Autonomous Surface Craft: prototypes and basic research issues.

Massimo Caccia

***Abstract*— An overview of the prototypes of Autonomous Surface Craft (ASC) developed in the last years is presented in this paper, together with a discussion of main research issues, design trends and technological developments.**

***Index Terms*— marine robotics, autonomous vehicles.**

I. Introduction

This paper will present an overview of the prototypes of autonomous surface craft (ASC) that have been developed, basically for research and military purposes, in the last decade. The fundamental research issues related to the development of ASC and their relationships with unmanned underwater vehicles (UUVs) technology will be discussed.

In section II the basic characteristics of the developed, to the author's knowledge, ASC prototypes will be examined focusing on:

- the family of autonomous vessels developed at MIT, consisting of the fishing trawler-like vehicle ARTEMIS, the catamarans ACES (Autonomous Coastal Exploration System) and AutoCat [1][2], and the kayak SCOUT (Surface Craft for Oceanographic and Undersea Testing) [3];
- the autonomous vessels developed in Europe such as the Measuring Dolphin of the University of Rostock (Germany) [4], the catamaran Delfim [5] and the boat Caravela [6] developed by the DSOR lab of Lisbon IST-ISR, the autonomous catamarans Charlie of CNR-ISSIA Genova (Italy) [7], and Springer, under development at the University of Plymouth (UK) [8];
- the unmanned surface vessels developed for military purposes such as the testbed of the SSC San Diego [9], the QinetiQ Ltd SWIMS systems [10], and the Israeli Protector USV.

Basic research issues will be examined in section III, starting from the definition and identification of practical ASC dynamics models, going to advanced methodologies for control, guidance and mission control. Fundamental legal issues for large scale civil applications of ASC technology will be introduced too.

The different proposed solutions from the point of view of mechanical design, propulsion, power supply and steering systems, will be examined and discussed in section IV. Attention will be paid to the sinergies between the activities of research and development on UUVs and AUVs on the basis of the experience of MIT AUV lab, where research activities on ASC and AUVs (Odyssey class vehicles) converged at the beginning of the new millennium [11], of IST-ISR DSOR lab, where the Delfim ASC was conceived to support the operations of the Infante AUV, and of CNR-ISSIA Genova (former CNR-IAN), where a family of ROVs for robotic research and marine science applications [12] had already been developed. In particular, the benefits deriving from a common software infrastructure, control architecture and mission controller will be outlined.

M. Caccia is with CNR-ISSIA, Via De Marini 6, 16149 Genova, Italy , max@ge.issia.cnr.it

II. Prototypes

A. ASC for education and civil applications in USA

A program for the development of autonomous surface craft has been carried out at MIT Sea Grant College Program from 1993 to 2000. The goal was to develop a light autonomous surface vessel to be used as a tool for educational purposes, as a precision survey platform and as a communication and navigation link to an AUV.

The first developed test platform was ARTEMIS [1], a 1.37 long scale replica of a fishing trawler, originally used for model basin testing, equipped with an electric motor and servo actuated rudder. The vessel, although too small for coastal and open ocean applications, demonstrated the feasibility of automatic heading control and DGPS-based way-point navigation, as well as the possibility of operating autonomously collecting hydrographic data. In particular, the installation of a radio modem allowed human supervisory control of the ASC.

In order to increase the ASC size, endurance and sea keeping performances, a kayak platform was considered, converting a 3m long kayak hull to an ASC and testing it in the Charles River. The resulting design was robust enough for severe sea states, but was not stable enough in roll for the collection of bathymetric data [2]. Thus, a catamaran shape, able to provide enhanced roll stability, greater payload, and redundancy in hull floatation, was selected for ACES (Autonomous Coastal exploration System, developed in 1996-97 [1]. The vessel, constituted by two commercial hulls linked by a main mechanical steel structure, provided by a quick release mechanism for facilitating transport, was equipped with a 3.3 Hp gasoline engine for propulsion, batteries for electrical power for computers, navigation and control system, and a generator for battery recharging. Engine throttle and rudder were actuated by stepper motors. Performances achieved in radio controlled tests were satisfactory, except for the tendency to pitch up at high speed and lack of feedback sensor in the rudder system. Nevertheless developing a reliable starter and gear actuator for the gasoline outboard motor was considered too complex for reliable autonomous operations [2].

