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ROAZ AUTONOMOUS SURFACE VEHICLE DESIGN AND IMPLEMENTATION

ABSTRACT

The design of an Autonomous Surface Vehicle for operation in river and estuarine scenarios is presented. Multiple operations with autonomous underwater vehicles and support to AUV missions are one of the main design goals in the ROAZ system. The mechanical design issues are discussed. Hardware, software and implementation status are described along with the control and navigation system architecture. Some preliminary test results concerning a custom developed thruster are presented along with hydrodynamic drag calculations by the use of computer fluid dynamic methods.

Keywords: autonomous surface vehicles, autonomous mobile robots, remote sensing robots, underwater robotics

1. INTRODUCTION

Autonomous mobile systems have relevant applications in numerous fields of human activity. The areas of environmental monitoring and surveillance are an example of this.

Aquatic environment scenarios provide interesting cases of application for robotic systems. These can be either autonomous underwater vehicles (AUVs) (Curtin, *et al.* 1993), (Wernli 2001), remotely operated vehicles (usually underwater in semi autonomous operation) (Gomes, *et al.* 2005), or autonomous surface vehicles (Caccia, *et al.* 2005) (Pascoal, *et al.* 2000), (Manley, *et al.* 2000). The latter can be used in different aquatic scenarios, from full ocean, to river or even confined water spaces operation.

Advantages over the use of robotic systems come from the large environment areas to be covered, repetitive tasks and the usual benefices of autonomy by reducing the human factor (both by reducing associated costs and by improving quality of results).

In research and development field there are various relevant projects on autonomous surface vehicles for several oceanographic scenarios. ASVs as the ACES, ARTEMIS (Manley, *et al.* 1997), AUTOCAT (Manley, *et al.* 2000) or the SCOUT (Leonard, *et al.* 2005) from the MIT are used specially for shallow water operations as test beds to execute operations of bathymetry and underwater archaeology research. Other important application is the use of small catamarans as SESAMO (Caccia, *et al.* 2005), MUMS, for data sampling of the water surface microlayer. The FAU University and Office of Naval Research developed an ASV for collect hydrographic data and to aid the underwater vehicle navigation (Leonessa, *et al.* 2003), this system serve as communication link between autonomous underwater vehicles and the on-shore base.

When the operation field is the sea or a place with very unstable conditions the first approach is to make more robust and larger vehicles, as an example we have LADAS a catamaran from WHOI operating on open ocean for collect water sampling data. Other major institution working in this area is the IST-ISR with their DELFIM and CARAVELA vehicles. DELFIM (Pascoal, *et al.* 2000) is a catamaran with several oceanographic sensors for marine monitoring and with acoustics communication for interact with autonomous underwater vehicles. The design of CARAVELA with the objective of developing a long range autonomous oceanographic vessel. The last vehicles were developed for coastal and open ocean research.

River and estuarine environments do not pose harsh restrictions in vehicle wave handling capabilities. In general, waves are not significant thus allowing operation of vehicles with relatively small dimensions.

The autonomous surface vehicle described in this work falls under this category. It is designed to be operated in river and estuarine scenarios with negligible wave conditions and relatively calm waters.

The vehicle was designed with two main objectives in mind. First to provide an autonomous platform for environment monitoring and characterization. And second, support operations of one or more autonomous underwater vehicles (Martins, *et al.* 2003).

A small autonomous surface vehicle can perform different environmental monitoring missions efficiently. One of the ROAZ applications is the bathymetry of riverbeds, estuaries, dam basins and harbours. The vehicle can carry multiple application sensors, ranging from bathymetric sonars, sidescan sonars, CTDs, water samplers etc. Water characteristics can be determined when necessary near the surface or eventually (although not the vehicle primary application) by mounting the sensors on a variable depth mechanism.

One of the main vehicle applications is the support of Autonomous Underwater Vehicle operations.

