

Autonomous Unmanned Surface Vessels for Hydrographic Measurement and Environmental Monitoring

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Key words: Unmanned Surface Vessels, USV, bathymetry, hydrographic measurement

SUMMARY

Logistic constraints and difficulties, as well as risks and economical impact of the bathymetric measurement activity, especially in shallow water, are known matters. This activity, in fact, normally implies the presence of human conductors and operators aboard motorized craft that often have to be transported in difficult to reach places or, even worse, have to operate in sites which are dangerous or hazardous for humans such as quarry lakes, landslides, risky or contaminated areas. In certain cases environmental constraints or water depth rule out craft powered by outboard engines. aerRobotix have developed a different approach based on the use of small “unmanned” craft capable of carrying out bathymetric measurements in partial or even total autonomy. Such an innovative solution avoids risks to humans, causes no environmental pollution, reduces the number of operators involved and makes the activity much more flexible. Efficient mission management, small size, handling ease and low power consumption yield low operational costs. A profitable collaboration with Geo Survey has given the opportunity to test on field such advantages in the bathymetry operations and to integrate state-of-the-art professional instrumentation. This paper describes this new approach and the relevant lesson learned. Based on examples related to successful applications of the unmanned twin-hulled “CatOne” vessel it provides details about the characteristics and advantages that unmanned surface vehicles offer for bathymetric measurement and also for other possible applications in the environmental field.



Figs. 1a, 1b – The CatOne family of Unmanned Surface Vessels (USV): rudder-less and air fan propelled.

SOMMARIO

E' ben noto come le attività di rilievo batimetrico, specie se in acque basse, siano condizionate operativamente ed economicamente dalle situazioni ambientali, dalle difficoltà di ordine logistico e dai fattori di rischio connessi. Di norma si tratta, infatti, di gestire natanti con personale a bordo, che spesso devono essere trasportati ed operare in luoghi di difficile accesso, talvolta pericolosi come nel caso di bacini di cava, di sponde franose o di ambienti contaminati. In certi casi ragioni di compatibilità ambientale o la ridotta profondità dei fondali impediscono di fatto l'impiego di natanti propulsi dai tipici motori fuoribordo. Allo scopo di ovviare a tali inconvenienti e di rendere più flessibile ed economica l'attività di rilievo ambientale aerRobotix ha messo a punto un approccio innovativo basato sull'impiego di una famiglia di natanti robotizzati sviluppati ad hoc, denominata CatOne. La collaborazione con Geo Survey ha consentito di sperimentare sul campo tali vantaggi nell'ambito del rilievo batimetrico e l'integrazione di strumentazione professionale allo stato dell'arte. Tale soluzione elimina i rischi per il personale, che resta a terra, annulla ogni tipo di inquinamento ambientale, riduce il numero di operatori coinvolti e permette una maggiore flessibilità operativa. La più efficiente conduzione dell'attività, la maneggevolezza permessa dalle ridotte dimensioni dei natanti ed il basso consumo energetico inducono evidenti benefici economici. Vengono qui illustrati il nuovo approccio adottato e le caratteristiche dei natanti robotizzati CatOne sia per l'impiego in batimetria sia per altre applicazioni nel settore idrogeologico ed ambientale.



Fig. 2,3 – La famiglia di natanti robotizzati CatOne (Unmanned Surface Vessels, USV) senza timone e propulsi da ventole aeree

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1. INTRODUCTION

It is very appropriate to say that, since the early days of bathymetry, a lot of water has flowed under the bridge. Man's attempts at measuring the seafloor, in fact, go back to 1800 B.C. , as shown by the Egyptian depictions described at Ref.1.

Although bathymetry is today largely used for measuring ocean depths there are also many different applications in lakes, dams, rivers and other fresh water basins, that are the very subject of this paper. A typical example refers to bottom mapping of hydroelectric plants, the infrastructures of which need to be periodically monitored. It is actually of great importance to know the total available volume and the depth distribution of the basin, particularly close to the dam discharge gate and the spillway submerged equipment. Although modern technology does not require a boat as large as that illustrated in Fig.5, still craft of a certain dimension is generally used today for this kind of survey. It must accommodate the helmsman as well as an operator of the measuring system, plus the relevant equipment. Unfortunately, basins to be monitored are seldom a nice touristic site. More frequently they are lonely places, often in mountain or very isolated areas, sometimes not particularly accessible by car and occasionally difficult to reach even on foot (Fig.4). In addition, the depth of the water can be very limited, especially close to the coast, thus making it difficult to launch boats of a certain dimension without a risk to propellers and/or rudders coming in contact with the basin floor. Quite clearly, the same boat is not suitable for all situations.



