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Underwater Robots Part I: Current Systems and Problem Pose

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This paper constitutes the first part of a general overview of underwater robotics. The second part is titled: Underwater *Robots Part II: existing solutions and open issues*.

1. Introduction

The ocean covers about 71% of the earth and each year of research and exploitation shows our ignorance and the difficulties we have in using this primordial and generous environment. Happily, this mysterious element has generated an unquenchable curiosity that pushed people like *Le Prieur*, *Cousteau*, *Piccard*, *Walsh*, and many others, to accomplish what was considered as impossible.

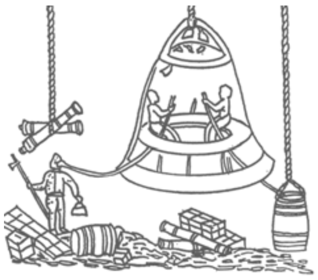

Fig. 1. Halley's diving bell, late 17th century. Weighted barrels of air replenished the bell's atmosphere. (U.S. Navy Diving Manual).

In 1531, *Guglielmo de Lorena* dived on two of *Caligula*'s sunken galleys using a diving bell on a design by *Leonardo da Vinci*. In 1776 *David Brushnell* invented the *Turtle*, the first submarine to attack a surface vessel, starting the long story of underwater warfare. In 1933, *Yves Le Prieur* created the first constant-flow open-circuit breathing set, allowing for individual and light underwater voyages. In 1960, *Jacques Piccard* and Lt. *Don Walsh* touched the deepest point in the sea in the Mariana Trench (10916 m.) onboard the bathyscaphe *Trieste*, and confirmed that life is everywhere[1]. All these people demonstrated the feasibility of underwater intervention and circumvented the set of technical obstacles of such missions. Their first objective was to design system

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[1] URL : http://www.aqualifediving.com/History7.htm

Source: Mobile Robots Towards New Applications, ISBN 3-86611-314-5, Edited by Aleksandar Lazinica, pp. 784, ARS/plV, Germany, December 2006

guaranteeing the preservation of the operator's health. Removing humans from the immerged system reduces the critical contraints, but poses the problem of the guaranteeing the autonomy of the vehicle, and its effective capabilities.

Navies were the first to show their interest in developing unmanned marine systems. In 1866, the Austrian Navy asked *Robert Whitehead* to develop a new weapon for warship. He demonstrated the efficiency of a self-propelled floating device, carrying an offensive payload[2]. The torpedo vehicle class was born. The missions in which this vehicle was involved did not require any sophisticated control or navigation systems. This system was autonomous, as a bullet could be.

In fact, the first Autonomous Underwater Vehicles (AUVs) were developed during the 60s and 70s with the *SPURV* (Self-Propelled Underwater Research Vehicle, USA) and the *Epaulard* (France). *SPURV* displaced 480 kg, and could operate at 2.2 m/s for 5.5 hours at depths to 3 km. The vehicle was acoustically controlled from the surface and could autonomously run at a constant pressure, sea saw between two depths, or climb and dive at up to 50 degrees. Researchers used the vehicle to make Conductivity and Temperature measurements along isobaric lines in support of internal wave modeling (Ewart, 1976). *Epaulard* was 3 tons and could operate by depth of 6000 meters during 7 hours, with a velocity of around 1 knot. An Ultra short Base Line (USBL) allowed for uploading orders and positioning relative to the mother ship (IOC UNESCO, 1985).

These systems were the forerunners of the over 2400 unhabitated undersea vehicles, presently in regular operation worldwide (O.N.a. T.S., 1998 and Danson, 2002).

The paper is organized as follows. The section 2 proposes to overview the current users that drive the development of underwater systems. Section 3 states the technological and theoretical demands in order to complete the desired autonomous operations. Section 4 presents the notation that will be used throughout the paper. Section 5 introduces the current systems in use, detailing their properties from the robotics point of view. Section 6 lists the desired performances in order to achieve the missions in a reliable way. Finally, Section 7 concludes this paper and Section 8 presents the references used in this paper.

2. Forces in project development

The rapidity in the development of robust systems routinely operated, or the design of new solutions, is strongly influenced by the investors involved. Designing an underwater system is an expensive task, but results in a cost-effective tool. In the commercial sector of the hydrographic industry, the UUV is already making a significant impact. Remotely Operated Vehicles (ROVs) and AUVs are currently routinely deployed for intervention on immerged structures or surveying wide range areas. However, private industry is not the largest sector that could, in the future, take advantage of these new technologies. Of the 1400 survey and research vessels in service world-wide, some 25% are engaged in missions related to public utility. Their work is principally focused towards charting navigation, for military and defence applications, for environmental assessments, monitoring, and for national economic application. Much of the world's marine data acquisition effort is concentrated within this range of activities; therefore much of the early development of AUVs was funded by the public sector (Danson, 2002).

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[2] URL : http://www.spartacus.schoolnet.co.uk/FWWwhitehead.htm

2.1 The industry

The biggest private users are the **Gas and Oil** companies that represent 58% of the offshore industry. 83% of its activity is taking place in water depths less than 300m, while the remainder is focused in the deep-water areas. As oil demand is increasing, this ratio will change with exploitation moving into ever-deeper waters (Whitcomb, 2000). Most of the currently used vehicles are Remotely Operated Vehicles (ROVs) designed to perform subsea inspection, construction, and repair operations. A ROV is teleoperated through an umbilical link, real-time connected to the operator, and has to be able to autonomously reach a desired location, search and lock onto a target on which the operator will perform manipulation: drilling, welding, configuring wellhead valve, plugging cables AUVs are involved in pipe inspection, terrain bathymetry and acoustic sediment analysis for pipeline installation and prospection for new oil and gas fields.

Fig. 2. Underwater crawler vehicle being launched, National Institute of Ocean Technology, India.

Non-living resource extraction is a major challenge for the next decade. For example, it is estimated that there are about 2,000 billion tons of manganese nodules on the floor of the Pacific Ocean near the Hawaiian Islands (Yuh, 2000), waiting for exploitation by **Ocean Mining** industries. The need is mostly similar to the oil and gas companies, except that the raw material dispersion requires the collector to move. This is a major problem and the actual technology does not yet provide a cost-effective solution that could allow for a generalized commercial exploitation. The present solutions propose heavy caterpillar-vehicles, teleoperated from the mother ship. This represents 10% of the global offshore industrial activity, and ocean mining is expected to be a growth area as the technologies are developed to harvest these products from the sea (Danson, 2002).

Telecomunication is another sector of the offshore industry that is evolving rapidly. Its 16% share of activities is on the increase as the demand grows for secure, robust and high-capacity telecommunication network to link the nations of the world. Cable-laying and inspection requires AUVs with a specific control of payload-variation effects. ROVs are also used for cable repair, (Hartley & Butler, 1991).