This can be translated in launch and recovery of AUVs, giving convenient access to the water medium and providing the convenience of radio communications with human operator on shore. In addition can eliminate de need for operation support boat.

Other aspect in the AUV operation support is providing good acoustic communication links acting as a communication relay on the surface. The possibility of taking GPS fixes, can provide also absolute positioning reference to an underwater acoustic navigation framework. The vehicle can also be part of coordinated missions involving multiple AUVs and ASVs (Martins, *et al.* 2003). The vehicle was developed under the research activity pursued on multiple autonomous robots, developed by the Autonomous Systems Laboratory at ISEP - Institute of Engineering of Porto.

In the following sections the vehicle design options and considerations are presented, followed by a brief description for the control and navigation system and ending with some preliminary results and final comments.

2. VEHICLE DESIGN

2.1. Mechanical considerations

Reduced operational logistic requirements coupled with a typical river operation scenario imposed limits on the overall vehicle dimensions. These were chosen in order to be able to easily transport the vehicle in a small car and deploy it without winch.

A twin hull configuration was implemented in order to allow suitable AUV docking capabilities (by convenient use of inter-hull space) and to reduce volume.

The vehicle was developed in fibreglass structure reducing weight. The thrusters are externally stern mounted (Fig 1).

Figure 1 · ROAZ Vehicle.

This configuration allows the ease of thruster exchange and good vehicle transport configuration.

The vehicle has relatively low area exposure above water with all the electronics in the bridge section between hulls, thus reducing wind effects. It has a flat top surface allowing solar panel coverage and depending on vehicle configuration can support a camera tripod or a communications mast.

The central section has structural fixation points underneath and a connectors access for application of different types of sensors and mobile AUV dock mechanism.

A payload up to 50 kg can be added. Battery support and fixation is provided inside the hulls.

A bottom sealed hatch in the central section can be configured with different plugs and connectors according with the sensor suite used.

The vehicle overall dimensions are 1.5x1x0.52m, and the hulls were designed in order to reduce hydrodynamic drag.

2.2. Thruster design

A dedicated thruster was developed for the vehicle. One of the main reasons for this development over the use of standard underwater thrusters was cost. Other option was the use of standard electric boat trolling motors, but these had the drawback of low voltage configurations (and high current), and usually without velocity or current measurement.

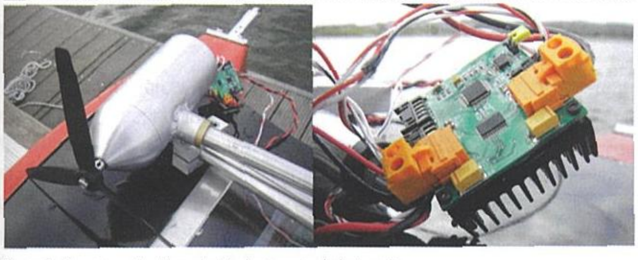

Figure 2 · Thruster unit with embedded axis control electronics.

A dedicated thruster control board was developed, with local processing in an integrated DSP and with current monitoring (Fig. 2). The local motor controller includes the power drive along with the processing for velocity or force control and diagnostics and failure detection. The system has a CAN bus interface thus providing a standard interface and is integrated in the thruster enclosure.

The connections to the thruster consist only in a four wire cable with power and CAN lines.

The use of CAN bus to communicate to separated electronic subsystems reduces cabling requirements with good reliability properties.

2.3. Autonomous Underwater Vehicle dock mechanism

Currently different dock mechanic designs are under test and consideration to be integrated in the vehicle for AUV support missions.

Vehicle twin hull separation distance was defined in order to achieve: good hydrodynamic characteristics, ease for logistics and operation and the possibility of docking for a shallow water AUV such as the Isurus vehicle (Cruz, *et al.* 1999) or multiple smaller vehicles as the Nekton Ranger AUVs (Hobson, *et al.* 2001).