Fig. 4 – Access to the survey area can be sometime difficult (source Ref. 3)



Fig. 5 – The same boat does not suit all different situations (source Sam DeBow, NOAA)

When the size of the basin is large, the above problems tend to reduce or even might vanish completely, but in this case it becomes onerous for the crew and expensive to carry out long endurance surveying sessions. A good alternative to such difficulties is offered today by the adoption of Unmanned Surface Vehicles (USV), robotic boats that can replace a human crew and automatically accomplish their mission. Robot are never tired, can perform their task accurately and their level of attention does not deteriorate because of boring, long endurance,

repeated task. Neither they need to rest for lunch, nor for other physiological needs! Removing the need to carry humans on board significantly reduces the size and weight of the boat and, as a consequence, its handiness. It is evident how this favourably affects the whole process, both in terms of efficiency, easiness of handling, cost and, last but not least, safety. The latter applies, in particular, to risky environment such as quarry lakes, glaciers lakes, landslides or contaminated areas. It must also be noted that, nowadays, the number of environmentally sensitive areas is increasing all over the world like, for instance, natural parks where only electrically-powered boats are allowed. This prevents many conventionally-powered boats from operating. Based on long experience acquired in many years of traditional bathymetric activity Geo Survey has found that a robot boat produced by the company aerRobotix is a valid alternative, as described later.



Figs. 6,7 – The typical equipment used in the past by Geo Survey for bathymetry measurements in shallow water. On the right side one can notice the single-beam echo-sound transducer fitted to a graduated pole.

2. UNMANNED SURFACE VESSELS

The concept of unmanned surface vehicles (USV) is not new and examples can be found quite far back in the past, even earlier than World War II [Ref. 4]. It is worth mentioning the interesting post-war application carried out by the U.S. Navy when unmanned boats were used to collect radio-active water samples after the atomic tests on Bikini Atoll in 1946. But it is only in the last two decades that a significant number of projects have been developed as a spillover of military applications and of the related technological progress. As usual in these cases, the civil environment takes advantage of the military research fall-out. Therefore we can now observe a continuous growth of a USV civil market that encompasses a huge range of different maritime solutions, of different performance, shape and sizes. Somewhat less developed so far is the market of vessels specialized in fresh water operations and, in particular, in shallow water. The continuous development in the field of electrical energy storage systems has given a powerful shove, thus allowing the building of small, handy and efficient solutions which are offered by a few qualified high tech companies in the world. Many research activities looking for new applications are currently being conducted as well. The newly established Italian company aerRobotix has developed the USV CatOne, specialized for fresh-water basins, that presents unique operational peculiarities.

3. THE INNOVATIVE USV FAMILY CatOne

3.1 General

CatOne is a family of multi-purpose catamaran-robots especially effective in situations that require recurring, very repetitive, long endurance activities or in those to be carried out in dangerous and hazardous environment and in sensitive ecosystems. Navigation is completely automatic, slaved to a GPS positioning reference system. In addition to the typical sonar for bathymetry, the robot can host and carry on board a large variety of sensors and equipment. Several specific characteristics make CatOne capable of operating in very shallow water, in presence of algae and in sensitive ecosystems, namely :

- very low draft
- absence of propeller and rudders in the water
- zero pollution emission (electric propulsion)
- low noise
- no disturbance to the depth contour of shallow water and to the flora and fauna.

Low weight and small dimensions makes CatOne's ground handling easy. The number of required operators can be reduced to just one person. Partially disassembled, the catamaran can be easily transported on the roof of a medium-size car or inside a Station Wagon . Time for assembly and preparation for the mission is in the order of just a few minutes.

3.2 CatOne concept of use and system architecture

The vessels are capable to fully autonomously conduct navigation along pre-programmed trajectories. The operator prepares the scanning routes or any arbitrary chosen trajectory in advance, as a sequence of waypoints (e.g., in WGS84 coordinates or other selectable reference systems). This phase is conducted with the comfort of an office environment, based on available cartography and mission requirements, through a user-friendly interface. Once on the field, the operator deploys the system (10 minutes), uploads the mission instructions through a wireless link and initializes it, together with the measurement device (payload). The complete mission is then executed autonomously by the robot, which then returns to base leaving to the operator the only task of downloading the survey data. Virtually no interaction and supervision is required during the mission. Nevertheless a Portable Control Device (PCD) allows a number of useful interactions with the vessel through a bi-direction data link. One can either modify the pre-programmed (and uploaded) paths even during execution, and monitor the health of the system and the progress of the survey. In lakes /lagoons in presence of other surface traffic (boats, ships) or any other circumstance not known forehead (like trees/obstacles in the water) the flexibility offered by the PCD is very valuable.

As an option, the operator has the possibility to directly steer velocity and direction of the vessel through a dedicated radio-control, bypassing the automatic system and taking full authority. This is useful for instance to trace the borders of a basin, or to navigate in any other circumstance where assigning a reference trajectory is impossible or not practical.

Autonomous modes include simple navigation towards a waypoint or more advanced modes such as fine-tracking of a reference line (very useful for building scan patterns on lakes or transverse paths on rivers). More specialized modes include for instance the so called "virtual buoy" mode, allowing the operator to "anchor" the vessel in the middle of the stream of a river in a position that can be slowly adjusted during the survey. Contingency modes are implemented in order to bring back the vessel in situations such as loss of control link, loss of GPS coverage, low battery charge level, etc.