Other industrial sectors of the offshore industry are intended to grow rapidly in the near future: surface transportation (Caravella Consortium, 1999), fisheries assistance (The Ifremer *Vital* Campaign[3]), support platform for divers…

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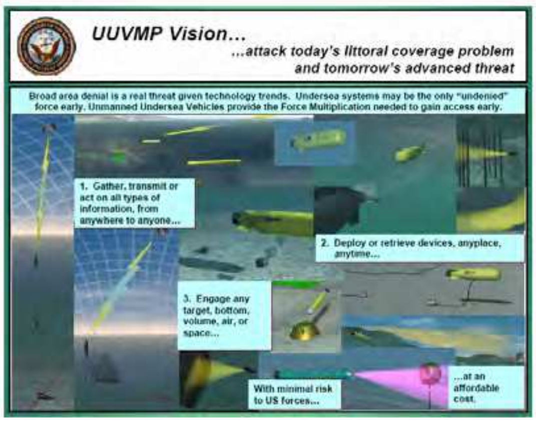
[3] http://www.ifremer.fr/vital/accueil.html

2.2 The Navy

Unmanned Underwater Vehicles are already in action in most of the military conflicts around the world. The 2004 US-Navy Unmanned Undersea Vehicle Master Plan (UUV Master Plan[4], 2004) specifies the use of unmanned vehicles as force multipliers and risk reduction agents for the Navy of the future and postulates a host of specific missions for which UUVs are uniquely qualified. The long-term UUV vision is to have the capability to: 1) deploy or retrieve devices, 2) gather, transmit, or act on all types of information, and 3) engage bottom, volume, surface, air or land targets (See Figure 3).

According to the 2004 UUV Master plan, nine high-priority UUV missions have been defined, and, in priority order, are:



UUVMP Vision...

...attack today's littoral coverage problem and tomorrow's advanced threat

Broad area denial is a real threat given technology trends. Undersea systems may be the only "undenied" force early. Unmanned Undersea Vehicles provide the Force Multiplication needed to gain access early.

1. Gather, transmit or act on all types of information, from anywhere to anyone...

2. Deploy or retrieve devices, anyplace, anytime...

3. Engage any target, bottom, volume, air, or space...

With minimal risk to US forces...

...at an affordable cost.

Fig. 3. the UUV Master Plan Vision, from (UUV Master Plan[4], 2004).

- Intelligence, Surveillance, and Reconnaissance
- Mine Countermeasures
- Anti-Submarine Warfare
- Inspection / Identification
- Oceanography
- Communication / Navigation Network Nodes
- Payload Delivery
- Information Operations
- Time Critical Strike

Recently, European Navies have opened invitation to tender on the subject of search and neutralize the remaining immerged explosive systems that are populating navigation routes and Atlantic coast since the 2nd World War. This type of mission requires a global survey to locate and identity suspicious objects, using small AUVs equipped with Side Scan Sonar and/or Electronically Pencil Beam Sonar. The problem of automatically identifying a possibly-dangerous-object in acoustic images is an open issue that is occupying a large number of robotic engineers. On a second level, object destruction is a dangerous and specific task that requires vehicles able to locate and approach the object to be neutralized. Atlas Electronik (Germany) and ECA (France) are proposing the *SeaFox* and *Caster* expandable vehicles, using teleoperation for the final approach and destructive phase.

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[4] www.orionocean.org/PDFs/UUV_USNavy.pdf

2.3 Civil Protection

Fig. 4. black-box recovery using ROV, form U.S. Dept. of Defence.

The growth in world trade results in a massive increase in naval traffic. The Coast Guard intervention capacity has not followed economic expansion. The variety and unique nature of Coast Guard mission adds a high degree of complexity to technological solutions.

Port Safety and security is a mission that involves many operational aspects. This implies an environmental responsibility for ports including shore side facilities. S.T. Tripp, in (Tripp, 2001), addresses US Coast Guard UUVs needs during their specific missions.

- Verifying that ships in port are seaworthy: ship hull inspection and internal inspection. ROVs are performing inspections that require a highly-precise relative positioning with respect to the hull.
- Verifying that shore facilities are operating safely: ensuring that all channels are free of obstacle and correctly and adequately marked. AUVs are well suited for this kind of missions, with the condition that the navigation system addresses collision avoidance, in areas where there is high boat traffic.
- Analysing and reacting to mystery sheen detection: mystery sheen is oil- or gas-like colouring in the water that has been spotted and reported to authorities. The source of these sheens typically is bilge pumped from a vessel in port. AUVs are tasked with sampling the sheen, with the condition that it is equipped with bio-chemical sensors able to surely identify the pollutant. The rapid reaction to the confirmation of the presence of a polluting slick could avoid dramatic oil or chemical tides. A fleet of Autonomous Surface Crafts (ASCs) are envisaged to be used, as described in (Jimenez *et al.*, 2006), towing a boom in order to obtain a good confinement of the spill over.
- Navigation aides: ensure the harbour entrance with autonomous surface scouts and determine the seasonal change in traffic. ASC are under development in many research labs, who are using these surface platforms to test and validate the algorithms that will be used on underwater systems. The problem of designing an autonomous tugboat implies being able to fuse many different aspect of the problem, including the control of traction effort. This is not an easy problem to solve.

Law Enforcement concerns fishing restrictions and identification of polluters and pollutants. This involves detection, identification, tracking and interdiction of suspect vessels. AUVs coupled with various technologies to detect illegal activity and/or sort/classify targets of interest will provide the cost-effective, 24/7 platform to cover large restricted areas effectively. Recording a law violation implies to obtain a 'prosecutable evidence'. Prosecutable evidence requires quality information of proven accuracy, reliability, and authentication. Assuming the AUV could obtain prosecutable evidence, the system must communicate the certificated data to an interested party, which requires remote transmission of data such as video, high-definition still picture, recordings, and position data. Moreover, the AUV must get to a position to use these capabilities, which requires performing a series of complex maneuvers. These maneuvers include detecting a target, moving to a position where that AUV could gather the required information, providing an alert or direct data transmission, and perhaps relocating to a preferred download location. Because of the size of many restricted areas, the multiple AUV option would likely be the most practical option. The AUVs must be networked not only each other but also with other Coast Guard assets (planes, helicopters, ships and small boats).

Fig. 5. The 'Prestige' tanker in distress, from CEDRE.

A rapid **Environmental Assessment** provides deployed forces with environmental information in coastal waters in a specified time frame. The widespread observation and monitoring of ecological and environmental systems is of increasing interest in order to improve the management of scarce resources and also dramatically improve our ability to react to major pollution and natural cataclysms. The Ifremer institute is underlying the absolute need for an ocean monitoring network to keep watch over geophysical, biological and chemical phenomena, in order to detect the imminent occurrence of a geophysical cataclysm, like a tsunami[5]. The Autonomous Benthic Explorer (ABE) is an AUV designed to address the need for obtaining spatial coverage of a defined area, over a period of many months. ABE is intended to operate from a near bottom mooring from which it will detach itself periodically and fly or crawl pre-programmed surveys (Yoerger *et al.*, 2000). The data so obtained can be transmitted through an umbilical link connecting the surface to the moored docking bay, onto which the ABE will reattach and shut down for power conservation until the next survey.

Arctic survey is considered as an issue of growing importance. The status of the circumpolar regions is a highly sensitive indicator of forerunner elements in global climate change. 2007-2008 is planned to be the third International Polar Year (IPY, the previous ones were held in 1882-83 and 1932-33), and will be an intense, internationally coordinated campaign of polar observations, research, and analysis that will further our understanding of physical and social processes in the polar regions, examine their globally-connected role

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[5] http://www.ifremer.fr/com/actualites/tsunami.htm

in the climate system, and establish research infrastructure for the future (NSF, 2004). In this context, new underwater systems are currently in development, and will take place in the future Artic Observing Network. Autonomous Sub-ice survey allows for long mission time and range with no risk to human life. Nevertheless, a sub-icecap AUV navigation is a particular and complex situation, where the impossibility to reach the surface imposes a highly robust system, with restricted communication media. Numerous vehicles have been lost (and sometimes recovered) in such operating conditions. Climate history is studied on the icecap fringe, using ROVs, sampling ice at various depths. This application requires a highly precise relative positioning, with station keeping capabilities in an environment where external disturbances may be strong (Caccia *et al.*, 2000).

