guaranteed by IP69 plugs that providing a weather and waterproof connection.

For propulsion, *Swordfish* uses two Seaeye SI-MCT01 thrusters with 13 kilograms of bollard pull force each. The vehicle also has three communications links: Acoustic, RF freewave and WIFI 802.11a/b/g. For surveillance and monitoring the catamaran has a wireless video system with a day/night video camera and a 2.4GHz wireless link. Additionally has a distributed on-board weather station based on a Mote wireless sensor network (WSN).

A raised area supporting a GPS module, Wifi antennas, a Freewave antenna, a video camera, a wireless video transmission system, the weather station and the signalization xenon lights and sound is implemented on the top of a tubular structure in the central platform.

B. Computational system

The *Swordfish* ASV was designed with the objective of low power consumption and long mission endurance. Therefore at an electronic level all systems have relative low power consumption.

The CPU is based on PC-104 architecture with a DC/DC power supply, a relay and a serial port expansion cards. The DC/DC power converter provides a 30W for the PC-104 stack system; the relay board is used to activate/deactivate the signalization xenon lights and horn; the serial expansion port board is used to connect multiple serial RS232/RS485 communication devices: GPS, IMU, compass, freewave radios, acoustic modem, altimeter sonar, sidescan sonar, mote wireless sensor network, and the propulsion thrusters device drive.

Besides the CPU stack a second DC/DC converter stack is provided to power all other sensors and electric sub systems. The IMU and Compass devices are also inside the CPU case due to its position on the central of the vehicle axis and the easiness of power and serial connection.

C. Sensors

For navigation and positioning purposes the vehicle is equipped with a GPS unit, an IMU sensor and a magnetic compass.

GPS – A Garmin 17HVS GPS module providing serial NMEA 0183 updates at 1Hz rate is used. GPS accuracy is < 15 meters, increased typically to 3-5m a DGPS system.

IMU – A Microstrain 3DM-GX1 IMU module combining three angular rate gyros with three orthogonal accelerometers and three orthogonal magnetometers outputs orientation, angular rate and acceleration at a rate of more than 50Hz. T

Compass – A PNI TCM2-50 electronic compass, magnetometer and tilt sensor module is also used although proved in field tests to be much less accurate than the IMU system (currently is only used in the navigation system to provide redundancy backup).

D. Propulsion

Leveraging previous technology and know-how at the USTL and ASL laboratories, the propulsion system uses a similar approach to the one used in the ROV KOS [11], namely the 48V thrusters and respective power drive and control subsystems.

Two stern mounted SI-MCT01 thrusters (See Figure 4) provide differential thrust to act as the vehicle steering. A mechanical structure allowing easy deployment and removal for hull transportation supports the thrusters. The connection for the thrusters to hull interior is made by wet and dry underwater connectors. RS485 and 48V are the communications protocol and power used for this type of motor. The motor has a power drive with overcurrent and over heating shutdown, and a current sense and rpm count allowing the creation of a current and velocity feedback control. Thruster control is performed at a 30Hz rate (velocity loop). The SI-MCT01 are brushless DC motors with nominal 350 Watts (W) of power and deliver a symmetric (forward/backward) capability of 13.2 Kilograms of force (Kgf) (See Figure 5).

Fig. 4. Seaeye SI-MCT01 Thruster
www.seaeye.com

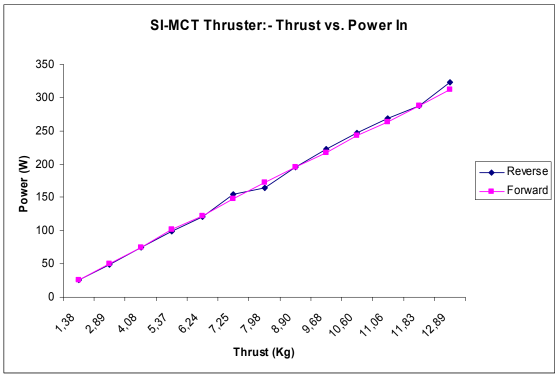

Fig. 5. Seaeye SI-MCT01 Thruster: Thrust vs. Power in.