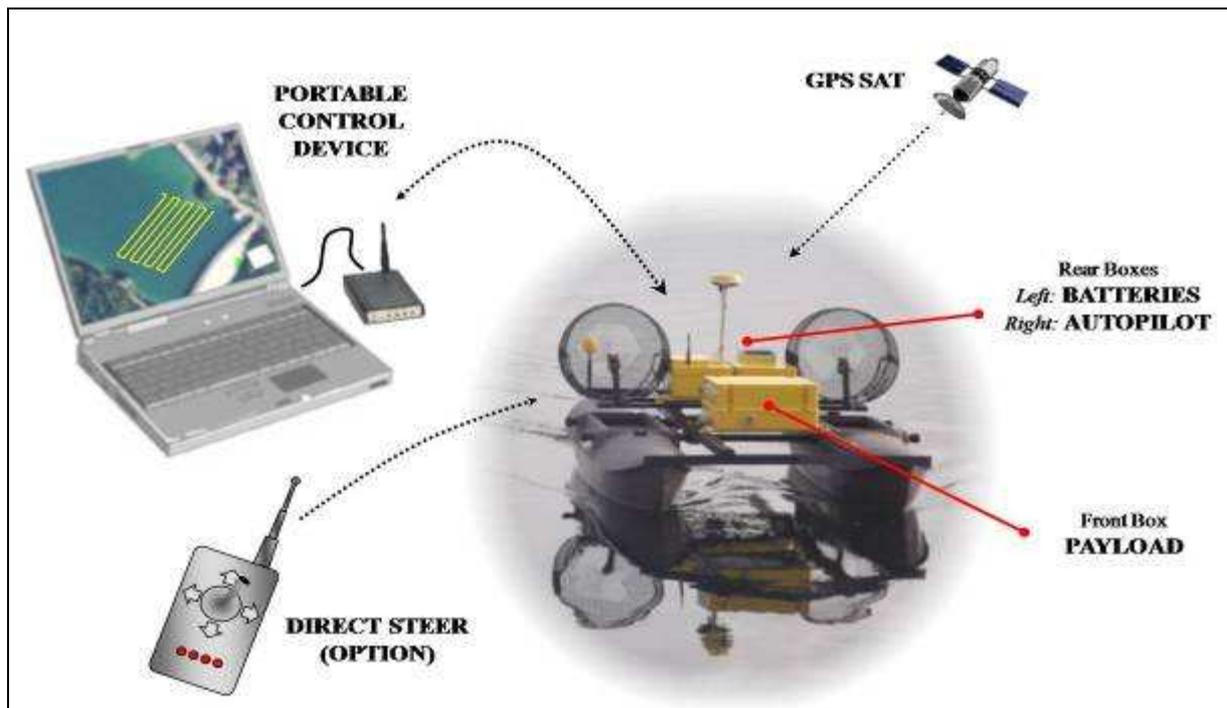


Fig. 8 – CatOne’s system architecture

3.3 The vessel



Fig. 9 – The twin-hulls, flat bottom, rudderless configuration of the robot-boat CatOne

The CatOne configuration is based on the catamaran concept for its favourable characteristics of roll stability. In addition, flat-bottom hulls allow the vessel to operate in very shallow water. Modularity is the principle inspiring this robotic family, in particular conceived to

accommodate in practice any kind of measurement device (i.e. bathymetric single-beam, multibeam, velocity profilers, water sampling devices etc.) with minimum, if any, modifications to the basic configuration. Propulsion is provided by two aerial propellers, each driven by a regulated electric engine. Symmetric management of the engines push exploits velocity control, including reverse motion; differential modulation provides directional stability and control. No rudders, hinges, fins or other devices are needed, and the only moving items are the engines ball bearings, shafts and propellers.

This design is driven by the requirements of simple operations without need for post-deployment calibrations, as well as of reliability for extended duration and minimum risk for the craft to be entrapped by underwater obstacles, debris etc. Power is provided by rechargeable batteries. Lithium-Polymer technology is the chosen standard, which allows up to 8 hours continuous operation on a single charge and quick recharging compatible with the logistics of a typical measurement campaign. Electrical power systems are reliable, clean, silent and require minimum and simple maintenance. Large volume quick-lock boxes host the pay-load, allowing for easy integration of modular battery packs and measurement devices. CatOne's main characteristics and performance are listed hereinafter.

Length	1.6 - 1.9 m
Width	1.0 - 1.2 m
Weight (empty)	12 - 20 kg
Pay load	up to 12 - 50 kg
Propulsion	Electrical
Energy	High energy density LiPo rechargeable batteries
Operational speed	5 km/h
CO2 emission	zero
Navigation modes	Fully automatic (pre-defined), remotely controlled or mixed
Endurance	8 hours (prolongable by additional battery packages)
Operators	One person can supervise up to three units
Transportation	Station wagon, monovolume car or car roof carrier

3.4 The control system

The control system assures autonomy and operational flexibility. It consists of :

- A computerized on board system. It autonomously drives the mission taking as a positioning reference GPS data, integrated by inputs from inertial and magnetic sensors. By comparing the vessel's current position and state with the uploaded reference values, the system controls velocity, attitude and stability by regulating the engines turn rate.
- A Portable Control Device (PCD), size of a netbook, equipped with a modem and related power source. It allows mission planning, rehearsal, health and mission monitoring, online re-planning, data download and first level analysis. The PCD is Windows based, and the interface with the operator is based on moving maps, drag-and-drop waypoints, softbuttons for mission activation, upload etc. This device includes also a "grid auto-planning" capability. This allows the operator to automatically create the scanning grids

for the autonomous navigation. This facility requires as input just the grid step (transversal distance between parallel cross-section) and the contour of the area to scan .