The previous items are of course not exhaustive, and we can list other civilian applications involving underwater systems: **Nuclear** Power plant pool and **dam inspection** and **Black-box recovery**. This last item is of major interest, since the increase in passenger transportation traffic will unfortunately be followed by a mounting number of crashes. This is a very complex mission that implies the consideration of many different situations. For a complete description of the problem, please refer to (Weiss *et al.*, 2003).

2.4 Scientific

The oceans are still, for the most part, a mystery. For example, only for the year 2004, 106 new fish species have been discovered[6]. Scientific missions involving UUVS are numerous, and the duty of underwater robotics is to reply to the scientific demand in terms of data collection and acquisition. In the sequel, we list a series of successful robotics solutions in different fields.

The Australian Institute of Marine Sciences is carrying out a survey project for **Reef Management**, designed to provide long-term quantitative data about corals, algae and marine life over the extent of the Great Barrier Reef. These data are for studies of abundance and population change in selected organisms on a large geographic scale. The reef surveillance task, as it is currently defined for the tethered *Oberon* vehicle, consists primarily of following an assigned path while maintaining a fixed altitude above the reef and avoiding collisions. Independent behaviours and arbiters, using decoupled controllers, have been developed as a modular means of accomplishing these various sub-tasks. For example, two behaviours have been developed for the path following aspect of the task; the first behaviour uses video input to track a rope laid out along the coral, while the second behaviour uses sonar to detect passive beacons. A centralized arbiter is then responsible for combining the behaviours' votes to generate controller commands (Rosenblatt *et al.*, 2000).

The protection of biodiversity requires a regular survey of well-chosen protected areas. Autonomous **Marine Reserve Habitat Mapping** allows for acquiring data with UUVs in order to estimate the health status of the protected zone. For example, marine biologists are watching closely the biological invasion of the algae *Caulerpa Taxifolia*, which is spreading over the Mediterranean Sea since 1984, from a common aquarium strain[7]. It is currently infesting tens of thousands of acres in the Mediterranean Sea and has now been found in two coastal water bodies in southern California[8]. Autonomously estimating the expansion of this parasite requires for the UUV to be able to extract from video images the border of this

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[6] http://www.delaplanete.org/Renseignements-environnementaux,193.html

[7] http://www.ifremer.fr/lerlr/caulerpa.htm

[8] http://swr.nmfs.noaa.gov/hcd/caulerpa/factsheet203.htm

seaweed field despite illumination problems, and follow this border in order to circumvent the colonized regions (ICES, 2006 and Rolfes & Rendas, 2004).

Hydrothermal vent study interests a number of scientists. These **Black Smokers** are populated with specific ecosystems that may contain a large number of endemic species and provide constraints on the genetics and evolution of seafloor organisms. These particular systems are generally very deep and their analysis requires the use of ROVs or highly-manoeuvrable ABE to survey and sample the zone (Yoerger and Kelley, 2000).

2005 was the international year of water. Many conferences and workshops have underlined the necessity for efficient and long term **Water Resource Management**. This implies a better management of existing resources, but also investigates the use of alternative water resources such as karst submarine springs. This is the aim of the European MEDITATE sixth framework programme[9], for which the LIRMM will deploy the Taipan 2 AUV (Lapierre & Jouvencel, 2006) to carry out physico-chemical water sampling, in order to detect and authorize for public exploitation these underwater fresh water plumes.

Another aspect of robotics application is the development of **Biologically Inspired** systems. This research is motivated by the intuition that natural solutions exhibit better performance than engineering designed systems. Indeed fishes are able to reach incredible records in terms of acceleration (250 $m.s^{-2}$ - northern pike fish - *Esox Lucieus*, Blake, 2004), velocity (46.3km/h, common eel - *Anguilla Anguilla*, Langdon, 2004 ; 108 km/h, Sailfish - *Istiophorus platypterus*, [10]), turning radius (0.055 turning radius / body lengh, Knifefish – *Xenomystus nigri*, Domenici, 1997) and propulsion (520 horsepower, Blue Whale, *Balaenoptera musculus*, Joseph *et al*., 1988). Thus, many robotic research labs have developed prototypes inspired by tuna-fish (Pike Robot Tuna[11]), eel-like robot (ROBEA Project[12]) Manta ray (Manta Project[13]) or even Turtle (Aqua Project[14]). The first particularity of these systems is the lack of propulsion system. The thrust is generated by internal body-shape deformations. Controlling the movement of such systems implies fusing the requirements coming from the thrust generation and the control of the system trajectory. This considerable problem is still an open issue. Recently, propeller-free aeronautical-inspired systems have demonstrated high efficiency in terms of power consumption and range of action. These are the **Underwater Gliders**. The thrust is generated using an active buoyancy system (ballast) that creates a vertical force and makes the vehicle fly through the water column. A fleet of *Slocum Gliders* has recently been successfully deployed in the scope of the development of the New Jersey Shelf Observing System (Creed *et al*., 2002).

3. The needs

3.1 Hydrodynamic Modelling and Naval Architecture

Designing an efficient underwater system requires a 'precise enough' knowledge of the underwater environment and the ability to model and predict the physical constraints the system will undergo during its mission. Borrowing from classic mechanics and

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[9] http://www.meditate.hacettepe.edu.tr/partner/part_third.htm

[10] http://www.elasmo-research.org/education/topics/r_haulin'_bass.htm

[11] http://web.mit.edu/towtank/www/Pike/pike.html

[12] http://www.irccyn.ec-nantes.fr/hebergement/ROBEA/

[13] http://www.imasy.or.jp/~imae/kagaku/

[14] http://www.aquarobot.net:8080/AQUA/

approximated solutions of Navier-Stockes' equation, the modelling process allows for estimating the forces and torques applied on the vehicle, due to its interaction with the fluid and its actuation. This has of course a significant impact on the choice of the vehicle's shape and its actuation; a long-range system will be profiled according to the need to minimize the fluid effect in reaction of the system movement, while a system for pose-stabilisation will be designed to exhibit holonomic behaviour and isotropy in its capacity to react to external disturbances (Pierrot *et al.*, 1998). Moreover, capturing in a significant manner the properties of movement of underactuated systems (case of the AUV) implies a dynamic modelling that injects nonlinearities and imposes to consider this model in the control design. A curious trade-off between precision of modelling and model controllability appears. The Society of Naval Architects and Marine Engineer is publishing a set of books of reference that are resuming the actual engineering knowledge in this field (Lewis, 1988).

3.2 Positioning

One of the most difficult questions to answer is the same since the origin of marine navigation, and concerns Positioning. This implies the ability for the system to locate itself on a geo-referenced map, and to estimate the relative position of the mission target. In air (aerial, terrestrial or surface), the geo-referenced positioning is facilitated by the use of GPS information. Underwater, this is no longer valid, satellites connection stopping at sea-surface. Different solutions are currently used. First, without GPS information, the classic dead-reckoning navigation is using proprioceptive sensors information and double-integrate acceleration meaurements to obtain an estimation of the displacement. This method is error-cumulative and implies a temporal drift in the precision of the estimation. Different strategies are used in order to upper-bound this drift.