E. Power supply

The power supply system is constituted by a bank of four 12V/56Ah navy sealed AGM (Absorbed Glass Mat) batteries housed in a waterproof Peli 1620 case. The battery case connects to the CPU case by a cable that distributes the 48V/2600W. Inside the CPU case there is a 48V distribution/protection board handling power sharing for the motors, CPU DC/DC and the additional DC/DCs for all the other the electronic devices. Vehicle power supply is protected against surge and overcurrent system failures.

F. Payload

Autonomous surface vehicles are used in marine missions for oceanographic data collection. *Swordfish* is equipped with several payload sensors for this purpose.

For bathymetric operations and underwater archeology research the *Swordfish* is equipped with an altimeter, sidescan sonar and an underwater video camera.

Altimeter – the Imagenex 863 digital sonar is used for pinging the bottom of the river/sea and builds an altitude map of the subsea floor. This device works at a 300 kHz rate. Additionally allows development of work in collision avoidance technologies.

Sidescan sonar – the Marine Sonics 900 kHz sidescan sonar is used for bathymetric 3D mapping of the sea floor and also for testing mine hunting techniques. An additional CPU PC-104 stack runs dedicated processing software and stores the various data files from the sonar sampling collecting. This stack has an ethernet link to the base station thus allowing the human operator to have an on-line feedback of the sidescan sonar image.

Underwater Video Camera – a Kongsberg Simrad underwater video camera is used for near surface structures inspection and serves as a useful tool in the AUV docking to the ASV.

Weather Station – the weather station onboard the *Swordfish* ASV was built on the expertise of Mote wireless sensor networks (WSN) providing temperature, humidity, luminosity and wind strength and direction measurements.

G. Communications

The major goal of the *Swordfish* ASV is to serve as a communication relay and support for AUVs and UAVs missions, therefore communication systems play a relevant role in the system design process.

For large package data transmission and a medium range of 1-2 kilometers it was chosen a WIFI 802.11a/b/g network. 802.11a/b/g allows relatively high bandwidth communication link supporting most of the data exchanges. Since 802.11 is a well developed technology it was easy to deploy and to interact with other vehicles. The ASV uses an Ovislink Access Point and a 12dBi omnidirectional antenna; at the base station is used an Ovislink Access Point and several directional (18 dBi, 23 dBi) antennas.

With the objective of long range and low data rate transmission it was implemented a Freewave (2.4 GHz) radio transmission network. The Maxstream freewave radios allowed up to 10 kilometers line of sight communications.

For underwater communications with underwater vehicles the ASV was equipped with a Benthos low frequency (9-14 KHz) acoustic modem. The acoustic modem allows a 2km range of underwater communication. Besides the underwater data exchanges, the modem also provides the range to other modems in the network allowing an acoustic positioning estimation.

H. Video and surveillance wireless system

One of the differences between the *Swordfish* and others autonomous surface vehicles is the capability of live video wireless transmission. It is equipped with an analog Raymarine CAM100 (PAL) video camera and a 2.4GHz wireless video link. The Raymarine camera allows day and night video capture and the wireless link has a 2 km range.

The video link and the day & night camera provide the feature of remote operated video surveillance. The catamaran could operate as a remotely operated vehicle for surveillance missions and allowing the interception and inspection of suspicious vehicles and marine activities.

This system gives the human operator at the base station the capability of seeing what and where the catamaran is going and doing. The tools for human interface with the ASV Command Control Communications and Intelligence will be described next.

III. Command Control Communications Computers and Intelligence

A. Vehicle software

The USTL researchers designed and implemented the modular software package called DUNE, which runs in the PISCIS project vehicles. DUNE is an onboard software platform for autonomous vehicles. The DUNE platform is the next generation of onboard software for the USTL AUVs, UAVs, ROVs and ASVs. Runs in several platforms and hardware's, and it have the principal purpose of being portable, deterministic, robust, expansible, and easy of programming. It allows joining Sensors, Actuators, Control, Simulation and transports in an easy and modular way.