4. APPLICATION TO BATHYMETRY

Bathymetry is the very first application of the CatOne robotic systems, which are now currently used for this activity on a regular basis. Hereafter the standard operational scheme is presented. Samples of two surveys jointly conducted by aerRobotix and Geo Survey are also reported, which are representative in terms of environment, challenges and system architecture.

4.1 Po river survey

The area to survey was the confluence of the Po and Stura rivers, not far from Turin downtown, Italy. Accurate cross-sectional depth-profile data were to be collected, approximately every 100 m along the axes of the confluent rivers (Fig.11b).

State-of-the-art bathymetric survey equipment was installed on CatOne, as depicted in Fig. 10, describing the system configuration. When GPS signals are good enough, depth data are measured by the echosounder and transmitted to the Leica GPS rover station, which is hosted onboard together with the SonarLite unit. The rover station stores the depth and data quality information with the GPS position data, which is measured automatically at fixed predefined linear steps (e.g. 2 meters).

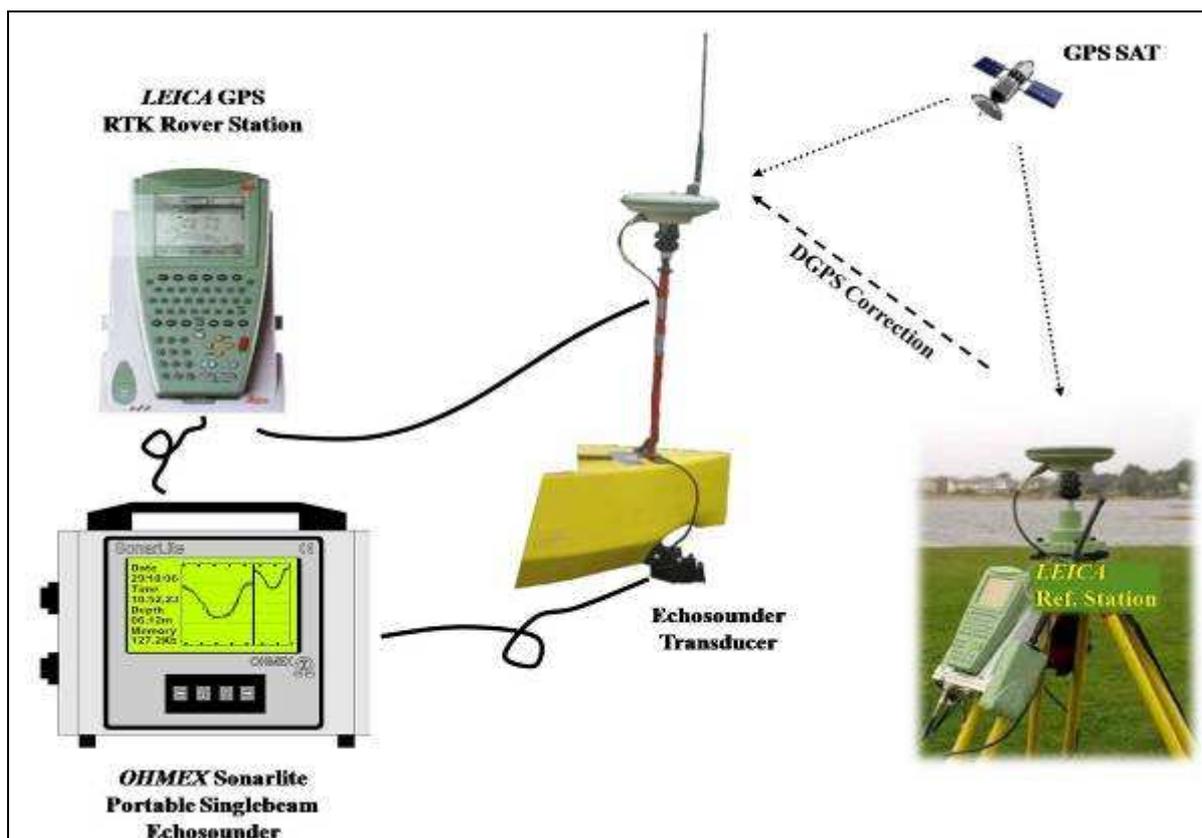
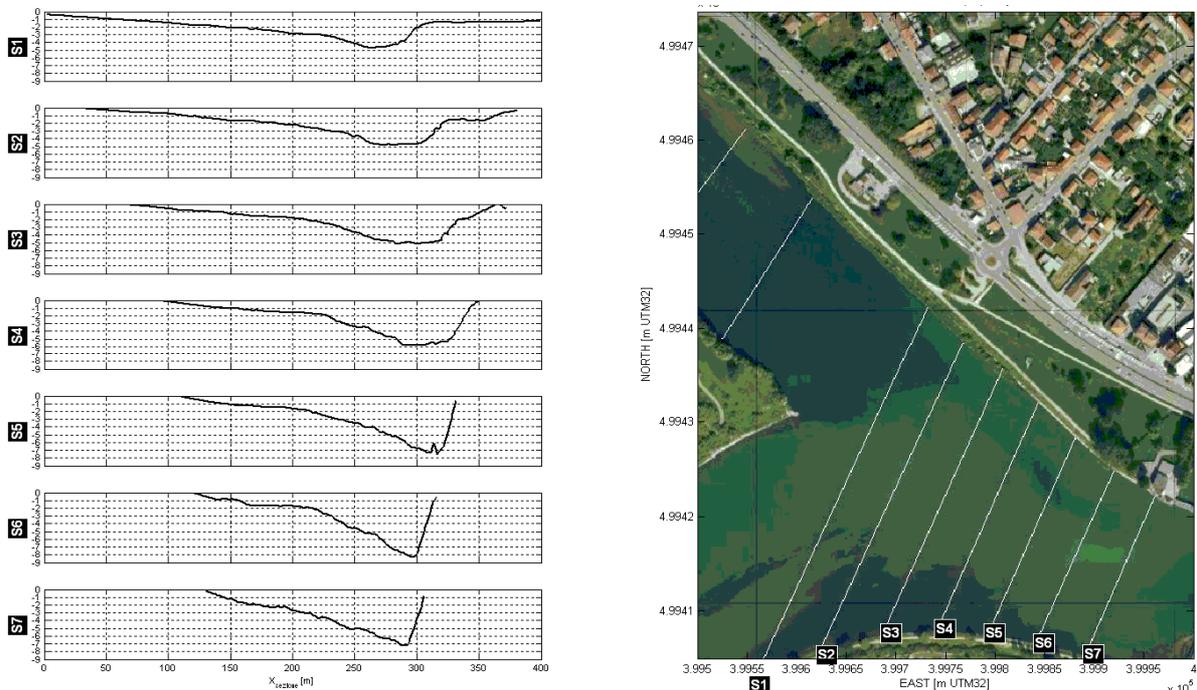


