State-of-the-Art System Solutions for Unmanned Underwater Vehicles

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Abstract. *Unmanned Underwater Vehicles (UUVs) have gained popularity for the last decades, especially for the purpose of not risking human life in dangerous operations. On the other hand, underwater environment introduces numerous challenges in navigation, control and communication of such vehicles. Certainly, this fact makes the development of these vehicles more interesting and engineering-wise more attractive. In this paper, we first revisit the existing technology and methodology for the solution of aforementioned problems, then we try to come up with a system solution of a generic unmanned underwater vehicles.*

Keywords

Unmanned underwater vehicle, autonomous underwater vehicle, navigation, control and guidance, underwater communications, systems engineering, software framework.

1. Introduction

Studies on Unmanned Underwater Vehicles (UUVs) have shown a dramatic increase especially in the last two-three decades. Many examples of Remotely Operated Vehicles (ROVs), Autonomous Underwater Vehicles (AUVs) and Single-Shot ROVs (SSRs) were developed and used successfully on various applications; such as oceanographic surveys, bathymetric measurements, underwater maintenance activities (e.g. those performed at oil platforms, fiber optic communication lines, etc.) and certainly military defense. Existing vehicles are showing continuous progress in terms of technology, advanced navigation and control functionalities, longer missions, flexibility and high capacity of payload in addition to a very diverse suite of sensors [1-2].

Recent advances in the battery technologies and the progress in the fuel cell research studies yielded the usage of autonomous underwater vehicles (AUVs) in longer missions, which could be performed by manned or tethered vehicles, previously.

Regarding the military applications of UUVs, mine countermeasure (or marine mine-sweeping) is the most typical one. Since marine mines are widely used and very dangerous even to the most modern naval forces, tedious and dangerous mine sweeping activities have become a necessity for many naval operations, and may become increasingly important for homeland security [3]. Anti-submarine warfare and harbor protection can be considered as the other major, but more complicated military UUV applications.

In this paper, which might be considered as a semi-tutorial for the researcher to study in development of UUVs, we try to summarize the main research topics together with their challenges and practical considerations. We try to sum up with a system (hardware/software) solution based on our experiences.

The paper is organized as follows. After this introductory section, we try to summarize the aspects of UUV navigation in Section 2, those in communication in Section 3, the ones in control in Section 4. Section 4 also includes the definition of the motion equations of UUVs. In Section 5, we try to give an essence our own system solution and implementation. The final section, which is Section 6, includes concluding remarks and probable future directions of the researches regarding UUVs.

2. Navigation in UUVs

Unlike aerial or terrestrial unmanned vehicles, UUVs face a uniquely challenging navigational problem, due to lack of high accuracy satellite-based navigation underwater. Certainly, for the tethered ROVs and SSRs, supplementary navigation (position, speed) information might be sent to the vehicle via a fiber-optic cable. But especially for the stand-alone UUVs, particularly for the AUVs, this would not be realizable in practice. Hence, when submerged, these vehicles must navigate using several different methods [4]. Considering the main application areas of AUVs, navigation accuracy is less critical for oceanographic surveys compared to bathymetric and underwater maintenance activities as well as military applications.

