# SWORDFISH: an Autonomous Surface Vehicle for Network Centric Operations

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***Abstract*—The design and development of the *Swordfish* Autonomous Surface Vehicle (ASV) system is discussed. *Swordfish* is an ocean capable 4.5m long catamaran designed for network centric operations (with ocean and air going vehicles and human operators). In the basic configuration, *Swordfish* is both a survey vehicle and a communications node with gateways for broadband, Wi-Fi and GSM transports and underwater acoustic modems. In another configuration, *Swordfish* mounts a docking station for the autonomous underwater vehicle *Isurus* from Porto University. *Swordfish* has an advanced control architecture for multi-vehicle operations with mixed initiative interactions (human operators are allowed to interact with the control loops).**

***Index Terms*—Autonomous Surface Vehicles, ocean robotics, marine science operations, unmanned survey vessels.**

## I. Introduction

The design and deployment of network centric vehicle control frameworks in a systematic manner and within an appropriate scientific framework requires a significant expansion of the basic tool sets from different areas, such as computation, control and communication. The major challenges come from the distributed nature of these systems and from the human factors. This is why we need to couple the development of scientific frameworks with lessons learned from experimental work with human operators.

Experimental work on collaborative control of Autonomous Underwater Vehicles (AUV), Unmanned Aerial Vehicles (UAV) and Autonomous Surface Vehicles (ASV) requires vehicles to interact and to exchange data at sea. This is not a trivial matter. Communication exchanges take place over interoperated underwater and wireless networks, with severe communication constraints. This is one of the reasons for the development of ASV communication platforms [1] [2].

This paper describes the design and development of the *Swordfish* ASV (Figure 1). *Swordfish* is a configurable ASV with several innovations. *Swordfish* has an advanced control architecture for network centric operations with several levels of interoperability. This is done in the framework of hybrid automata. In the basic configuration, *Swordfish* is a survey vehicle, with modular sensor payloads, and a mobile gateway for air-to-underwater communications. *Swordfish* can also mount a docking station (not depicted in the figure) for the autonomous underwater vehicle *Isurus* from Porto University (Figure 2).

Fig. 1. The SWORDFISH Autonomous Surface Vehicle.

The *Swordfish* platform is basically a catamaran with two Seaeye SI-MCT01 thrusters and a structure for a docking station. The platform design builds on the ASL know-how developed with the design of the ROAZ ASV [3] [4]. Power is provided by electric batteries. The computer system is based on the PC-104 technology. It has a GPS unit and an IMU for navigation; GSM, Wi-Fi and Freewave radios for wireless communications; and a Benthos acoustic modem for underwater communications. The standard sensors include a wireless video camera and a sensor network.


Fig. 2. The ISURUS Autonomous Underwater Vehicle.

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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. *Swordfish* was developed in the context of the PISCIS project. The PISCIS project concerns the design and development of new vehicles and technologies for oceanic operations. The PISCIS systems include two AUVs, the *Swordfish* ASV, an acoustic navigation network, acoustic and radio communications and a distributed Command and Control Interface [5] [6].

This paper is organized as follows: Section II describes the *Swordfish* ASV. Section III presents the *Swordfish* command and control framework. Section IV discusses the role of *Swordfish* in tests of concepts for network centric operations developed at both USTL and ASL. Section V briefly discusses the first sea trials. Finally section VI provides some conclusions and discusses future work.

## II. THE SWORDFISH SYSTEM

*Swordfish* is more than a vehicle, it is an ASV system. The design of the *Swordfish* system was done in the framework of Systems Engineering [13]. Figure 3 presents the System Breakdown Structure (SBS). Space limitations preclude discussion of the design matrix. As it is the case with the design of most autonomous vehicles size, weight and onboard energy were some the key design parameters.

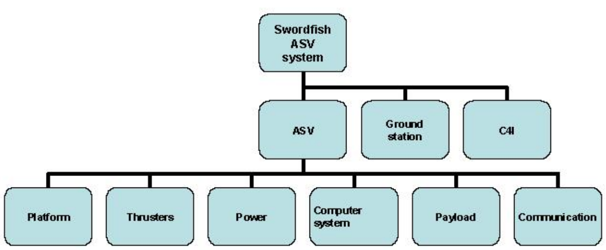


Fig. 3. Swordfish System Breakdown Structure.