A modified version of the catamaran, characterised by a modular fiberglass plastic composite structure and hull-housed batteries, was tested from 1999 [2]. Main changes were made to the power and propulsion systems adopting an electric trolley motor and heavy-duty gel cells. A further upgrade led to the installation of a second motor and the adoption of a motor controller able to drive the motors in reverse. Controlling the motors was dramatically simpler with the electric ones. On the other hand, the temptative of introducing an optical encoder for rudder control based on feedback position sensing failed due to the unreliability of the developed system, and led to the introduction of a steering mechanism based on the differential rotation speed of the two motors. The stabilised platform was renamed Autocat and integrated, from the point of view of human operator interface, mission planning and computer architecture, with the MIT Odyssey class AUVs.

Following this trend, in 2004 four ASC named SCOUT (Surface Craft for Oceanographic and Undersea Testing) were built by the MIT Department of Oceanic Engineering for developing robust control software for cooperating AUVs [3]. The vessels consist of high density polyethylene kayaks equipped with single board computer, lead acid batteries, Wi-Fi and radio modem communication systems. The propulsion is guaranteed by an electric trolling motor with speed regulated by an electronic motor controller. Steering is performed by a modified hobby servo motor that rotates the thruster shaft. PID control based on GPS and compass data is supported by the free software, Linux-based, MOOS operating program [13]. Main applications focused on the implementation of basic systems of autonomous navigation in accordance with the rules of the road (Coast Guard Collision Regulations - COLREGS) [14] and the use of ASC for developing and testing of distributed acoustic navigation algorithms for undersea vehicles [15].

B. European research vessel prototypes

From 1998 to 2000 the German Federal Ministry of Education, Research and Technology sponsored the MESSIN project for the development and testing of the prototype ASC Measuring Dolphin for high accuracy positioning and track guidance and carrying of measuring devices in shallow water [16]. A catamaran-type craft was designed for optimising loading capacity and minimising movement in rough seas. The hulls, built in glass-fibre material, were designed using the SWATH principle. Propulsion and steering were guaranteed by a rudder with counter-rotating propellers on each hull, while a hybrid energy supply system (lead-acid accumulators plus an internal combustion engine for electrical power generation) was developed. Accurate DGPS and compass based navigation, as well as model-based H2 automatic course control, allowed the application of MESSIN for depth and current profile measurements.

In the period 1997-2000, the European Union funded the project ASIMOV (Advanced System Integration for Managing the coordinated operation of robotic Ocean Vehicles) for the development, among other things, of an ASC for supporting a fast direct acoustic communication link with an AUV, and, thus, between the AUV and a support vessel [5]. To this aim, the Instituto Superior Tecnico of Lisbon designed and developed Delfim, a 3.5 m catamaran, characterised by a wing-shaped central structure able to carry acoustic transducers, and propelled by two bladed propellers driven by electrical motors [17]. Navigation, guidance and control, and mission control were managed by on-board resident systems, using sensor data obtained from attitude reference unit, Doppler velocimeter and DGPS. The vessel was also used as a stand-alone unit for collecting bathymetric maps and marine data.

In addition to Delfim, Lisbon IST is developing Caravela [6], a long-range autonomous research vessel, for testing advanced concepts in vehicle/mission control and radar-based obstacle avoidance and demonstrating technologies for the marine science community. Power supply is provided by two diesel generators charging a pack of electrical batteries. Propulsion is guaranteed by two electrical propellers at the stern of the vehicle.

Following the trend of the Multi-Use Microlayer Sampler (MUMS), a radio-controlled catamaran for sea surface microlayer sampling developed in the framework of the Italian National Program of Research in Antarctica (PNRA), in 2002-2004 CNR-ISSIA designed and developed Charlie, an autonomous catamaran, initially designed for supporting sensors and samplers for the study of the sea-air interface in Antarctica, where it was exploited in 2004 [7]. In order to minimise the possibilities of *polluting* the collected samples, the hulls of the electrical-powered vessel were build in glass-fibre varnished with epoxy resin. The original steering system based on the differential revolution rate of two stern propellers was upgraded with a rudder-based system in 2005, and the vehicle is currently used for testing of mission control, and navigation and guidance algorithms, and for evaluating the possibility of using this technology for civil harbour protection in the presence of marine traffic.

A twin-hull, electrically powered ASC Springer, is being developed by the University of Plymouth, UK, for tracing pollutants. The unmanned Springer will be around 3m long and 1.5m high [8].