A structural fixation mechanism is incorporated in the vehicle design in order to allow the test of multiple dock mechanical designs.

Some work is already under development in the AUV charging device. Preliminary tests have been performed with a small scale inductive power coupling device.

2.4. On-board computer system and communications

The vehicle main on-board computer consists in a low power single board computer. This is responsible form the mission control and vehicle navigation.

A CAN bus network is implemented to connect the vehicle subsystems, from the navigation sensors to the thruster controllers. Currently only the thruster controllers have been tested in operation and the remaining sensors communicate through serial port.

CAN bus interface nodes are under development and will be integrated in the near tests to be performed.

The CAN bus allows the interconnection of a considerable number of systems with reduced cabling and reliability. Additionally the requirement for a serial port expansion board is eliminated from the SBC. The vehicle uses 12V NiMh battery packs with 24V nominal voltage for the thrusters.

Radio communications are achieved through an external IEEE 802.1b/g ethernet modem with external antenna (in various configurations and gains).

The vehicle can be equipped with an acoustic modem for underwater communications with similar equipped AUVs, providing this way a surface radio communications relay to host stations on shore or in a support ship. This configuration takes advantage of good properties of vertical acoustic channel by the ASV use directly above the AUV as in similar ASVs operations (Pascoal, *et al.* 2000).

The vehicle can also be used as a mobile acoustic beacon for a LBL navigation system (Matos, *et al.* 1999). Further multiple AUV coordination and navigation developments (Martins, *et al.* 2003), (Martins, *et al.* 2004) will be supported by ASV.

Application sensors can use available CPU and disk space with appropriate connection. An exception for this is the use of sidescan sonar requiring an additional computer system. This is due to the large communication bandwidth and disk space along with closed system interface (both interface electronics and processing software).

The vehicle has a standard composite video camera with a dedicated video radio transmitter. This camera is used by an external human operator in a tele-operation mode. The vehicle can also use standard USB digital cameras with a computer vision system (Silva, *et al.* 2006) for navigation and docking