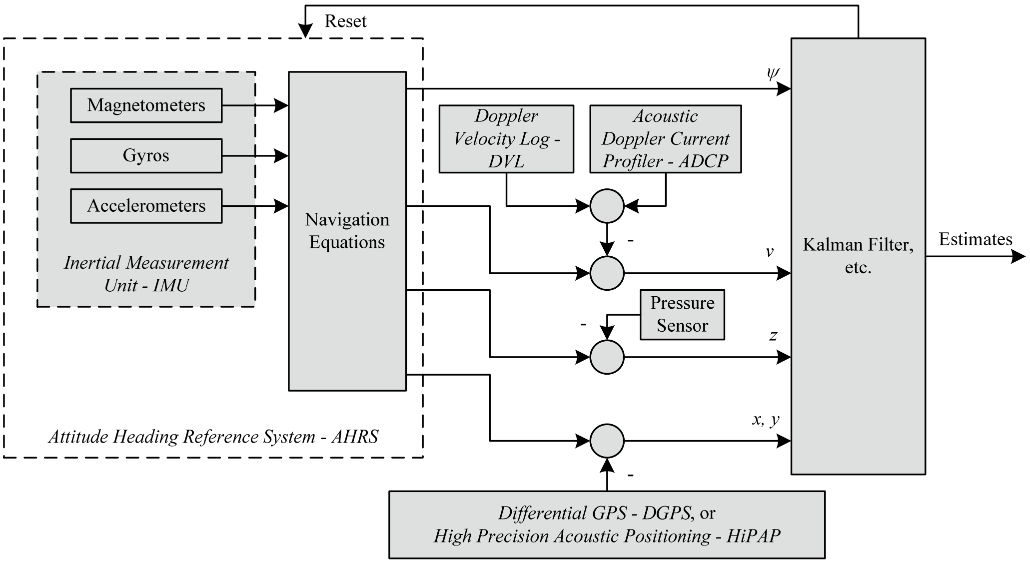


Fig. 1. Typical and generic navigation architecture for a UUV (particularly an AUV) – (based on [6]).

Three primary methods for the navigation of AUVs exist in the literature [5]: (1) dead-reckoning and inertial navigation, (2) acoustic navigation, and (3) geophysical navigation techniques.

The first technique basically relies on the usage of inertial navigation equipment (e.g. Inertial Navigation System (INS), Attitude Heading Reference System (AHRS)), which has financially become feasible especially after the inception of MEMS technology.

Since the errors in the measurements of inertial navigation equipment are monotonically increasing and unbounded, other auxiliary means (e.g. Differential Global Positioning System (DGPS) for the position; Doppler Velocity Log (DVL) or Correlated Velocity Log (CVL) for the ground speed; pressure sensors for the depth, Acoustic Doppler Current Profiler (ADCP) for the current speed, etc.) shall be integrated for the navigation aid [6]. In principle, it is recommended to get regular DGPS measurement updates for high accuracy navigation of AUVs [4]. However, this might not be practical especially in under-ice applications, or tactically critical military applications, unfortunately. Moreover, since CVL and DVL are devices relying on the Doppler shift phenomenon, they principally operate on the reflections of their own transmitted signals (from the sea bottom). Hence, for the effective usage of these devices, the UUV shall be sufficiently slow (in order to be able to receive the reflected signal); and the UUV shall not be very far away (in the order of 200-300 meters) from the sea bottom.

Acoustic navigation is based on the usage of acoustic transponder beacons for the AUV to determine its position. The most common methods are the long baseline (LBL), which uses at least two widely separated transponders mounted usually on the sea floor; and the ultrashort baseline (USBL), which uses GPS-calibrated transponders on an accompanying surface vessel. Both methods have a limited range (around 10 km for individual LBL; in deep water, about 4 km, whereas less than 0.5 km in shallow water for USBL networks [4]). Since LBL requires installation of beacons, its applicability is limited to missions performed at fixed-positions (e.g. harbor protection). Moreover, installation and maintenance of the beacons are both difficult and expensive. USBL might not be applicable in some military applications due to tactical restrictions, since it requires an accompanying surface vessel.

Geophysical navigation is based on obtaining an estimate of the position by means of observable physical features (e.g. by existing maps of the area or by construction of such maps during the mission). Even though this technique provides the best accuracy compared to other techniques, it requires expensive payloads with high power consumptions (e.g. optical sensors, cameras) and high computational power. In addition, they are more suitable for missions performed at previously visited areas.

In summary, the AUV navigation sensor configuration shall be selected according to the mission needs, and appropriate navigation solution architecture shall be defined. A generic and typical AUV navigation architecture, which is based on [6], is illustrated in Fig. 1. As seen in the figure, there is need to combine the measurements of various sensors in order to estimate the position of the AUV together with the errors.

The most common method is to utilize the well-known Kalman filter (KF) [7], which is the optimal Bayesian estimator of the state of a system if it is linear, Markovian, and with Gaussian uncertainties. For AUVs, the system could not be modeled linearly; hence, extended Kalman filter (EKF) [8] or unscented Kalman filter (UKF) [9] formulation shall be used for the analytical or statistical linearization of the system model, respectively. Particle filter (PF) can also be applied for the same purpose [10, 11]. It is also applicable for the cases where uncertainties are non-Gaussian; but it should be noted that its implementation is computationally expensive.