- The system can regularly reach the sea-surface in order to access to GPS information, and recalibrate its position. This solution is energy-consuming.
- Buoys, immerged calibrated acoustic devices or even ASC systems can relay GPS information to the UUV, on condition that the horizontal relative distance geo-referenced-acoustic-device / UUV can be precisely estimated, (Pilbrow *et al.*, 2002) , (Gomes *et al.*, 2000) and (Vaganay *et al.*, 1996).
- A recent solution, named Simultaneous Localisation And Mapping (SLAM, Leonard *et al.*, 2002) is demonstrating interesting performances. This terrain-based method uses visible (sensitive) land marks to build an egocentric map onto which all the *a priori* terrain-knowledge is projected. Then, revisiting a previously mapped region allows for associating the current sensor data with previously spotted land mark, thus bounding the position estimation error.
- The relative position with respect to the mission target can be estimated using an appropriate sensor, without requiring a geo-referencing. This is called sensor-based navigation, and may require heavy data treatment such as feature extraction from image (video or acoustic).

Moreover, data collected for later analysis can be meaningful if and only if, the precise location of the vehicle is known at the time the information is recorded. Then, a reliable UUV must be able to constantly determine its global position, and if possible, within certain certified error.

3.3 Motion Control

As the previous chapter stated, the UUVs are tasked with different objectives, which require different strategies of Motion Control.

- Point stabilizing: also called station-keeping, the goal is to stabilize the vehicle at a given point, with a given orientation, despite external disturbances. ROVs are well suited for this type of application, taking advantage of the holonomic and isotropic design that allows them to apply forces and torques on all the 6 degrees of freedom. Nevertheless, point stabilization presents a true theoretical challenge when the vehicle has nonholonomic (or non integrable) constraints, since there is no smooth (or even continuous) state feedback law that will do the job (Brockett, 1983).
- Manipulating: the manipulation task implies many different aspects and requires decision capabilities that, for the moment, impose an efficient communication link with an operator. Assuming that the platform (the arm carrier) is able to maintain its pose - despite disturbances coming from sea current or umbilical and manipulator dynamic coupling effect – the teleoperation task requires the position control of the manipulator and the force control of the end-effector (tool). Recent applications using Intervention Autonomous Underwater Vehicle (IAUV), have demonstrated the feasibility of an autonomous underwater manipulation, controlled via an acoustic link (Badica *et al.*, 2004), thus removing the parasite effects of the umbilical cable. The underwater condition imposes a very low rate of communication (few bits/second) and the teleoperation with delays is an opened issue (Fraisse *et al.*, 2003).
- Trajectory-tracking: the vehicle is required to track a time-parameterized reference. The trajectory-tracking problem for fully actuated vehicle is now well understood. However, in the case of underactuated systems, that is when the vehicle has less actuator than state variables to be tracked, the problem is still a very active topic of research (Encarnação & Pascoal, 2002).
- Path-following: the vehicle is required to converge to and follow a path, without temporal specifications. The underlying assumption in path-following control is that the vehicle's forward speed tracks a desired speed profile, while the controller acts on the vehicle orientation to drive it to the path. Typically, smoother convergence to a path is achieved, when compared to trajectory tracking control laws, and the control signals are less likely pushed to saturation (Lapierre[a] & Soetanto, 2006) and (Lapierre[b] *et al.*, 2003).
- Obstacle-avoidance: assuming that the UUV is equipped with proximity sensors able to detect the presence of an obstacle, obstacle detection can trigger many different reactions. This could be considered as a critical uncharted event and induces the system to stand by, waiting for operator orders. The imminent occurrence of a collision can trigger a mid-level reaction and proceed to a path replanning, or directly impact at the control level (Lapierre[a] *et al.*, 2006).

3.4 Mission Control

The previous section described various type of missions in which UUVs are deployed with different required degree of autonomy. But, even in a very simple mission contains different tasks to be sequentially executed, and the possibility to encounter uncharted critical situations has to be considered. The concatenation of these different tasks, or sub-objectives, and the reaction to uncharted events is in charge of the Mission Control system (Oliveira *et al.*, 1996). The transition between basic tasks is not a trivial problem, since each task may require its own control law, navigation system, possibly interfering sensors, security manager… Then, each transition should be preceded with a global check of the system status before authorizing the transition to proceed. Moreover, the occurrence of an uncharted event has to produce a rapid system response. The mission control system is generally described using Petri Nets. Moreover, this tool allows for verifying system properties as determinism, and reactivity. The mission control aggregates low-level robotic tasks into mid-level behaviours, and organizes this collection of behaviour in order to complete the mission objectives, degrade them or even abort the mission according to the criticity of the uncharted events the system has met.

Another important element, which could be considered as a part of the mission control system, is the **Man/Machine Interface**. This system is interfacing the machine with the operator, and is tasked with the mission programming – in terms that belong to the common end-user vocabulary – the mission monitoring – dependant of the communication media – and the results display and mission replay.

3.5 Software Architecture

Consisting of computers, micro-controllers, electronic interfaces and potentially interfering sensors, the system is conducted by the Software Architecture. This is the collection of the computer processes that has to be choreographed in order to realize, in a deterministic way, the set of robotic tasks that the system is nominally able to perform. The determinism implies to guarantee all the processes execution time and the coherence of the recruitment of the system's components. Acoustic emitters are of general use underwater and induce powerful insonification that might interfere with an inappropriate receiver. This problem is solved with a precise scheduling of the acoustic devices recruitment, cadenced by a deterministic and real-time task manager.

3.6 Hardware Architecture

The Hardware Architecture is the technological target onto which the previous software will be uploaded. This architecture has also to exhibit a deterministic behaviour, which impacts on technological choices. Most of the actual systems are over-dimensioned, 'statistically' guaranteeing the system performances, but energy-consuming. Recent applications based on the co-design of the software and hardware architectures are currently working, with deterministic guarantee without requiring over-dimensioning.

3.7 Control of Flotilla

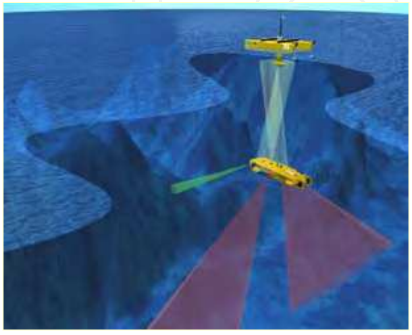

Fig. 6. The ASIMOV project, from ISR, Lisbon, Portugal.

Recently, there has been a surge interest in the problem of Coordinated Motion Control of Fleets of Autonomous Vehicles. The work reported in the literature addresses a large class of challenging problems that include, among others, leader-following, formation flying and control of the centre (or radius of dispersion) of swarms of vehicles. An interesting aspect of this problem concerns the control of flotilla composed by dynamically heterogeneous vehicles. Consider the application of the *ASIMOV* (Gomes *et al.*, 2000) Project where an ASC is required to follow a desired path, and an AUV operating at fixed depth is required to follow similar horizontal path (vertically shifted) while tracking the ASC motion along the original path. In this example the AUV acts as a mobile sensor suite to acquire scientific data, while the ASC plays the role of a fast communication relay between the AUV and the mother-ship and GPS satellites' net. The ASC effectively explores the fact that high data rate underwater communications can best be achieved if the emitter and receiver are aligned along the same vertical line. Notice that communication bandwidth is guaranteed if the vehicles are vertically aligned, within an upper-bounded limit defined by the emitting and receiving cones. This upper-bounded limit imposes a maximum horizontal relative positioning error, underneath which the communication is effective (Lapierre^c *et al.*, 2003). The, the control objective is to guarantee this condition on the maximum relative position allowed.