Fig. 10 - System Configuration for operation with GPS coverage

The GPS system is configured in order to receive the differential corrections transmitted by the reference station on ground, previously geo-referenced.

The robot's mission had been planned by pre-programming a single long scan, including all target cross-sections, each executed three times in order to collect the data to build a local Digital Terrain Model (DTM). The vessel could easily cope with the moderate stream of the river, automatically compensating for the drift by "pointing the bow" upstream and continuously minimizing the lateral position error relative to the nominal/target cross section. Main features appreciated by the survey team have been:

- Agile logistics: not having to deploy a rubber boat with outboard engine allowed to conclude the work in half a day. A sample of the post-processed data is reported in Fig.11a.
- Workload: the fact that navigation was carried out autonomously and with a very high degree of accuracy reduced the tasks for the team to monitoring the total stations.



Figs. 11a,11b – Cross-sectional depth-profile data (Confluence of Po and Stura rivers, Torino, Italy)

4.2 Santa Caterina dam basins survey

The area to survey was located in the Dolomite mountains region (Auronzo di Cadore, Italy). Accurate bathymetric data of two artificial basins (namely Santa Caterina and Comelico) originated by hydroelectric dams were collected, for a total surface of around 80 hectares. A dense measurement grid was required for the areas close to the dams' installations (i.e. 1 meter), while a more sparse sampling was accepted for the rest of the areas (i.e. 10-20 meter). Due to the proximity to the mountains which border the lakes the low quality of the GPS

signal didn't allow the use of the RTK technique. For this reason the prism reflector technique was employed instead throughout the campaign.