### A. Platform

An ocean going platform needs to be stable, robust and hydrodynamically efficient. The design of a new hull was out of question because of the cost factor. After surveying hull shapes and boats solutions we choose a commercial ocean going catamaran as the *Swordfish*. It is a stable platform with low hydrodynamic drag. Moreover, it has a wide space between the hulls, which can be used for cargo and payload.

The *Swordfish* ASV consists of two catamaran hulls in HDPE (High Density Polyethylene) connected by two transversal aluminum tubes which also support a stainless steel central platform for payload. The vehicle specifications are presented in the following table.

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 | Wi-Fi, Freewave, Acoustic modem |
| Software | Dune, Neptus and Seaware |
| Operative System | Linux kernel 2.6 |
| Power | 48V / 2600W |

Mounted on the central platform there are two robust *Peli* cases: one with power system and the other with the CPU and sensor systems. The power case has four 12V AMG batteries providing a 48V power output; the CPU & Sensors case lodges the computational system and sensors. The *Peli* cases protect computers, sensors, batteries, and power converters from the harsh environmental conditions at sea.

The external connectors for power and signals are weather and waterproof IP69 plugs.

For optimized communications we mounted the communication antennas, the GPS module and the wireless video transmission system on the top of a tubular structure, as depicted in Figure 1. The red and green signal lights and a horn are also mounted on this structure.

### B. Computational system

The computational system is based on the PC-104 architecture. There is a CPU stack with a DC/DC power supply and expansion cards for relays and serial ports. The DC/DC power converter provides 30W for the PC-104 stack; the relay board is used to activate/deactivate the signalization xenon lights and the 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 device drivers for the thrusters. The IMU and the compass are also located inside the CPU case to simplify the wiring connections and also due to the central location of this case in the vehicle.

Besides the DC/DC power supply for the CPU stack, there is a second DC/DC converter stack to power all other sensors and electric sub systems.

### 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 provides serial NMEA 0183 updates at 1Hz rate. The GPS accuracy is < 15 meters (3-5m for a DGPS system).

IMU – A Microstrain 3DM-GX1 IMU module combining

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three angular rate gyros with three orthogonal accelerometers and three orthogonal magnetometers outputs orientation, angular rate and acceleration at a rates greater than 50Hz.

Compass – A PNI TCM2-50 electronic compass, magnetometer and tilt sensor module was also used in the first sea trials. Being less accurate than the IMU unit, it provides for added redundancy.

### *D. Propulsion*

Leveraging on the previous experience and know-how from the USTL and ASL laboratories, the propulsion system is basically the same as the one used in the ROV KOS [9]. It uses the same SI-MCT01 thrusters (see Figure 4) and their respective power drive and control subsystems. The SI-MCT01 are 48V/350 Watts brushless DC motors providing symmetric (forward/backward) 13.2 Kilograms of force (Kgf) (see Figure 5).

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

Two stern mounted SI-MCT01 thrusters provide differential thrust for vehicle steering. A mechanical structure allowing easy deployment and removal for transportation supports both thrusters. Wet and dry underwater connectors provide power (48V) and signal (RS485) to each thruster. The motor has a power drive with over current and over heating shutdown. It also comes with current sensors and rpm counters for current and velocity feedback control. Thruster control is performed at a 30Hz rate (velocity loop).

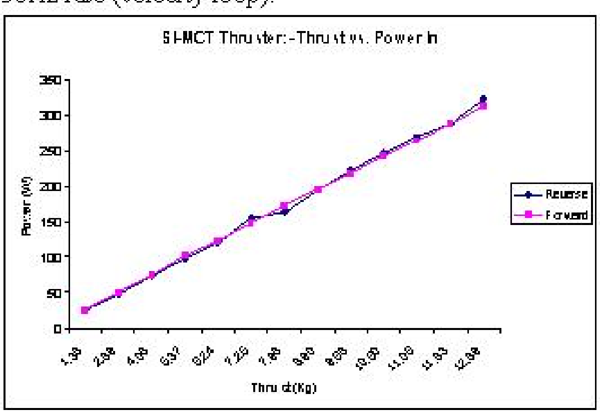


Fig. 5. Seaeye SI-MCT01 Thruster: Thrust vs. Power in

### *E. Power supply*

The power supply system is composed of a bank of four 12V/56Ah navy sealed AGM (Absorbed Glass Mat) batteries housed in a waterproof Peli 1620 case. The battery case is connected with the CPU case by a 48V/2600W cable. There is a 48V distribution/protection board inside the CPU case. This board handles power distribution for the motors and for the DC/DC converts. The vehicle power supply is protected against surge and overcurrent system failures.