In the specific case of *Swordfish* it has a Linux kernel running on the computational system. It is a real-time preemptive scheduling kernel that handles the onboard DUNE (DUNE: uniform navigational environment) software.

B. Seaware Communications Middleware

Seaware is a publish/subscribe middleware [12] that addresses the problem of communications with real-time, heterogeneous, and dynamic environments (See Figure 6), specifically developed at USTL for multi-vehicle networked systems.

Within *Swordfish*, Seaware is integrated as a library with the on-board DUNE vehicle software and enables the communication infrastructure for Wifi, Freewave radio and acoustic modems. This allows communication between *Swordfish*, other autonomous vehicles and Neptus C4I consoles (see section III.C) in the operation scenario. Planned developments within Seaware for the *Swordfish* ASV and other vehicles include also support for GSM/GPRS based communications.

The publish/subscribe messaging mechanism uses an abstraction of the knowledge of the network status, allowing an application to dynamically register communication nodes, with different communication link settings and specifying the *topics* a node wishes to publish and subscribe, without the need to know in advance who its peers are or where they are located. These capabilities enable a dynamic and heterogeneous networked environment connecting multiple vehicles and control consoles, particularly in the case of *Swordfish*, where more than one type of communications link is used and multiple and dynamic interactions can occur.

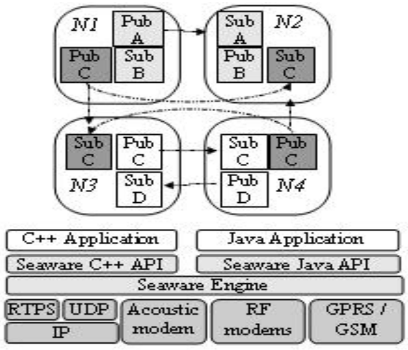

Fig. 6. Seaware publish/subscribe framework and architecture

Publish-subscribe is a powerful tool for the abstraction of the nodes and data exchange at a complex communication network. It as been used in distributed systems like industrial and robotic scenarios because the publish/subscribe handles all the issues related with the communication flow and run time re-configuration.

C. Neptus

Neptus is a distributed command, control, communications and intelligence framework for operations with networked vehicles, systems, and human operators [13]. The interactions with human operators are classified according to the phases of a mission life cycle: world representation; planning; simulation; execution and post-mission analysis [14]. The Neptus infrastructure commands and controls the interactions of multi heterogeneous autonomous vehicles teams.

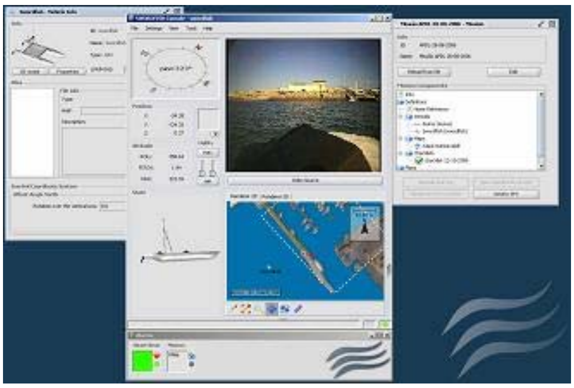

Fig. 7. The Neptus swordfish human interface console

Neptus supports concurrent operations where vehicles, operators, and operator consoles come and go. Operators are able to plan and supervise missions concurrently. Additional consoles can be built and installed on the fly to display mission related data over a network. Neptus supports the concurrent control of multiple vehicles. There is one Seaware node per vehicle and per operator console. Each vehicle node is characterized by a topic domain identifying the vehicle to allow for a set of messages to be exchanged with the corresponding operator console.

IV. Sea Trial Tests

The Swordfish was designed and developed with the purpose of open sea marine operations. To test this specification it was taken to the Leixões Harbour to perform innumerous robustness, maneuverability, communications, and endurance tests.