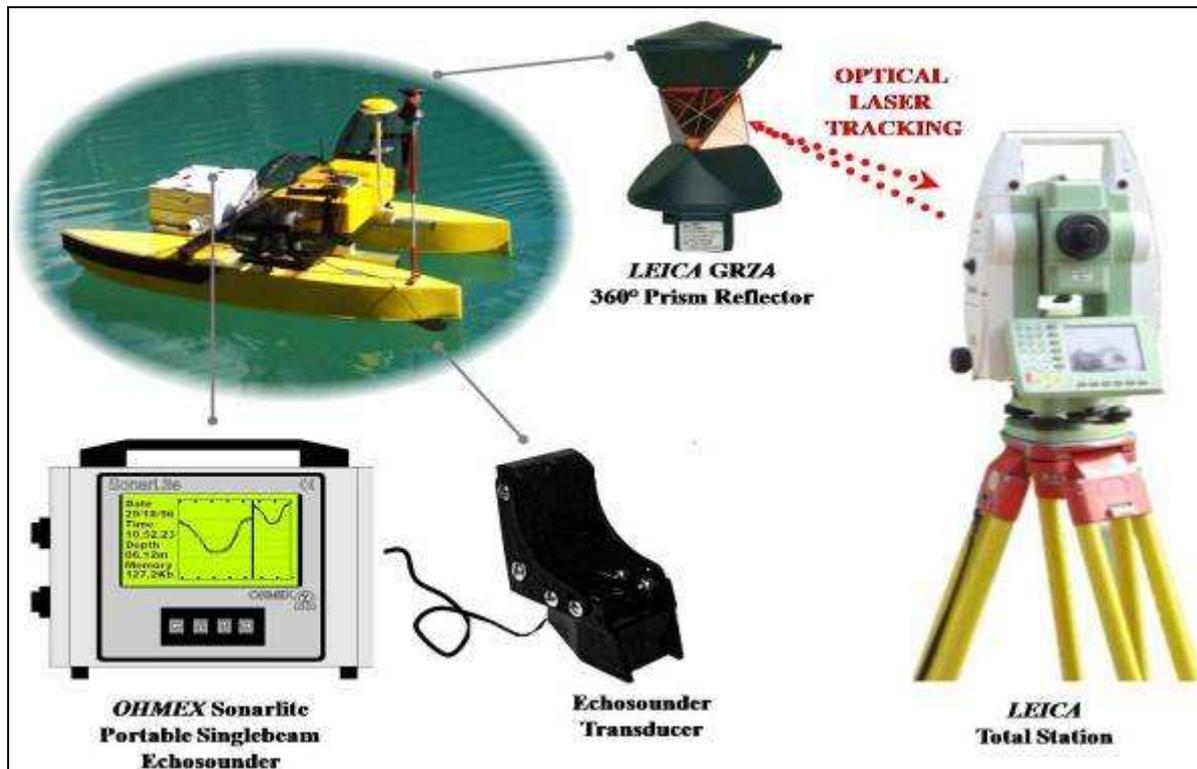


Fig. 12 - Configuration for survey without GPS coverage.

In this case the Ohmex SonarLite singlebeam echosounder is hosted stand-alone onboard, with the transducer installed at the stern of the left hull. A Leica GRZ4 360° passive prism reflector is mounted right above the echosounder. The depth data are stored onboard in the SonarLite unit, tagged with the time information (internal unit clock). The robotic total station, tracking the prism, measures and logs the planimetric information. Later on, during post-processing, this is correlated to depth data through the time tags. Echosounder and total station clocks are accurately synchronized beforehand.

Prior to the automatic survey, the contour of the lakes was accurately measured by directly steering the vessel along to coastline. This provided the perimeter of the lake, useful in post-processing for the accurate definition of the DTM; such data were used by the auto-planner to automatically create the scanning grids for the autonomous navigation of CatOne.

The survey team appreciated, in particular, the following features :

- High productivity, associated to a reduced workload. As an order of magnitude, the Santa Caterina survey (2.5 x 0.5 km) took place in 3 half days, for a total of 41 km of linear navigation, most of which performed in autonomous mode. In Fig. 13 a detail of the Santa Caterina lake DTM as extracted in post processing is reported.
- Simplified logistics and safety: the Comelico canyon-like valley is very deep and hard to reach, and the deployment of a motorized rubber boat would have significantly complicated the logistics. Moreover, during the execution of the survey, a slide of rocks

fell into the water, not far from the vessel navigating close to the mountain wall: fortunately without any consequence for CatOne. This event represent a typical hazard to which a survey company doesn't want to expose his personnel .