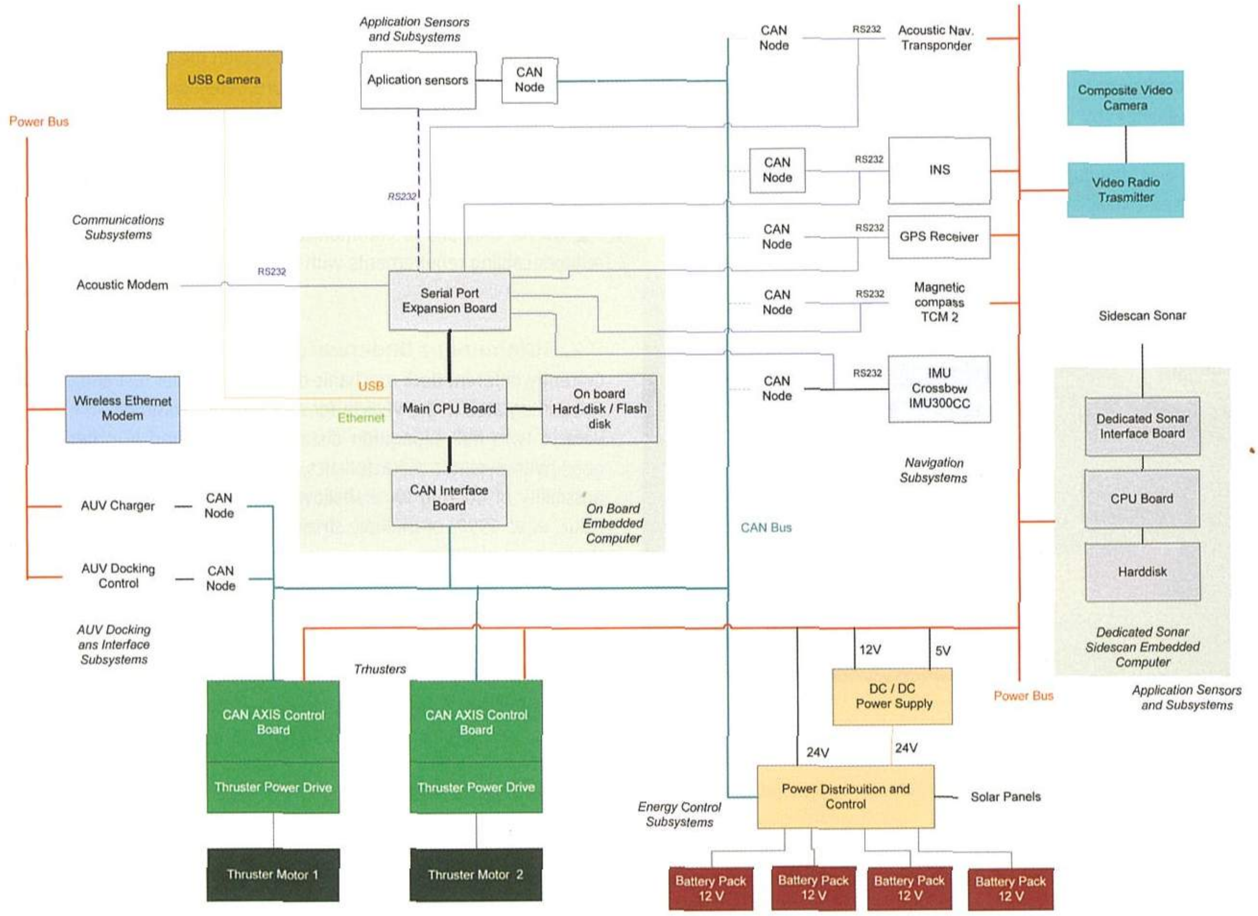

Figure 3 · Vehicle hardware architecture.