4. Notation and Definitions

4.1 Notation

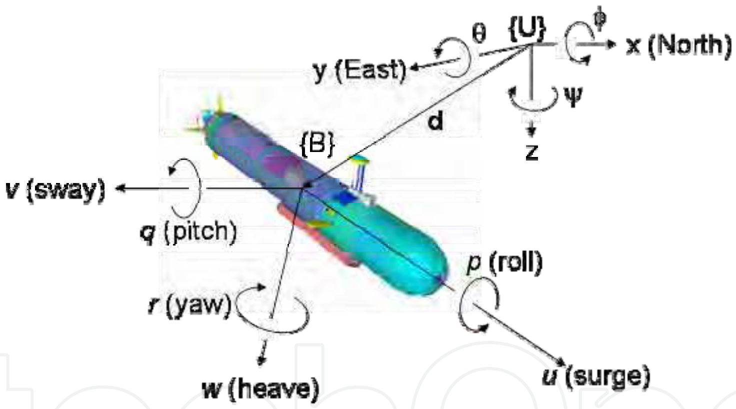

Fig. 7. Frames definition for an UUV.

Referring to Fig., the following notation will be used throughout the paper.

- The symbol $\{A\}:=\{\mathbf{x_A},\mathbf{y_A},\mathbf{z_A}\}$ denotes a reference frame with origin O_A. Let $\{U\}$ and $\{B\}$ be the inertial (or universal) and body axis frame, respectively. Traditionally, $\mathbf{x_U}$ is pointing north, $\mathbf{y_U}$ is pointing east and $\mathbf{z_U}$ is pointing the sea-bottom. The origin of $\{B\}$ is usually chosen to coincide with the system's centre of gravity when this point belongs to the principal plane of symmetry, or at any other convenient point if this is not the case; $\mathbf{x_B}$ is the longitudinal axis directed from aft to fore, $\mathbf{y_B}$ is the transversal axis directed to starboard and $\mathbf{z_B}$ is the normal axis directed from top to bottom.

- Let **R** be the rotation matrix from the universal frame {*B*} to the body frame {*U*}.
- Let $\boldsymbol{\eta} = [x \quad y \quad z \quad \phi \quad \theta \quad \psi]^T$ be the vector that expresses the body situation with respect to the universal frame.
- Let $\mathbf{v} = [u \quad v \quad w \quad p \quad q \quad r]^T$ be the vector denoting the body's velocity with respect to the universal frame, expressed in the body frame axis {*B*}.
- Let $\dot{\boldsymbol{\eta}} = \mathbf{K}(\boldsymbol{\eta}) \cdot \mathbf{v}$ denotes the system kinematics model, expressing the relations between $\dot{\boldsymbol{\eta}}$ and $\mathbf{v}$.
- Let $\boldsymbol{\tau}$ be the vector of forces and torques generated by the actuation system, expressed in {*B*}.
- Let $\boldsymbol{\tau} = \mathbf{f}(\mathbf{v}, \dot{\mathbf{v}}, \boldsymbol{\eta}, \mathbf{P})$ denote the system dynamic model, where **P** is the vector of the constant physical parameters of the system, necessary to express the dynamic model.
- If x is a measurable physical quantity, let $\hat{x}$ be an estimation of x and $\tilde{x} = x - \hat{x}$ be the estimation error.
- Let $\boldsymbol{\tau} = \mathbf{B} \cdot \mathbf{u}$ be the actuation model, where **u** denotes the vector of actuation inputs.

4.2 Definitions

The **Navigation System** provides estimates of the vehicle states based on a set of motion sensor suites.

The **Guidance System** processes Navigation/Inertial reference trajectory data and output set-points for desired vehicle's velocity and attitude.

The **Control System** generates actuator signals to drive the actual velocity and attitude of the vehicle to the value commanded by the Guidance system.

5. Systems

Existing systems have been designed according to the required specificities imposed by the missions the systems are tasked to perform. From the robotic point of view, these characteristics concern the system actuation, the body shape, the communication medium and its bandwidth… and award the system with different properties and possibility of action.

5.1 Remotely Operated Vehicle (ROV)

Fig. 8. The ROV Panther Plus, from SeaEye Company, Fareham, England.

A ROV is generally designed to perform sub-sea intervention or survey of a delimited zone. These systems generally carry one or more manipulators, real-time-teleoperated via an umbilical link to the mother-ship. The umbilical and the manipulator generate coupling effects on the vehicle, beside the local environmental disturbances. Then, ROVs are generally exhibiting the following properties:

i. **Iso-actuated**: the vehicle is equipped with as many actuators as the number of the controlled degrees of freedom. The remaining degrees of freedom (if any) have to be naturally stabilized.

ii. **Hovering**: this imposes to the system being able to react in static water, which implies the use of propeller-, or jet-, driven thrusters. Moreover, this pose-stabilisation has to be guaranteed despite external disturbance.

iii. **Isotropic properties**: the thrusters' location has to be chosen in order to guarantee that the system reaction capacity will be equivalent in all the direction.

iv. **Tethered**: the umbilical is physically linking the immerged system with the mother-ship. This allows for on-line teleoperation and deported energy supply. Moreover, the presence of the tether improves greatly the guarantee of system recovery. Nevertheless, the cable is undergoing disturbances (e.g. waves and current) on all its length, inducing a heavy parasite-load on the system.

v. **Hybrid Position/Force controlled**: performing a manipulation on an immerged structure implies to explicitly control the force exerted by the tool on the structure. A free-floating manipulation (in opposition to the clamped situation) requires combining the control of the vehicle's position, the manipulator effort on the structure and the compensation of the umbilical effects.

vi. **Terrain-based navigation**: a precise estimation of the relative distance between the system and its target is of major importance in ROVs applications. First, it relaxes the precision necessity of the global positioning estimation, and second, it greatly helps in the vehicle stabilisation.

5.2 Intervention Autonomous Underwater Vehicle (IAUV)

Fig. 9. The IAUV *Alive*, from Ifremer and Cybernetix, Marseille, France.

The IAUV system is designed to perform similar operations than ROV, but without tether. The consequence is that the system carries its own energy supply. Moreover, manipulation is a complex task that involves a high degree of autonomy, which imposes for the moment to keep the operator in the decision and control loop. These systems are acoustically connected with the mother-ship. Their streamlined nature, in order to reduce the energy consumption and their ability to perform robust pose-stabilization require different types of actuation. These systems can combine control surfaces, stern powerful thrusters and hovering thrusters, awarding them with an over-actuated property.

i. **Over-actuated**: the control of this type of system implies to solve an over-dimensionned problem, requiring the pose of complementary criteria, or to sequentially manage different actuation configurations. The stability property of the different switches between these configurations is a present subject of study.

ii. **Energy consumption management**: this imposes to minimize the energy consumption, which constraints the hydrodynamic system shape and requires an explicit management of the sensors recruitment.

iii. **Transmission delays**: the low bandwidth acoustic communication channel induces delays in the reception of the data. Teleoperation with delays is a very active topic of research.

iv. **Vertical acoustic transmission**: since the best underwater communication is achieved when the emitter and the receiver are vertically aligned, the mother-ship has to be positioned on top of the IAUV horizontal location, guaranteeing that both systems remain in the communication cones, defined by the acoustic modem aperture.