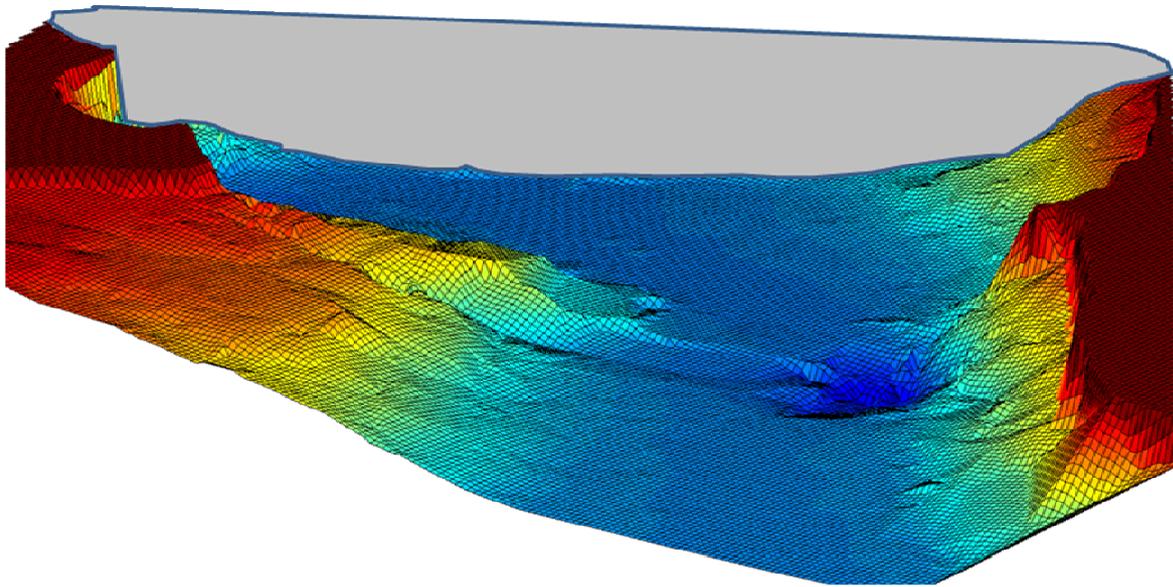


Fig. 13 - Detail of the Santa Caterina lake DTM as extracted in post processing

4.3 Lessons learnt and future development

Based on the first year of activity, the use of the USV CatOne for bathymetry has proven very effective. The suitability of this configuration has been carefully assessed and optimized, in particular, for use in fresh water and small-medium size basins. The fact that a single operator can manage the entire process has positively influenced its cost effectiveness. For these reasons, in this respect, aerRobotix has now undertaken a fully operational routine

The customers have declared their satisfaction and have helped considerably in identifying additional requirements for consideration in the development of new versions and improvements. In line with this continuous improvement philosophy, aerRobotix are also aiming at increasing the bathymetric mapping productivity and meeting the growing customer requirements for identifying the smallest detail which might lie on the bottom. Therefore the installation on board of multi-beam echo sounders and side-scan sonar is presently subject of assessment. Further efforts shall be devoted to provide the boat with a “see-and-avoid” capability to locate unexpected obstacles and to autonomously undertake the necessary actions.

5. OTHER APPLICATIONS

The robot CatOne can host and carry on board a large variety of sensors and equipment. In addition to the aforementioned bathymetric field, other areas of applications are being considered, tested and developed, ranging from hydro-geology to environment monitoring.

5.1 Seepage detection in water canals



Figs. 14a,14b - The aerRobotix CatOne robot boat tows the electrode array during tests in a canal

An interesting application of the USV CatOne is presently subject of a joint research carried out by the DIATI department of the Politecnico di Torino and the Dipartimento di Scienze della Terra of the Università di Torino (Italy) [Ref.5] with the contribution of aerRobotix. The purpose of the study is related to the protection of water resources. The high percentage of water lost because of seepages in irrigation and hydroelectric plants canals is a very sensitive problem on a global scale. For this reason, efforts are dedicated worldwide to ensure a more efficient use of hydraulic resources. To this end, a significant need exists to provide the relevant organizations with effective methods for rapidly localizing canals losses, mainly due to cracks in the lining, and to evaluate the seepage intensity. The idea under evaluation combines a variety of electrical parameter measurement techniques. One of these relies on the identification of anomalies in the electric resistivity distribution along the canal by means of waterborne CVES (Continuous Vertical Electric Soundings) . Such measurements have been experimentally carried out with the robot boat CatOne towing a specialized electrode array (Fig. 14). During the test, the electrical cable connecting the probes was kept afloat by means of a rough and ready (but effective) series of empty mineral water bottles. The enclosed Fig. 15 shows, as an example, a very evident anomaly observed in the canal segment (section at 140 m). A strong resistivity decrease is pointed out by soundings, linked with an highly vegetated zone at the correspondence of the end of the concrete sides of the canal. A small inlet zone has been observed in the same location. It is clear how, in this case, the availability of a flexible, easy to handle, small automatic boat such as CatOne can exploit the potentiality of this innovative application. The preliminary results achieved so far have demonstrated the high potential of this method and justify the researches that the team is presently carrying out aimed, among other things, at a real time monitoring of the survey.