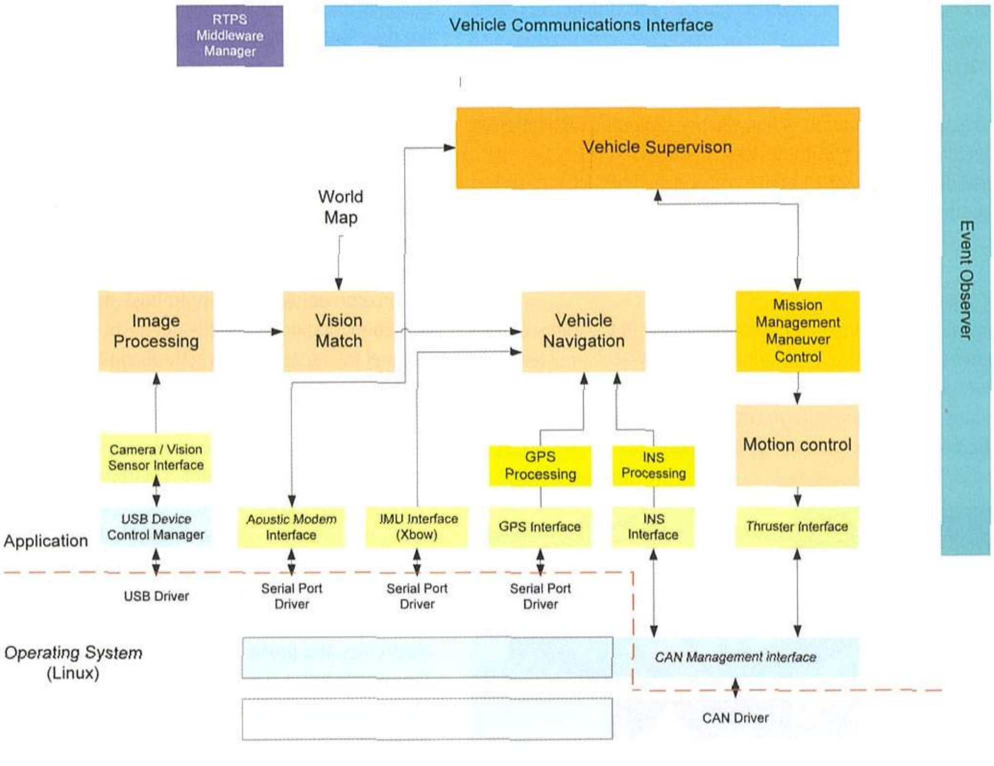

Figure 4 · Software architecture.

aid. This artificial vision system can also use transparently the dedicated hardware vision system BoaVista (Lima, et al, 2004).

2.5. Software considerations

A modified Linux operating system provides the base support for the on-board software.

The vehicle application is organized in a set of modules and with multiple processes and threads.

A middleware communications publish/subscribe infrastructure (Dias, *et al.* 2006) is used to facilitate intra-vehicle and extra vehicle interaction. One example for an external interface is the Neptus system (Sousa, *et al.* 2005).

An event observer module (see Fig. 4) detects all the relevant events (required for the mission control) and for vehicle supervision.

A CAN bus management module is implemented to allow a publish/subscribe access to the bus and abstract the operating system device driver implementation. Currently a migration from serial port communication with several sensors to a CAN bus based one is under development.

3. CONTROL AND NAVIGATION

3.1. Vehicle model

A 3 DOF model for the vehicle can be obtained by considering movement limited on the horizontal plane.

Using standard SNAME (SNAME 1950) notation the vehicle horizontal model state is given by (η ν) where η is the vehicle position and heading angle and ν is the vehicle velocity measured in a body fixed frame.

The dynamics model for a (partially) submerged body is given in a matrix form by:

$$M\,\nu + C(\nu)\nu + D(\nu)\nu + g(\eta) = \tau(\eta,\nu) \tag{1}$$

Where *M* is the mass matrix (considering added mass and inertia terms), *C* is the centripetal and Coriolis effects matrix, *D* is the damping matrix (dominated by hydrodynamic drag), *g* is the gravitational effects matrix, and τ is the external forces and moments vector.

The transformation between body fixed coordinates and inertial frame measured positions is given by:

$$\eta = J(\eta)\nu \tag{2}$$

with *J* the standard (Fossen 1994) coordinate transformation matrix.

Considering only horizontal movement the gravitational restoring forces and moments do not exist, and since C is composed of second order terms it can also be neglected; see (Fossen 1994) or (Healey 1993).

The reduced model is thus given by:

$$\begin{bmatrix} m - X_{\dot{u}} & 0 & 0 \\ 0 & m - Y_{\dot{v}} & mx_G - Y_{\dot{\gamma}} \\ 0 & mx_G - N_{\dot{v}} & I_{zz} - N_{\dot{\gamma}} \end{bmatrix} * \begin{bmatrix} \dot{u} \\ \dot{v} \\ \dot{r} \end{bmatrix} + \begin{bmatrix} -X_u & 0 & 0 \\ 0 & -Y_v & -Y_\gamma \\ 0 & -N_v & -N_\gamma \end{bmatrix} * \begin{bmatrix} u \\ v \\ r \end{bmatrix} = \begin{bmatrix} X \\ Y \\ N \end{bmatrix} \tag{3}$$

With the external forces X and Y and yaw moment N resulting from the rear thruster forces, depending only on the thruster configuration and position. The *M* matrix elements are the vehicle mass *m*, centre of gravity position, moment of inertia I_{zz} and added mass coefficients. The damping matrix coefficients represent the hydrodynamic drag and depend on shape and quadratically on velocity over the water, so equation (3) is valid for a nominal vehicle velocity.

3.2. Control and navigation system

A hierarchic architecture is considered to integrate the vehicle's navigation and control systems and a hybrid systems framework was adopted in order to design control and navigation algorithms.