5.3 Autonomous Underwater Vehicle (AUV)

Fig. 10. The Taipan 2 AUV, from LIRMM, Montpellier, France.

The AUV system is designed to perform long-range survey missions. Its fully-autonomous status implies an onboard decision capability and a rigorous energy consumption management. Moreover, the AUV generally carries powerful stern thrusters to propel its torpedo-shaped body in a preferred direction of movement

i. **Under-actuated:** the vehicle has less actuator than states variable to be tracked. Control surfaces are used to induce a change in the relative fluid/flow direction.

ii. **Actuated with control surface** (fins): thrusters are loosing efficiency as the flow is misaligned with the propeller's axis. Since AUVs are running for high-velocity and long-range missions, the vertical plane actuation is performed using control surfaces. Notice that the system controllability imposes a non-null forward velocity; otherwise the control surfaces will not generate any significant action. Moreover, the control surface action capacity is dependant of the relative AUV/fluid velocity.

iii. **Full-autonomy**: The system decision capabilities will greatly impacts on the set of missions the system will be able to perform. The security management and the system ability to react to uncharted event are of major importance.

5.4 Autonomous Surface Craft (ASC)

The ASC system is the surface version of the AUV. It benefits from a direct connection to GPS information. Nevertheless, surface sailing is sensitive to environment disturbances (wind, waves and current), and boat traffic requires an explicit consideration of collision avoidance.

Fig. 11. The ASC Delfim, from ISR, Lisbon, Portugal.

i. **GPS navigation**: the possibility to periodically estimate the global system coordinates greatly simplifies the navigation problem.
ii. **Collision avoidance**: this implies the ability to detect an obstacle with radar (surface) and sonar (underwater) devices. The avoidance manoeuvre can be performed at different level in the control architecture: mission-replanning, path-replanning and low-level reflex behaviour.
iii. **Environmental disturbances sensitivity**: wind and waves produce a forced-oscillatory disturbance on the system. Then, an ASC-based terrain survey (bathymetry, for instance), will have to be explicitly corrected in function of the attitude of the system, estimated by the navigation system. Indeed, the bathymetric measurements will be spread around the desired route, in function of the pitch and roll oscillatory behaviour.

5.5 Glider Systems

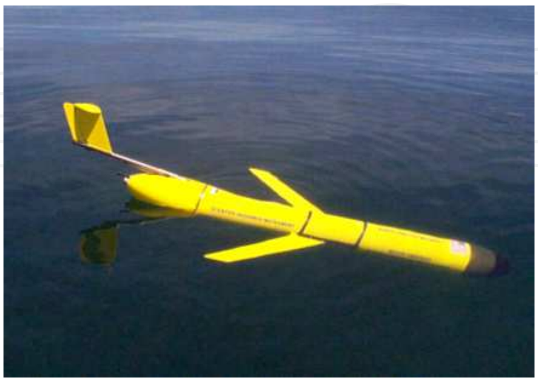

Fig. 12. The Slocum Glider, from Webb Research Corporation, Massachusetts, USA.

An underwater glider is a buoyancy-propelled, fixed-wing autonomous underwater vehicle. Attitude is controlled by means of internal mass redistribution and in some cases with external control surfaces. Initially conceived by Henry Stommel (Stommel, 1989), autonomous underwater gliders offer many advantages in ocean sensing: long duration missions, greater operational flexibility and low-cost operations. The thrust is achieved using transition between downwards and upwards glides, roll and pitch are controlled by moving internal mass. Yaw (heading) is controlled using the rudder mounted on the vertical tail of the glider.

i. **Active Buoyancy control**: this allows for tuning the vertical position of the buoyancy centre, inducing an explicit control of the vertical force (heave), despite the velocity and direction of the flow. Notice that the system's vertical dynamics is dependant of the ballast-pumps flow rate.
ii. **Active mass control**: the horizontal management of the weighting components of the system allows for tuning the horizontal position of the gravity centre. Combined with the buoyancy control, the system is able to generate a pitch control.
iii. **Hydrodynamic design**: the shape of the projected system surface, perpendicularly to the fluid flow, has a significant incidence on the system dynamic reactions. As the weathercock aligns itself with the direction of the wind, the glider has to naturally pitch negatively (pointing down) when a descending force occurs (induces by negative buoyancy). This behaviour results in a system that is naturally orienting in the flow direction, inducing the desired flying effect.

5.6 Biologically Inspired Systems

Fig. 13. RoboEel mk2, from Modular Robotics and Robot Locomotion Lab, Singapore.

Coming from the intuition that natural solutions exhibit good performances, biologically inspired solutions have motivated a large number of robotics applications. For example, *Soryu I* and *II* are three-tracked snake-like robot specially designed for rescue operation, to inspect the debris of building just after earthquake (Takayama & Hirose, 2003). Legged-robots are studied in many labs, and humanoid-systems are currently in development all over the world (Bryan *et al.*, 2000). For underwater purpose, a simple look at the performances fishes can reach – in terms of acceleration, manoeuvrability and their ability to move by change of shapes, and not by propellers – justifies the marine engineers' interests in underwater biomimetic systems. Thuna-robot[11], eel-like systems[12] and lobster robot[15] are currently under development, and theoretical opened problems are discussed in a large number of papers.

i. **Modelling**: the modelling of a supple system, as the body of a fish, for control design purpose results in an hyper-redundant serial system. Classic dynamic modelling using Newton-Euler or Lagrangian-type derivation provides a complicated set of N-dimensionnal equations which requires specific mathematical tools to be solved.
ii. **Locomotion**: the control of the movement of such a system borrows from *vertebrate locomotion theory*. *In vivo* observations of fishes and eels, allowed identifying periodic body-shape evolutions – also called *gait* – that induces an efficient thrust.
iii. **Gait control**: the gait is classically a time-parameterized articular reference, tracked with a trajectory controller. The limitations of the trajectory tracking application have been exposed previously. Designing an autonomous gait (time-independent) allows for posing the control problem in terms of path following. Notice that the control loop is closed on an arbitrary reference, without direct measurement from the fluid flow. It results in a system that effectively produce a thrust, but without guaranteeing that all the system links (vertebrae) are properly involved in the movement.
iv. **Local flow control**: fishes are using lateral line baro-sensors to locally control the flow quality along their body, in function of the locally measured pressure. An interesting approach is to reproduce such control ability in measuring the actuation torque in order to correct the nominal gait profile, and guarantee that the whole system is involved in the thrust production.