### *F. Video and surveillance wireless system*

One of the differences between *Swordfish* and other ASVs is the capability of live video transmission. This is done with the help of 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 allow for remote operated video surveillance. *Swordfish* can operate as a remotely operated vehicle for surveillance missions and inspecting other vehicles and marine activities. This capability is provided at the ground station with the help of the Neptus command and control framework, which is described in the next section.

### *G. Sensor payload*

In addition to the video camera, *Swordfish* has been configured with other sensor packages. These include:

Altimeter – the Imagenex 863 300 kHz rate digital sonar can be used for bathymetry.

Side-scan sonar – the Marine Sonics 900 kHz sidescan sonar is used for bathymetric 3D mapping of the sea floor and also for mine hunting. An additional CPU PC-104 stack runs dedicated processing software and stores the sonar data files. 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 visual inspections. It is also used as one of the sensor systems for AUV docking.

Weather Station – the weather station builds on the expertise on wireless sensor networks (WSN). It is based on Mote nodes with temperature, humidity, luminosity and wind strength and direction sensors. Some of these nodes are mounted on the tubular structure depicted in Figure 1. The weather station is easily extended since it does not require wires.

### *H. Communications*

The major goal of the *Swordfish* ASV is to serve as a communication relay and support for AUVs and UAVs missions.

Wi-Fi 802.11a/b/g networking capabilities provide for a relatively high bandwidth communications link supporting most of the data exchanges over a medium range (1-2 Km). *Swordfish* has an Ovislink Access Point and a 12dBi omni-directional antenna; the base station has an Ovislink Access Point and several directional (18 dBi, 23 dBi) antennas. This is a mature technology thus making it quite simple to interface to other vehicles and computers.

GSM also provides for additional communication capabilities, which depend on the network availability.

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Maxstream Freewave radios (2.4 GHz) provide for extended range (up to 10Km) and low bandwidth communications.

The Benthos low frequency (9-14 KHz) acoustic modem is used for underwater communications with autonomous underwater vehicles. This is a low bandwidth link. The range is quite dependent on the operational conditions, and it can go up to 2Km. Besides the underwater data exchanges, the modem also provides the range to other modems.

*Swordfish* has a gateway for these transports. This is done with the help of Seaware, a real-time publish-subscribe tool described in section III.

### I. Ground station

For the purposed of modularity and operational flexibility the ground station is based on laptop PC which does not need any special hardware configuration. The communication devices are mounted externally and connected to the serial and USB ports on the laptop. The configuration of the laptop is done with the help of the C4I tools described in section III.

## III. Command and Control framework

### A. Network centric concepts

The concepts for network centric operations propose a paradigm of collaboration in which vehicles and operators interact over interoperated networks with the help of a command, control, communications and intelligence (C4I) framework. In a network centric system, information and commands are exchanged among multiple vehicles, and the roles, relative positions and dependencies of those vehicles change during operations. This means that: 1) the structure of the system changes with time; and 2) the properties of the system depend on its structure.

We observe that the components in the network are part of a system, within which new properties arise, some of them as planned, some of them emergent, and eventually leading to unpredictable behaviors. A significant part of this “system” is embodied not as physical devices, such as sensors, vehicles or communication devices, but as software applications which may be mobile, in the sense of migrating from one computer unit to another one, as part of the evolution of the system.

### B. Control architecture

*Swordfish* implements the vehicle control layer of the control and planning architecture developed at USTL for multiple vehicle systems [14]. The USTL control architecture consists of two main layers: multi-vehicle control and vehicle control. Each layer, in turn is further decomposed into other layers. The vehicle control architecture is standard for all the vehicles; it consists of the following layers: low-level control, maneuver control, vehicle supervision and plan supervision. The multi-vehicle control structure is mission dependent. We developed the control architecture in the framework of dynamic networks of hybrid automata.