C. Military USV

After the experience of the rapid development and application of a shallow water influence minesweeping system (SWIMS) by QinetiQ Ltd to support MCM operations in Iraq in 2003, the use of multiple unmanned surface vehicles from mother ships in military operations is now a near-term reality. In particular, the SWIMS system basically consisted in the development of a conversion kit to transform existing Combat Support Boats, already operated by the British Army, in remote controlled vessels [10]. It is worth noting that military applications focus on combinations of human-computer interactions rather than on the development of fully autonomous systems to optimise system performance over a wide range of mission conditions. Since RIBs are usually already operated by navies and can carry larger fuel tanks to increase the endurance of the mission, at present many

military projects are based on this class of vessels as in the case of the Spartan USV programme for the development of a main platform with a set of modular mission payloads.
Another interesting prototype is the USV testbed at SSC San Diego, based on the Bombradier SeaDoo Challenger 2000 and powered by a Mercury 250-hp OptiMax fuel-injected V-6 [9]. Kalman filter and waypoint navigation system developed at SSC San Diego has been transferred to the USV. The requested waypoints are positioned on a graphics control unit. Once the path of waypoints has been created, it is downloaded to the USV which executes the path at the operators command. The path can be stopped, paused and resumed at any time.
As far as the attack role is concerned, the RIB hull platform based Israeli Protector USV, equipped with electro-optic sensors, radar, GPS, inertial navigation system and a stabilised 12.7 mm machine gun is remembered.

III. Research issues

A. Modelling and identification

Model basin and on-board sensor-based identification techniques have been applied to different ASC leading to practical models for speed, steering and track deviation equations.
Manoeuvring tests of the full-scale model of MESSIN at Potsdam model basin conducting zig-zag and turning manouvres led to the identification of linearised course and track models of different order, where functional dependences of the coefficients on the craft's speed were considered. In particular, a second-order course model of Nomoto was selected:

$$\psi(s) = \frac{k_S}{s\left(1 + sT_S\right)}\delta(s) \tag{1}$$

where ψ is the course angle, δ is the rudder angle, k_s and T_S are the turning ability coefficient and the time constant respectively. In particular, identification experiments showed an increasing growth in the turning ability coefficient approximately linear in relation to speed.
In the meantime a fourth-order transfer function for track deviation characterised by a double integral behaviour, a second-order delay, and a second-order differential behaviour, was identified. Experiments showed that both delay and differential constants reduced with the increase of speed.
On-board sensor-based, i.e. GPS and compass, modelling and identification of the Charlie ASC through the execution of suitable maneouvres at sea led to the following practical speed and steering equations

$$\begin{aligned} \hat{m}_u \dot{u} &= \hat{k}_{u^2} u^2 + \hat{k}_{n^2\delta^2} n^2 \delta^2 + n^2 && (2) \\ \hat{I}_r \dot{r} &= \hat{k}_{r|r|} r|r| + n^2 \delta && (3) \end{aligned}$$

where u and r denote surge and yaw speed respectively, and n is the advance propeller revolution rate. The increasing of the turning ability coefficient of the vessel with the speed is confirmed.

B. Guidance and control

As clearly discussed in [17] basic ASC control problems can be divided in control in the horizontal plane, trajectory tracking and path following, and cooperative motion control.

1) Control in the horizontal plane: Operational results showed that in many practical applications a simple P(I)D heading controller is sufficient for guaranteeing satisfactory performance, as in the case of the sea surface microlayer sampling carried out by CNR-ISSIA Charlie [7] and of tests performed with the SCOUT ASC. Anyway, more advanced control techniques have been evaluated. For instance, a dual nested loop H2 controller, where the inner yaw rate loop guarantees stability, robustness and disturbance rejection, and the outer position one improves follow-up performance, has been satisfactorily applied to MESSIN course control. A more general approach has been proposed in [17], where gain-scheduling controllers, interpolating the parameters of linear controllers designed at different forward speeds, are proposed. In particular, the H_∞ performance criterion used for designing the linear controllers allows a unified treatment of control and motion estimation, performed through complementary filter techniques, in a frequency domain based approach [18].