The global control design relies on the concept of manoeuvre, which is modelled by a hybrid automaton (Henzinguer 1996, Lygeros, *et al.* 1999). This can be briefly described as a set of discrete states and transitions between them, being a set of controlled continuous flows associated with each one. The manoeuvre implementation involves not only the vehicle hybrid control law, but also the navigation filters. The control and navigation systems are integrated in the manoeuvre design. In addition, more complex manoeuvres can be obtained by the hierarchic composition of simpler manoeuvres.

Figure 5 depicts the information flow diagram.

Vehicle motion control uses information from the fused navigation information and mission objectives.

A low cost custom designed INS system provides acceleration, velocity and position/orientation for the vehicle.

On board GPS system provides absolute positioning and inertial sensors (low cost INS and/or other sensors) provide fast dead reckoning information. Vehicle heading is determined by an external compass or by the low cost custom designed INS system.

Extended Kalman filtering techniques are used to perform sensor fusion and provide a navigation state estimate. Currently only GPS and INS orientation information are used.

The computer vision system (LSAvision) (Silva, et al 2006) can also provide navigation information by extracting relevant scenario features and performing adequate matching with a know environment map (Almeida, *et al.* 2004).

This vision system will also be used in the future on docking tasks with AUVs.

4. PRELIMINARY RESULTS

4.1. Computer fluid dynamics tests

The drag force for a given object can be obtained by:

$$F_D = C_D \cdot \frac{1}{2} \cdot \rho \cdot A \cdot V^2 \tag{4}$$

were F_D is the drag force measured in N (Newton) and C_D is the drag coefficient, measured in N/m², i.e. the drag force per square meter frontal area of the object shape.

Table 1 · Drag force values for a velocity interval of 0 to 3 m/s.

VELOCITY (m/s)	$\text{FORCE}_{\text{DRAG}}$ (N)
~ 0	~ 0
0,5	3,81
1,0	15,19
1,5	34,89
2,0	67,60
2,5	107,41
3,0	154,46

Drag calculations using computer fluid dynamics code were performed based on a CAD model for the vehicle hulls. In Table 1, the longitudinal drag values are presented for different forward fluid velocities. These values correspond to the Xu hydrodynamic coefficient in the vehicle model previously presented. Similar calculations can be used for the other parameters determination.