A. Porto Harbour marine operation

In the last year fall, the Leixões harbour authority (APDL) supported the preliminary sea tests to the *Swordfish* ASV. This allowed conducting a major setup of tests to the ASV platform and interactions with other vehicles and ground stations.

TABLE I
SWORDFISH PRELIMINARY SEA TRIAL TESTS

Performed Tests
1. deployment and recovery setup
2. platform structural robustness
3. propulsion differential thrust
4. dynamic maneuverability
5. platform stability
6. payload cargo capability
7. long endurance operational mission
8. GPS and Inertial navigation systems
9. payload sensor operations
10. long range communications link
11. wireless video surveillance
12. ground station operability

Fig. 8. Preliminary marine operation at Leixões Harbour

First, we tested the vehicle structural robustness, buoyancy and stability. The mechanical structural simplicity, the catamaran shape and the high fluctuation hulls, allowed the vehicle to present high stability and hydrodynamic performances. Low drag under 26 Kgf of available thrust propelled the ASV to an average speed of 3 knots.

Second, the wireless link and the operator capability to drive the vehicle remotely operated thru the human interface console were tested. The wireless video had a 2 kilometers range and permitted the base station to remotely inspect some sea structures inside the harbour.

Third, all the Swordfish communications were tested and permitted to cover a network communications with other systems in the entire harbour perimeter. Figure 9 shows the signal strength, and communications response time to pings, with the increase of communication distance from the ASV to base station. The wireless communications maintained a 2,4Mbps data link transmission over a 1.2 kilometers range.

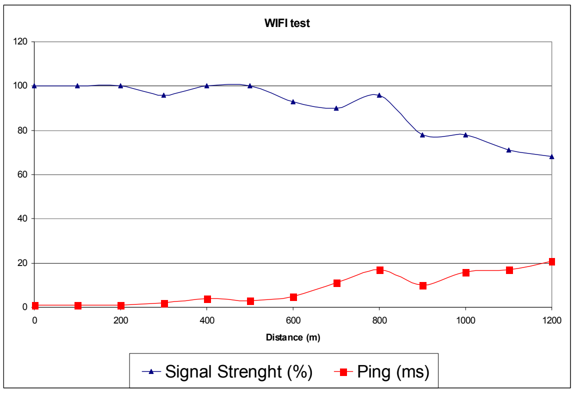

Fig. 9. Wifi communication tests

In terms of navigation: a set of tests allowed to refine the navigation system and to validate the GPS/INS subsystems. The *Swordfish* estimated state position proven to have an error minor then 4 meters and the instant heading error is minor then 3 degrees.

The Neptus ground station C4I proven to be a powerful and human-friendly tool for operations with networked vehicles.

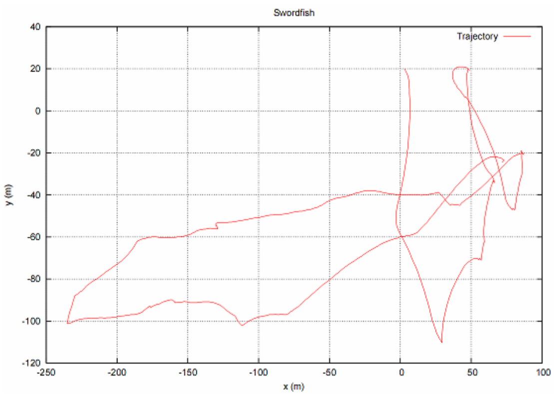

Fig. 10. Estimated state position

V. Conclusion

This work describes the design and operational marine capabilities of the *Swordfish* autonomous surface vehicle. The *Swordfish* ASV is at an early stage of design and oceanographic deployment. It proven in sea trials to be a reliable, robust, low cost and multi functional vehicle.

Swordfish can be integrated into a multi-vehicle network, or work as a stand-alone unit. It works as a support vehicle for AUVs missions at open sea; as a mobile sensorial platform for ocean data collection; or as a surveillance and interception unmanned surface vehicle.

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