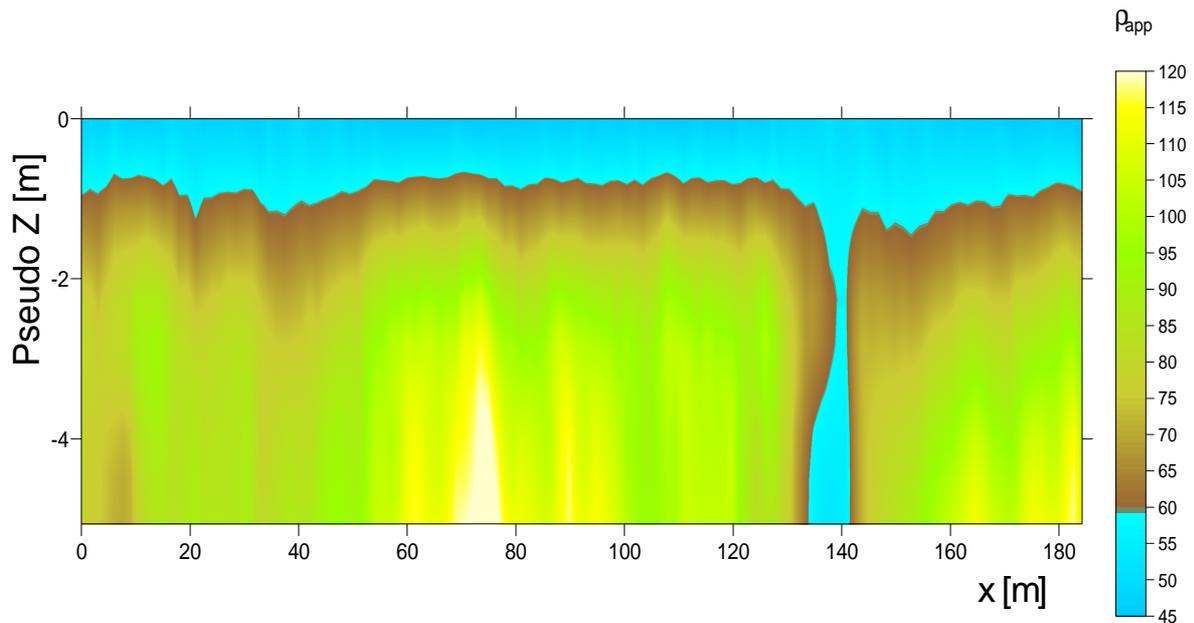


Fig. 15 – A detected strong resistivity decrease points out a flow variation in the canal

5.2 Discharge measurements via ADCP Doppler systems

Thanks to the reasonably large volume and weight available for the service payload, another possible easy installation is that of Acoustic Doppler Current Profilers (ADCP) for mapping the water flow intensity across river and canal sections. Such measurements are normally carried out by operators on the ground (e.g. on footpaths or bridges) or on boats, who drag buoyant hulls carrying the ADCP sensor and instrumentation.

The advantage of not requiring bridges and being able to perform the measurements everywhere is quite obvious, as well as the possibility of doing away with manned boats. It is mainly for this reason that this CatOne application is being developed.

5.3 Water quality measurement/monitoring and other potential applications

The environment friendly characteristics of CatOne make it very suitable for being used in ecologically sensitive and protected areas. Several applications in this frame can be envisaged. The relatively large payload capability of the USV CatOne allows for the integration of devices specialized in collecting water samples (temperature and dissolved oxygen are just examples of the parameters to be measured). The integration of a winch capable of lowering the measuring probes at different depth is being developed. This will allow for the use of CatOne either for environment data mapping or as a temporary replacement of fixed data acquisition station. CatOne can, in fact, operate continuously for days and nights, also maintaining a predefined static position (buoy mode) that might be changed from time to time. There are, in addition, a number of niche applications which present interesting potentialities worth to be explored in view of possible future development of the CatOne family.

A video system is foreseen that will support the see-and-avoid system but will also be at disposal for surveillance of the water surface, for the search of objects and/or animals, both in the visible and in the I/R range of frequency. Another possible application implies a precisely localized distribution of colouring water markers on the surface, to be optically tracked from ground and/or by aircraft with the purpose to identify water surface movements.

Also chemical products (fertilizers, pesticides etc.) might be efficiently automatically dispersed. Finally, someone is envisaging a possible use of USV for detecting and scaring birds over drinkable water basins and fish breeding ponds in a non-fatal and environmental-friendly manner [Ref. 6]. The aforementioned high level of eco-compatibility makes CatOne a good candidate to develop all such applications.

6. CONCLUSIONS

The effectiveness of using the USV aerRobotix “CatOne” for bathymetric surveys has been demonstrated and several advantages have been proven, especially in fresh shallow water basins and during relatively long-endurance mapping missions.

The unique propulsion system, based on aerial fans, and the absence of propellers and/or rudders in the water strongly reduces the risk for the small boat to be entrapped by floating obstacles like algae formations, plastic bags etc. . The boat’s limited weight and size make it very easy to move and, together with a very user-friendly control system, allows transportation and management by a single operator.

The bathymetry process has been optimized based on the long specific experience of Geo Survey and effective improvements have been identified for new variants of the product.

Other innovative applications are subject of research activity within aerRobotix which is available to establish contacts with groups interested in joint new developments.

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BIOGRAPHICAL NOTES

Alberto Romano, born in Biella (Italy) in 1970, graduated at the Surveyors Institute “Vaglio Rubens” (Biella) in 1989. After passing the state surveyor examination he was put into the surveyors register of the Province of Biella (Italy) in 1993. Between 2003 and 2007 he attended several specializing courses and seminars as, among others: advanced course in “GPS methods and measurement” (Farad s.r.l. Firenze), “Multi Reference Real-time GPS permanent stations network” (Politecnico, Torino), “Permanent GPS bases” (A.G.I.T. Verona), “Basic Offshore Safety Induction & Emergency Training, HUET and EBS (5700), “Danger deriving from presence of H2S” (Apt. Antincendio Bornasco, Pavia). In the frame of his volunteer activity in the frame of the Mountain Rescue 1998 he was awarded a diploma of snow observer. He is now responsible of the Geo Survey company, specialized in Topography, Engineering and measuring Systems

Pierluigi Duranti, aeronautical engineer, started his career as Assistant Professor at the Technical University (Turin, Italy) in the seventies, then moved to the aerospace industry and for more than thirty years has been involved in several international aircraft projects. His main management roles have been exploited in charge of the departments of Flight Test Engineering, Flight Simulation, Aircraft Technologies, Aircraft System Integration and Industrial Compensations.

After retirement from industry he has founded the engineering company aerRobotix, one of whose first products is the family of Unmanned Surface Vehicles “CatOne”, patented. He has authored many technical, air-sport oriented and flight-historical publications.

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