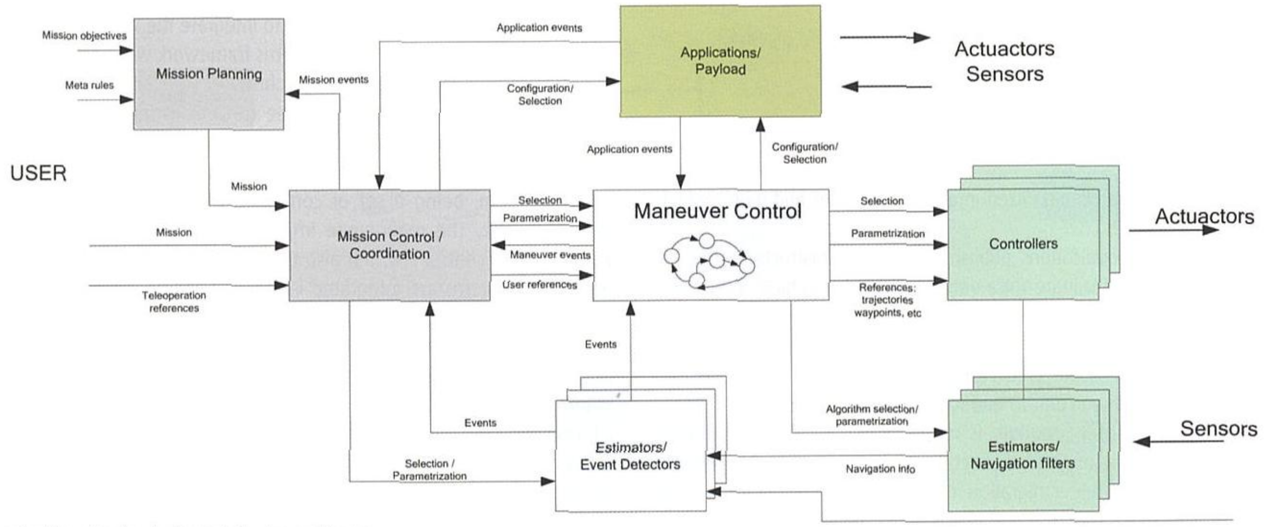

Figure 5 · Information flow for the control system architecture.

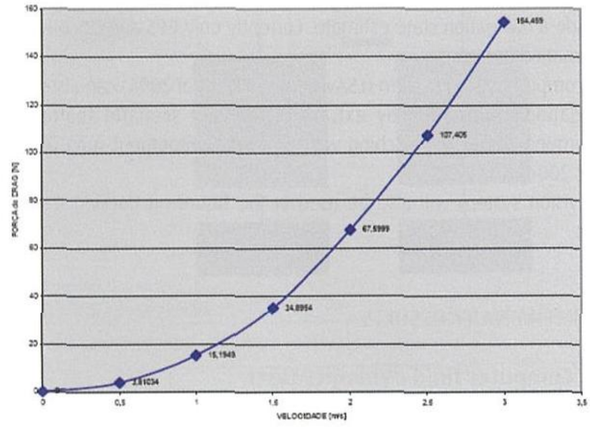

Figure 6 · Hull Drag force for different fluid velocities.

There were also made tests on the water and for the 0,5 m/s and a 3 m/s velocities were obtained a 3 N and 13 N forces of drag, what is very consistent with the CFD values.

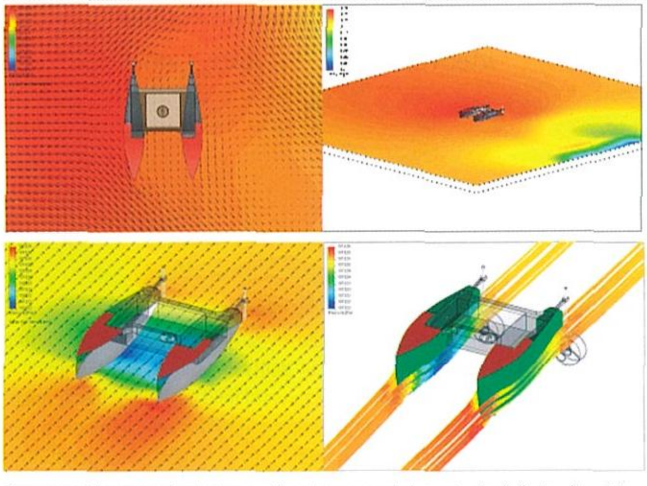

Figure 7 · Hull pressure distributions and flow from CFD calculation for the hulls (top lateral flow 1m/s, bottom longitudinal flow 1m/s).

In Fig. 7 one can observe the pressure distribution along the hull for a 1 m/s lateral flow fluid velocity and a 1m/s longitudinal flow. These calculations were performed without taking in account the thruster influence, hence the highly laminar flow observed on the bottom.