5.7 UUV Platoons

The problem of coordinated motion control of marine robots is a very active topic of research. The positioning problem can be greatly simplified with the use of an ASC, relaying GPS information to the immerged system. This implies to be able to precisely estimate the relative horizontal distance ASC/UUV. Multiple UUVs control requires also estimating the relative position between the members of the platoon, in order to guarantee the formation cohesion. This implies a very-low bandwidth horizontal communication capacity that requires minimizing the necessary information exchange. The interest of making different vehicle collaborating is to sum the advantages and possibility of action of all. The consequence is that the platoon may be composed with systems that exhibit heterogeneous dynamical behaviours.

i. **Efficient Vertical Communication**: the vertical plane induces the best communication rate. Then, an ASC/UUV combined system is constrained by the maximum relative horizontal distance between the vehicles, as for the IAUV systems.
ii. **Minimal Horizontal Communication**: The control of a UUVs flotilla requires estimating the relative position between all the platoon's elements. This estimation can be performed in a global way, with respect to a unique frame, or in a relative manner in estimating the distance to the closest vehicle. Nevertheless, exchanging

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[15] http://www.neurotechnology.neu.edu/

information in the horizontal plane is a difficult task and imposes to minimize the quantity of data exchange.

iii. **Coordinated manoeuvres**: UUVs flotilla is composed with dynamical heterogeneous systems and implies different dynamics behaviour, in terms of minimum turning radius, reaction time… Moreover, in the scenario of a combined ASCs/UUVs control, the surface systems are undergoing different environmental disturbances than the immerged ones. Then, the guidance system of each vehicle has to consider manoeuvres generation according the system dynamics and the respect of the formation.

iv. **Obstacle Avoidance**: operating different vehicle at a same depth requires an explicit consideration of the collision avoidance problem. Moreover, the onboard acoustic modem can be elegantly used to estimate and control the relative distance between vehicle and the respect of the formation.

v. **An efficient management of the terrain knowledge**: in front of the difficulties of localising a deep UUV, terrain-based navigation offers an incontrovertible complementary solution. Simultaneous Localisation And Mapping (SLAM) allows for projecting on an egocentric map all the terrain knowledge, previously recorded or currently acquired, (Reece & Roberts, 2005). This map can help for navigation, when the sensors information can be currently associated with a particular location on this *sensorial* map. Coordinated mapping using a fleet of autonomous vehicle, enabling a global map construction is a challenging problem that raises a lot of exciting questions. Pooling the resources of each of the flotilla member into a collectively used global map is restricted with the communication underwater conditions. It is not conceivable that each vehicle broadcasts its locally acquired information, as done for aerial or terrestrial applications. Underwater, the transmitted data will be a degraded or reduced to a particular region of interest. It is also imaginable that the exchange of information could be done on demand, a vehicle requesting a complement of information in order to clarify an ambiguous measurement. The multi-SLAM principle is an appropriate tool to be integrated into the necessary collaborative space that UUVs fleet control requires.

5.8 Navigation Sensors

Underwater robotics would not be conceivable without the recent progress in the domain of sensing. Originally, sailors were using stars to triangulate their position, which is in fact not far from GPS technique. This archaic navigation was greatly improved with the invention of stable clocks (Eco, 1996). It is interesting to notice that accurate time measurement is still a requirement that is problematic to meet. As we will see later, precise synchronisation is one of the key factors in coordinating a fleet of collaborative vehicles. Moreover, time is a global reference that greatly simplifies the estimation of the relative position between a geo-referenced acoustic beacon and the UUV. Despite the time, the measurement needs, for navigation purpose, are related to position (and attitude), velocity and acceleration, as the structures of the vectors $\boldsymbol{\eta}$ and $\boldsymbol{\nu}$ suggest. Various sensors provide estimates of these quantities, with different accuracy and sampling rate.

i. **Magnetic compass** is an old Chinese invention, which probably dates back to 100 BC, and is still in use everywhere. It is constantly pointing the north, hence allowing for the estimation of the global heading ($\hat{\psi}$) of the vehicle onto which it has been attached. Sensitive to the Earth magnetic effect, the magnetic compass may be parasited by the local magnetic field, generated by the active elements onboard the vehicle or present in the environment.

ii. This problem was overcome after the introduction of the **gyroscopic compass**. A gyroscope is a disk mounted on a gimbals in such a way that the disk can spin freely on it *x*- and *y*- axis. A properly mounted gyroscope will always turn to match its plane of rotation with that of the Earth, thus indicating the north along its axis of rotation without undergoing the effects of the local magnetic field.

iii. **Fiber-optic gyro-compasses** are based on the *Sagnac*[16] effect and offer great accuracy in the measurement of the yaw-rate ($\hat{r}$) without requiring any moving parts. Three fiber-optic gyro-compasses mounted along the 3 axis of the body frame combined with 3 accelerometers, allow for estimating the complete set of the Euler angle ($\hat{\phi}$, $\hat{\theta}$, $\hat{\psi}$) without temporal drift.

iv. This sensors combination, called **Inertia Navigation Unit**, also provides estimations of linear accelerations ($\hat{\dot{u}}$, $\hat{\dot{v}}$, $\hat{\dot{w}}$) and angular rates ($\hat{p}$, $\hat{q}$, $\hat{r}$), besides ($\hat{\phi}$, $\hat{\theta}$, $\hat{\psi}$). Moreover, given the initial geo-referenced location of the system, successive integrations of the linear accelerations provide the body frame velocities ($\hat{u}$, $\hat{v}$, $\hat{w}$), and after appropriate transformation to the inertial frame, the global horizontal system position ($\hat{x}$, $\hat{y}$). Notice that this integration induces a temporal drift in the estimation error.

v. **Doppler Velocity Loch** (DVL) provides a great improvement, in directly measuring the body frame velocities ($\hat{u}$, $\hat{v}$, $\hat{w}$) without requiring integration. Based on the *Doppler* effect, DVL is using the measurement of the difference in frequency between an emitted acoustic signal and the echo in return. In function of the insonification power and the temporal window of listening, the echo may come from the surrounding particle of water or the sea-bottom, thus providing the estimation of the body-frame velocities with respect to water, or inertial frame, respectively. This makes DVL used also as a currentmeter.

vi. **Pressure sensors** provide an estimation of the depth ($\hat{z}$) without temporal drift. The previously described sensors compose a sufficient sensor suite to provide a complete estimation of the system states $\hat{\boldsymbol{\eta}}$ and $\hat{\mathbf{v}}$. Nevertheless, the integration-based position estimation is error cumulative, and requires referring to an external calibrated reference in order to bound it.

vii. The most common approaches that UUV use are acoustic Long BaseLine (LBL), Short BaseLine (SBL) or **Ultra-Short BaseLine** (**USBL**) methods requiring external transponders. This is based on triangulation of the measurement of the time-flight of the acoustic signal between the vehicle and the geo-referenced transponders, effectively providing a non-drifting estimation of ($\hat{x}$, $\hat{y}$, $\hat{z}$). However, signal attenuation varies with distance, frequency, and temperature, and positioning systems with acoustic beacons are expensive and often impractical (Vaganay *et al.*, 1996). Nevertheless, these transponders can be

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[16] http://en.wikipedia.org/wiki/Fiber_optic_gyroscope.

located on ASCs that, thanks to their GPS connection, can regularly calibrate the beacons location. Moreover, a temporal synchronisation between the ASC and the UUV allows for estimating the UUV location with one single transponder, and ASC. The control of such a collaborative system involving underwater and surface system raises a lot of exiting problems.

6. Sub-problems and Desired Performance

The most displeasing experience with an UUV is to loose it, even for few minutes. This is an unacceptable eventuality and it is the goal of the system designer to reject its occurrence, while certifying the quality of the mission results in nominal conditions. Underwater, nominal conditions mean to define the domain of action of the system up to a certain sea-state, under which the system performances are guaranteed. These objectives are implicit guide-lines to the system design process. The analysis of its components, in order to evaluate these guarantees, reveals the necessity for all the components to exhibit **global guaranteed performances**.