The concept of maneuver – a prototype of an action/motion description for a vehicle – plays a central role in the USTL control architecture: it facilitates the task of mission specification, since it is easily understood by a mission specialist; it is easily mapped onto self-contained controllers, since it encodes the control logic; and is a key element in modular design, since it defines clear interfaces to other control elements.

We abstract *Swordfish* as a provider of maneuvers and services. This presents a uniform interface to high level external controllers which can be mobile in network centric operations. The *Swordfish* library of maneuvers is extensible. In the current version it includes the basic set of maneuvers required for testing: *tele-operation*; *goto(point)* and *follow(path)*. We are working on new maneuvers for multi-vehicle operations. These include: *follow(vehicle)*; *track(target)*; *dock(AUV)*; and *track(signal)*.

We use the Dune/Seaware/Neptus tool set, developed at USTL, to support the implementation of the USTL planning and control and framework for *Swordfish*.

### C. Vehicle software

DUNE is the USTL onboard software platform for autonomous vehicles. At the core of DUNE there is a platform abstraction layer, written in C++, enhancing portability among different computer architectures and operating systems. DUNE can be extended in the native compiled programming language C++ or using an interpreted programming language such as Python or Lua. The platform abstraction layer accommodates support for multiple operating systems: Linux, Sun Solaris 10, Apple Mac OS X, FreeBSD, NetBSD, Microsoft Windows 2000 or above and QNX 6.3.

DUNE attains loose coupling between components by partitioning related logical operations into isolated sets (or Tasks in DUNE's nomenclature). Tasks are executed in a concurrent or serialized fashion and may also be grouped into single concurrent or serialized execution entities, usually several concurrent and serialized execution tasks will coexist within DUNE. Communication and synchronization between tasks is achieved by the exchange of messages using a lock-free/wait-free message bus analogous in design to the Observer pattern. The internal message format is also used for logging purposes and communicating with external software modules over network links.

The DUNE implementation on *Swordfish* runs on a Linux kernel with real-time extensions. The addition of new devices to *Swordfish* is quite simple in the DUNE framework.

### D. Seaware Communications Middleware

Seaware is a publish/subscribe middleware toolkit [10] that addresses the problem of real-time communications in heterogeneous, and dynamic environments (Figure 6). Within Sworfish, Seaware provides the communication infrastructure for Wi-Fi, GSM, Freewave radio and acoustic modems.

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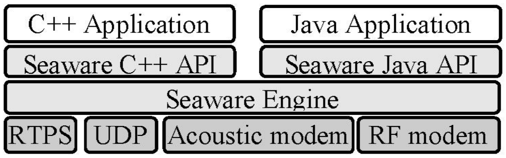


Fig. 6. Seaware publish/subscribe framework and architecture

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 it wishes to publishes 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.

### *E. Neptus C4I*

Neptus is a distributed C4I framework for operations with networked vehicles, systems, and human operators. It is designed in a way that abstracts the vehicles (and types) it controls. This allows a mission to be defined once and executed by various different vehicles [11]. Neptus implements the multi-vehicle control layer of the USTL control architecture with provisions for mixed initiative interactions (operators in the planning and control loops).

Operators play an important role in the entire mission life-cycle: world representation; planning; simulation; execution and post-mission analysis [12].

In the planning phase, operators use the Mission Planner module to define missions for future execution. A mission is composed by maps, vehicles and vehicle plans. Missions are recorded as XML files and then translated to the different vehicle's native mission formats for execution, using XSLT style sheets. In the execution phase, operators can monitor and control the vehicle's actions by using one of the available consoles. If needed, the operator can also adapt a console to its needs or build one from scratch.

Fig. 7. Neptus Swordfish human interface console

The environment is created by continually merging the data coming from the vehicles that exist in the network. The entire world state becomes available in real time and can be viewed in 2D or 3D and logged to disk.

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 monitoring and 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. NETWORK CENTRIC OPERATIONS

The *Swordfish* ASV family plays a key role in the field tests of the command and control framework for network centric applications developed at USTL.