KF and PF formulations are applicable for inertial navigation. For acoustic and geophysical navigation approaches, Simultaneous Localization and Mapping (SLAM) [12] and Concurrent Mapping and Localization (CML) [13] algorithms can rather be used.

A-priori navigation error analysis is difficult for AUVs, since the navigation error is tightly correlated to the mission profile (e.g. mission speed, mission duration, horizontal and vertical patterns followed, etc.) in addition to the navigation sensor capabilities. For that reason, high-fidelity simulations with well-defined scenarios shall be developed and defined respectively for highly accurate navigation error estimations. However, rough error estimates existing in the literature can be used as rule-of-thumb references [4]:

- For short-range missions up to around 10 km, calibrated INS can provide sufficient accuracy for survey missions, regardless of the path taken by the AUV.
- For longer-range missions up to 100 km, the path taken by the AUV has a large effect on the accuracy of the navigation system used. Several geophysical techniques correct incremental inaccuracies in the AUV’s position when it returns to a previously visited area. This is necessarily true for any technique that uses a map generated over the course of a mission. If the AUV’s path contains many crossover points, then these mapping techniques will perform well.
- Conversely, if the AUV follows a linear path or a single large loop, geophysical techniques provide only a limited improvement from the resulting sequential registration of landmarks and will not significantly aid navigational performance during the mission.
- For missions above 100 km, implementation of an accurate navigation system is more difficult because the best INS will be affected by significant drift over these distances. The deployment of a beacon network over such a large area is not practical and the number of landmarks used by geophysical techniques over such a large area requires more advanced techniques.

3. Communication of UUVs

Communication is a very important requirement of UUVs especially during the execution of coordinated missions. As in the case of navigation, for tethered vehicles, this can be achieved via a fiber optic channel. However, such cases are limited in practice.

As stated before, underwater is a challenging environment for reliable communications with high bandwidth. An underwater network might consist of any type of UUV, and other various sensor nodes (either released from surface platforms or moored). These surface platforms (if not prevented due to restrictions imposed tactical conditions) might serve as gateways and provide radio communication links to on-shore stations [14]. Typical acoustic modems that are used to establish underwater links operate at low data rates and ranges up to a few kilometers. At much shorter ranges of tens to hundreds of meters, communication links with higher performance can be established by using high frequency acoustics.

Traditionally, submarines used to rely on acoustic waves for underwater communication. Acoustic waves in water have large propagation distances, which imply that the links are long range. For instance, at a carrier frequency of 30 kHz, the waves are attenuated only by 0.3 dB/m. On the other hand, acoustic communications might not be desired for some underwater vehicles for the following reasons [15-17]:

- It requires large modems, which might be a problem for vehicles that are designed to carry only small payloads.
- Further, time varying multi-path causes high bit error rates, causes temporary losses of connectivity, and makes the decoding of the transmitted signal difficult even for high received signal to noise ratios.
- Moreover, large (five orders of magnitude higher than that of radio frequency (RF) terrestrial channels) and time-varying latencies will cause another problem.

In underwater environment, low radio frequencies are less affected by attenuation (compared to high frequency radio frequencies), and offer a suitable alternative for short-range communication with acceptable power consumption and latency; but the limitations on the available bandwidth for data communication still exist. The short range implies that large-scale networks are multi-hop wireless networks. It also implies that the channel can be space-multiplexed between participants sufficiently far apart. In terms of local and global information distribution in the case of UUV swarms/platoons, limited range radio links can be considered advantageous.

Long wave radio communication is a possible alternative to acoustic communication. However, if the wavelength is very long, then big antennas will be required, which is again a problem for small UUVs. Therefore, a high carrier frequency shall be used. On the other hand, it should be noted that high frequency radio waves suffer from severe attenuation in the underwater environment. Hence, the carrier frequency shall be carefully chosen [17].