The streamlined hull design advantages in manoeuvrability were further *confirmed in our initial tele-operation tests in pool.*

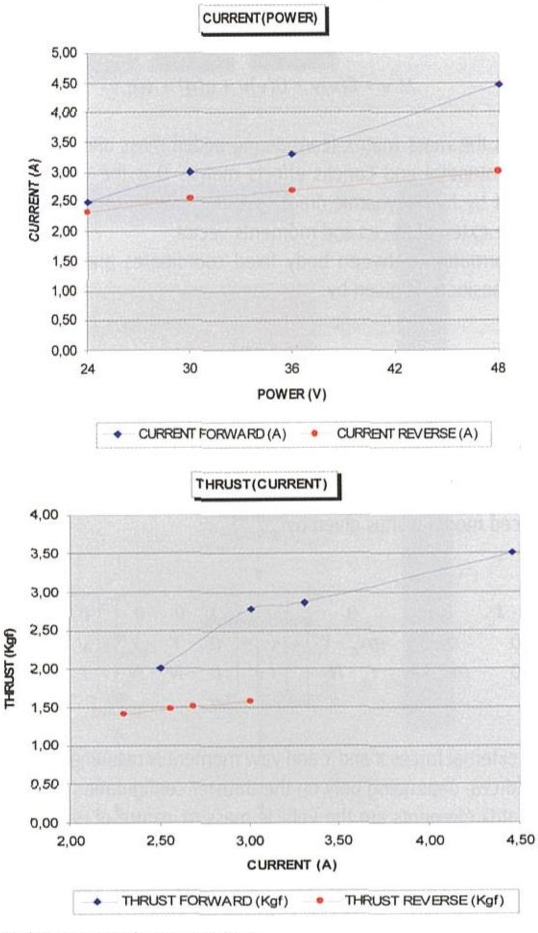

Figure 8 · Thruster curves of current and thrust.

4.2. Thruster characterization

The developed thrusters were tested individually and the bollard pull thrust results and currents are presented in Fig. 8.

Open water tests where performed with the thrusters mounted on the vehicle, and for an approximate 1 m/s of maximum velocity a 2.5 A maximum current in each motor was measured (Fig. 9) by the local control board. In the following figure it can be observed one example for a commanded step to maximum speed.

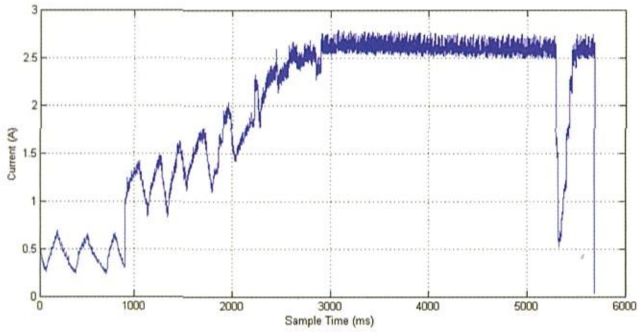

Figure 9 · Thruster motor current evolution for open water vehicle maximum velocity.

5. CONCLUSIONS

In this work the design and current status of implementation for the autonomous surface vehicle ROAZ was presented.

The vehicle was designed to perform missions in river and estuarine scenarios. Multiple mission applications can be executed ranging from bathymetry, environment monitoring and support to Autonomous Underwater Vehicle missions.

AUV support missions are one important objective for the vehicle. This support can be either in the recovery and launch or in providing an external surface link, either by performing an absolute navigation fix or by interface with an acoustic underwater communication system.

The vehicle is considered to be part of an ongoing research activity and strategy for the coordinated use of multiple AUVs and ASVs in an integrated mission.

A mechanical design was validated by computer fluid dynamics calculations and implemented. The onboard processing systems and some basic navigation sensors where integrated. A custom thruster was developed and some characterisation tests performed.

The vehicle has already performed test missions in a semi-controlled environment (either pool and outdoor canoeing lanes). These tests included operational missions with AUV's and the vehicle provided relevant support to AUV operation in recovery assistance and communication relay.

Further vehicle model identification tests are under development along with more autonomous capabilities to the control system. Some preliminary tests with a sidescan sonar as an application sensor suite where also performed although not presented in the present work.

The work described, consists on the initial steps in the further development of a truly integrated ASV for a multiple heterogeneous autonomous vehicle missions (including AUVs and/or Autonomous Aerial Vehicles) currently under research.

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