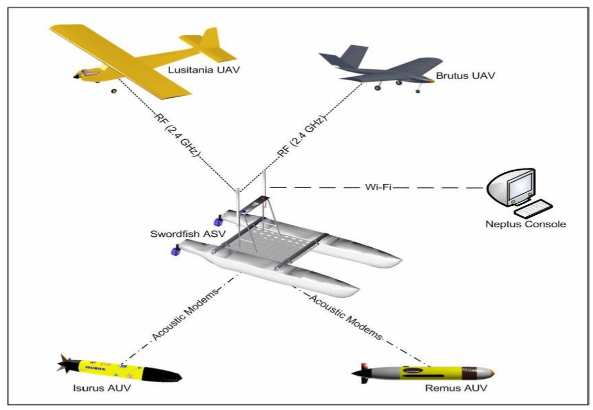


Fig. 8. Network Centric Operations

*Swordfish* is a communications node is equipped with mature data transfer technologies (Figure 8). The GSM communication module takes advantage of the high degree of coverage provided by GSM mobile phone networks. It has been used to remotely supervise mission execution and for publishing mission information on-line on web server. A serial Freewave RF Maxstream OEM 2.4GHz module allows the ASV to communicate over long distances. We will use this capability to communicate with aerial vehicles, moored buoys and ground stations. Wi-Fi 802.11a/b/g Ethernet is the main transport for short range communications with other vehicles and ground stations. 802.11a/b/g provides for a relatively high bandwidth communication link supporting most of the data exchanges. The ATM-885 Benthos acoustic modem provides a data link to submerged vehicles and underwater networks. Since both underwater and Wi-Fi are short range communications, for operations at sea, we will use *Swordfish* as a mobile gateway for maintaining connectivity, when feasible, or as a data mule using Disruptive Tolerant Network (DTN) technologies for this purpose. These two aspects of operation pose new control problems which can be formulated as invariance problems in relative reference frames and as control problems with intermittent observations and controls.

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## V. Sea Trials

The first sea trials of the *Swordfish* system took place last October in a restricted area inside the Leixões harbour with the logistical support of the harbour authority (APDL).

The ground station was mounted inside a van parked at one of the peers. This allowed us to conduct communication tests at different locations with a minimal setup.

Fig. 9. First sea trials at Leixões Harbour

First, we trimmed the ASV for buoyancy and for weight distribution. Second, we tested the ASV for structural robustness, buoyancy and stability. The ASV showed good stability and hydrodynamic performance. Low drag under 26 Kgf of available thrust propelled the ASV to an average speed of 3 knots. Third, we tested the wireless link and the remote control of the vehicle with the help of a Neptus console (which proved to be a powerful tool for network centric operations). This enabled the operator to remotely inspect a structure in the harbor with the help of the wireless video link (2 km range). Fourth, we tested the wireless networking capabilities of *Swordfish* in the entire perimeter of the harbor. This involved other consoles. Finally, we conducted tests to refine the navigation system and to validate the GPS/INS subsystems.

The excellent results from the first sea trials showed the maturity of the *Swordfish* concept.

## VI. Conclusion

The design and the operational capabilities of the *Swordfish* ASV system were described. The *Swordfish* ASV system will be used both for operational missions and for testing and evaluating advanced control and operational concepts for multi-vehicle systems.

There are several directions for future work in 2007. The docking station for the *Isurus* AUV will be tested and evaluated under several operational conditions. This will be done with the help of a visual tracking system developed by ASL [4]. Advanced path and trajectory following maneuvers will be implemented and tested. The gateway capabilities of *Swordfish* will be tested first in static configurations and latter in dynamic environments with submerged vehicles. Leader-follower strategies for *Swordfish* and for the *Isurus* AUV will be tested with feedback loops closed over the acoustic channel. These developments will allow the ASV to do AUV track following and to aid the AUV navigation with global and acoustic position updates [15] [8]. This will enable us to further develop recent work on rendezvous missions for AUVs (based on underwater communications [7]). We are also planning for air-surface-underwater communication relays with the help of the UAV Lusitânia [16].

## Acknowledgment

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