2) Trajectory tracking and path following: Trajectory tracking is defined as requiring the vessel to follow a time-parameterised reference curve, i.e. to be in specific points at specific instants of time. This, in the case of vehicles characterised by a preferred direction of motion and in presence of external disturbance, such as waves, sea current and wind, typically leads to high actuator activity and jerky motions. Thus, in practical applications, temporal constraints are usually relaxed, maintaining only the forward vehicle speed reference, and the so-called path following problem is faced, i.e. the vehicle has to follow a planar path without temporal constraints.
A number of path following techniques has been proposed basically originated by ideas developed for wheeled robots. Path following algorithms have to define, compute and reduce to zero the distance between the vehicle and the path as well as the angle between the vessel speed and the tangent to the path. A solution based on gain-scheduling control theory and the linearisation of a generalised error vector about trimming paths has been proposed in [17] and implemented and run on the Delfim ASC. Currently, research focuses on the development of nonlinear control design methods able to guarantee stability globally and not only locally as in the above-mentioned approach. In particular, backstepping control design methodologies and *follow-the-rabbit* path following techniques have been combined [19][20], but experimental validation has not been performed yet to the author's knowledge. The role of the guidance system, computing all the reference signals needed to make the physical system autonomous, as weel as the need of developing the guidance theory at the kinematic level in order to make it as general as possible, are discussed in [21], where a parameter adaptation technique is proposed to introduce

integral action for environmental disturbance compensation. It is worth noting that, in many practical applications, requiring the vessel roughly navigating through a sequence of way-points, conventional line-of-sight guidance, based on directing the vehicle prow towards the goal at each time, provides satisfactorily performance, in particular, from the point of view of motion smoothness and actuator activity.

3) Cooperative motion control: The use of ASC as *light*, in terms of logistic requirements, testbeds for the study of cooperative and collaborative marine robot behaviour is pointed out in [3]. In addition, one of the most interesting ASC applications concerns their use as communication relay for a companion AUV, making clear the need of developing coordinated motion control techniques. In particular, the problem of a *leader* and a *follower* vehicle following two parallel paths has been studied in relation to the ASIMOV project, where the Infante AUV and Delfim ASC have to navigate remaining on the same vertical in order to guarantee high bandwidth acoustic communications. In particular, a kind of extension of the *follow-the-rabbit* strategy to the coordinated path following problem is proposed in [22]. The *leader* follows its reference path at the desired speed, while the *follower* executes a path following algorithm, controlling its speed according to a measured generalised *along-path distance* between the two vessels. Only simulation results are available for this methodology, relying on controllers designed in the basis of Lyapunov theory and backstepping techniques.

C. Mission control

Mission planning and control of autonomous marine vehicles is basically limited to the definition of multiple setpoint and/or multi-waypoint sequences and of a few emergency actions, e.g. *abort* and *stop*. The MESSIN system is just a bit more complicated: the planned path is a combination of basic track units constituted by straight lines with defaulted length and direction and circular arcs with defaulted radius [16]. In this context, a MATLAB-based Mission Planner has been developed at MIT AUV Lab to generate syntactically correct mission files through a graphical interface [11]. Intuitive human-machine interfaces for mission design and execution have also been developed for the Infante AUV and Delfim ASC. In this case, mission control system design and implementation relies on the concept of *vehicle primitive*, i.e. parameterised specification of elementary operations, which can be suitably combined to form mission procedures and, in a recursive way, mission programs. The execution of mission programs, i.e. the scheduling of vehicle primitives, is supervised by a Petri net based mission controller [17][23]. A Petri net-based approach has also been adopted for the development of the Charlie2005 ASC execution control level [24], able to guarantee in real-time the safety of the system by checking the commands sent to the functional level preventing it from entering in an unconsistent condition with respect to a model of desirable or undesirable states.

It is worth noting that the possibility for the operator to online change the way-point sequence is a basic requirement in many human supervised applications, and that local replanning of way-points in response to sensor data have not been integrated in any ASC system yet [10].

D. Legal issues

With the exception of military applications, when operations in an area forbidden to civil traffic are the rule, autonomous/unmanned marine vehicles will have to operate routinely with little or no human involvement into navigable waters, but maritime regulations and laws have not been written to support unmanned vessels. For instance, an unmanned vessel at sea may be taken by any claimer. Thus, at this stage, there are no regulations for the operations, type-approval, insurance responsibilities, and so on, of this kind of vehicles. The result is that institutions usually operating unmanned vehicles at sea, such as the French IFREMER, to safeguard themselves from insurance and penal risks can only establish an internal dogma for their AUVs stating that surfacing is allowed only if acoustic communication is possible, i.e. a ship can guarantee there are no possible colliding vessels [25]. In addition, reliable obstacle avoidance systems for ASC have not been demonstrated yet. In this direction, research carried out at MIT and Naval Undersea Warfare Center (USA) on the implementation of an ASC collision avoidance system in accordance with the rules of the road prescribed by the COLREGS is very interesting [14]. The proposed approach relies on the integration of a multi-objective optimisation, interval programming, method in a behavior-based control framework. Preliminary experiments have been carried out with a couple of SCOUT ASC exchanging information about their position, heading and speed.