6.1 Modelling accuracy should be quantified.

As we will see later this problem is complex, and theoretically unsolvable. The modelling objective is to cast the specificities of the underwater phenomena into a mathematical framework, which allows for predicting the system dynamic behaviour; in order to guide the control design and compute the actuation input that generates the desired movement. Rigid-body dynamics is now well understood, but viscous-fluid dynamics injects complex and nonlinear terms in the system model, which becomes difficult to control. The resulting system dynamic model is written as

$$\boldsymbol{\tau} = \mathbf{f}_1\left(\mathbf{v}, \dot{\mathbf{v}}, \boldsymbol{\eta}, \mathbf{P}\right)$$

Environmental disturbance modelling results in a set of time-varying nonlinear equations. The consideration of their mathematical expression in the control design leads too much complexity. Hence, for control design purpose their effect on the system will be expressed as a 6×1 vector of torques and forces, $\mathbf{w}$, acting on the system and the dynamic model becomes:

$$\boldsymbol{\tau} + \mathbf{w} = \mathbf{f}_2\left(\mathbf{v}, \dot{\mathbf{v}}, \boldsymbol{\eta}, \mathbf{P}\right)$$

The assumption of a bounded effect of environmental disturbances, $\mathbf{w}$, is related with the sea-state, and the presence of ocean current. Despite the environmental disturbances, modelling, model estimation and controllability-requirement impose approximations. With some notation abuse, the dynamic model is rewritten:

$$\boldsymbol{\tau} + \mathbf{w} = \hat{\mathbf{f}}_2\left(\mathbf{v}, \dot{\mathbf{v}}, \boldsymbol{\eta}, \hat{\mathbf{P}}\right) + \tilde{\mathbf{f}}_2 + \hat{\mathbf{f}}_2\left(\mathbf{v}, \dot{\mathbf{v}}, \boldsymbol{\eta}, \tilde{\mathbf{P}}\right) \quad (1)$$

where $\tilde{\mathbf{f}}_2$ represents *the unmodelled dynamics*, $\hat{\mathbf{P}}$ is theamic parameters vector and $\hat{\mathbf{f}}_2\left(\mathbf{v}, \dot{\mathbf{v}}, \boldsymbol{\eta}, \tilde{\mathbf{P}}\right)$ denotes the dynamic effects induced by the dynamic parameters misestimation. Then, the goal of the control design is to express a control expression based on the knowledge of $\hat{\mathbf{f}}_2\left(\mathbf{v}, \dot{\mathbf{v}}, \boldsymbol{\eta}, \hat{\mathbf{P}}\right)$ (which in the sequel will be written as $\mathbf{f}$) in order to guarantee the behaviour of the system described in Equation (1). Nevertheless, the assumption of bounded effect of the unmodelled dynamics is necessary, but unquantifiable in mathematical terms; since this phenomenon is excited by the system states, and the boundedness assumption implies to assume the system states stability; which can be guaranteed under the assumption of bounded external and unmodelled disturbances. This situation forbids a clear statement for the modelling error. Then, it is assumed in the sequel that the *unmodelled dynamics* $\tilde{\mathbf{f}}_2$ is negligible.

6.2 State estimation error has to be bounded

State estimation concerns the estimation of the system position and velocities, assuming that these quantities are measurable, to provide $\hat{\boldsymbol{\eta}}$ and $\hat{\mathbf{v}}$. Nevertheless, the sampling periods and the precision of these measurements are generally very different, in function of the sensor or the measurement necessary conditions. Notice that the boundedness assumption implies for the system to be equipped with appropriate sensors. Global positioning requires the use of GPS information, directly acquired at the sea surface, or relayed by an acoustic device system. Without these measurements, a *dead-reckoning* navigation, based on the double-integration of the acceleration measurements, is error-cumulative, and the system states estimation error cannot be bounded. But a measurement of the global position, even at a very low frequency, will allow for bounding the estimation error. Of course, the goal is to obtain the best estimation, then to reduce as much as possible the guaranteed bound. The navigation system is in charge of this estimation. The objective is the following: given the sensors measurements denoted $\boldsymbol{\mu}$, compute $\hat{\boldsymbol{\eta}}$ and $\hat{\mathbf{v}}$ such that $\tilde{\boldsymbol{\eta}} < \boldsymbol{\varepsilon}_{\boldsymbol{\eta}}$ and $\tilde{\mathbf{v}} < \boldsymbol{\varepsilon}_{\mathbf{v}}$, where $\boldsymbol{\varepsilon}_{\boldsymbol{\eta}}$ and $\boldsymbol{\varepsilon}_{\mathbf{v}}$ define the maximum guaranteed error on the state estimate.

6.3 Guidance and Control systems should exhibit global practical convergence

Global practical convergence induces on the system to reach its objective, within a certain bounded error, whatever its initial position and the eventual obstacles the system has met. In the case of a pose-stabilisation this means that for any initial position $\boldsymbol{\eta}_0$, the system is guaranteed to reach and stabilize on the desired position $\boldsymbol{\eta}_d$, within a certain (hyper-) sphere Ω_ε of radius ε. For path-following, this property implies to reach the desired 3D path, within a certain (hyper-)tube B_ε of radius ε, whatever $\boldsymbol{\eta}_0$. The respect of this condition impacts on the control design methods.

6.4 Mission Control system and the Hardware and Software Architectures need to be reactive and determinist.

Mission Control is tasked with the mission management. In a nominal situation, the mission is composed with sub-objectives, to be sequentially executed. These objectives are composed with elementary tasks that the system is nominally able to perform. The occurrence of an uncharted event, inducing a critical non-nominal situation, impacts on the mission planning (replanning or aborting). But in any situation, the Mission Control system has to deterministically guarantee that the system is constantly evolving toward a safe situation. The software architecture concerns the management of all the computer processes in charge of the elementary tasks of the system and has to exhibit real-time performances, in order to guarantee the execution time of all the processes. This is linked with the choice of the operating system onboard the computer, the communication mechanism between processes, the tasks scheduling and the recruitment management of the system components. Moreover, since a system breakdown can never be completely dismissed, a self monitoring of the system is necessary. The hardware architecture has to also exhibit a deterministic behaviour, in order to guarantee that the previous properties will be respected by a reliable physical system.

7. Conclusion

The previously exposed requirements constitute a sufficient set of conditions in order to award the system with global guaranteed performances. These questions are currently subject of a great number of researches. We expose in the chapter titled *Underwater Robots Part II: existing solutions and open issues*, the state of advancement of these research, and the remaining open issues.

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Mobile Robots: towards New Applications

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The range of potential applications for mobile robots is enormous. It includes agricultural robotics applications, routine material transport in factories, warehouses, office buildings and hospitals, indoor and outdoor security patrols, inventory verification, hazardous material handling, hazardous site cleanup, underwater applications, and numerous military applications. This book is the result of inspirations and contributions from many researchers worldwide. It presents a collection of wide range research results of robotics scientific community. Various aspects of current research in new robotics research areas and disciplines are explored and discussed. It is divided in three main parts covering different research areas: Humanoid Robots, Human-Robot Interaction, and Special Applications. We hope that you will find a lot of useful information in this book, which will help you in performing your research or fire your interests to start performing research in some of the cutting edge research fields mentioned in the book.

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