IV. Discussion

As shown in section II a number of prototype ASC have been developed for civil, i.e. (semi-)autonomous bathymetry and water sampling, and military applications, i.e. mine counter measures and coastal surveillance, in the last years. If, on one side, *naive* approaches, where design and development was performed by graduate students, led to very interesting demonstrations of proof of concept and limited applications, on the other hand, industrial research and development gave, in particular with the at-field demonstration of USV effectiveness in military applications such as the MCM application of the SWIMS system, a strong impulse to the development of ASC technology and its transfer to civil operations. Nevertheless, the development of this class of robotic vehicles is in a pioneer stage, and the choice between different approaches in basic design issues and trends is still open:

- the hull shaped vehicle, which optimises the easiness of mounting and the loading capacity of different payloads minimising movement in rough sea, is usually preferred by research developers, while, in the military field, RIBs are preferred due to their diffusion as standard vessels for naval operations and their capability in carrying on larger fuel tanks;

- electrical power supply is preferred for environmental sampling applications, where the constraint of not polluting the operating area is mandatory, while, when long missions have to be performed, e.g. in the case of coastal surveillance or MCM operations, gasoline propulsion is more practical; the use of hydrogen fuel cells, already adopted by AUVs [26], is not known by the author in the ASC field;
- the design and development of new vehicles is typical of research institutions, while the needs of low cost development and easy transfer to the end-user motivated, even in military applications, the development of *conversion kits* to transform existing vessels in remoted controlled ones.
- the goal of fully autonomous operations is the pole star of civil and research applications, while military applications see in remote controlled vessels the solution, through suitable human-computer interactions, to optimise system performances in many different mission conditions.

Common trends are the modularity and easiness of transport of ASC, since logistical constraints are usually very narrow, as well as the introduction of constructive materials such as fibre-glass in order to built robust and light hulls.

The convergence, in a number of research institutions such as MIT Cambridge, IST-ISR Lisbon, and CNR-ISSIA Genova, of USV and unmanned underwater vehicles (UUV) research deserves a special mention. In addition to the perspective goal of cooperative ASC and AUV operations, with ASC acting as communication relays with companion AUVs, the common development of different marine robots is leading to the development of generic hardware and software architectures, guidance algorithms, mission control systems, and human-computer interfaces for mission supervision and design. Examples are given by: *i*) the platform, based on commercial-off-the-shelf hardware and free software, and by the control architecture developed at CNR-ISSIA for the Romeo ROV and the Charlie ASC [27]; *ii*) the use of the CORAL mission control system for the Infante AUV and the Delfim ASC; *iii*) the common hardware architecture and mission design tools used for MIT AUVs and ASC. It is worth noting that, due to their higher easiness of use, ASC are giving a strong impulse to fast experimentation and development of guidance and cooperative control algorithms.

The main limitation to an extended use of ASC technology for civil applications, i.e. in areas not restricted to maritime traffic, relies, in the author's opinion, in the lack, at the current state-of-the-art, of a reliable methodology for obstacle avoidance. If the first basic steps in the direction of implementing collision avoidance strategies according to the rules of the road have being taken [14], the bottleneck is yet in the availability of effective and reliable obstacle detection sensors even if preliminary work is being carried out in the military field such as in the temptative of integrating a radar and artificial vision devices on the SSC San Diego [9]. Laser-gated intensified CCD (LGICCD) could represent a dramatic improvement in obstacle detection at sea.

V. Conclusions

This paper presented an overview of the recently developed ASC for civil, research and military applications. Basic research issues have been discussed, summarising fundamental results and open problems. In the next years, the at-field experimentation of obstacle detection devices and advanced guidance techniques, able to drive a robotic vehicle in the presence of traffic according to common maritime laws, might lead to an extended use of this class of vessels for civil applications such as coastal surveillance, environmental monitoring and automated bathymetry.

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