Since the message exchange among underwater nodes is limited, the most common approach for ocean-bottom or ocean-column monitoring is to record data at the nodes (i.e. at UUVs) instead of exchanging during the mission [14]. Unfortunately, this approach has the following disadvantages [15]:

- No real-time monitoring,
- No on-line system reconfiguration,
- No failure detection,
- Limited storage capacity.

In general, network topology is a crucial factor in determining the energy consumption, the capacity and the reliability of a network. Hence, the underwater network topology should be carefully engineered and post-deployment topology optimization should be performed, when possible [15].

Other challenges in the design of underwater acoustic networks can be listed as follows [15-17]:

- Limited battery power, usually incapability of battery recharge due to unavailability of solar energy;
- Failures due to fouling and corrosion.

4. Control and Guidance of UUVs

The design of guidance and control systems of UUVs (especially AUVs) requires knowledge of a broad field of disciplines, including vectorial kinematics and dynamics, hydrodynamics, navigation systems and control theory [18]. The main problems of the UUV control are the parametric uncertainties (e.g. added mass, hydrodynamic coefficients, etc.), non-linear and coupled dynamics [19].

For AUVs, in order to achieve a high degree of autonomy, several engineering problems associated with the high density, non-uniform and unstructured seawater environment (disturbances, etc.), and the nonlinear response of the vehicle must be considered and overcome [20].

When the literature regarding the underwater vehicles is analyzed, it can be observed that the term 'control' addresses a broad range of research studies. To our belief, these studies can be classified under three main categories listed below and a schematic explanation is given in Fig. 2 (based on [21]):

- Motion control: Focuses on subjects such as the platform response to an input and stability of a UUV,
- Mission control: Focuses on the execution of the behavioral modeling of an AUV, where this behavior is predefined parametrically,
- Formation control: Focuses on coordinated behavior of multiple UUVs (mostly AUVs) - (i.e. UUV swarms or platoons),

where motion control has been under investigation of several researchers especially since the pioneering study of Fossen and Sagatun [22]. Initial solid contributions on this topic were published in early 1990s. That decade later witnessed the studies regarding motion control. The current decade, concentration has increased on the improvement of swarm formations. However, the scope of this paper will be limited to the motion control of UUVs, rather than mission and formation control.

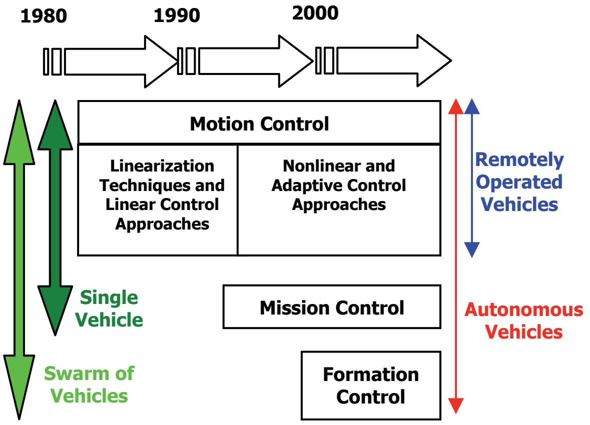


Fig. 2. Studies regarding the control of unmanned underwater vehicles (based on [21]).

4.1 General Notation for Motion of Marine Vehicles

The motions of all (both surface and underwater; both manned and unmanned) marine vehicles can be described in 6 degrees of freedom (DOF), since 6 independent coordinates are necessary to determine the position and orientation of a rigid body. The 6 different motion components are defined as 'surge', 'sway', 'heave', 'roll', 'pitch' and 'yaw', as shown in Tab. 1.

When analyzing the motion of marine vehicles in 6 DOF, it is convenient to define two coordinate frames as indicated in Fig. 3. The moving coordinate frame $X_0Y_0Z_0$ is fixed to the vehicle and referred to as 'the body-fixed reference frame'. The origin O of the body-fixed frame is usually chosen to coincide with the 'center of gravity (CG)', when CG is in the principal plane of symmetry or at any other convenient point if this is not the case.

The motion of the body-fixed frame is described relative to an inertial reference frame. For marine vehicles, it is usually assumed that the accelerations of a point on the surface of the Earth can be neglected.

DOF		forces and moments	linear and angular velocities	positions and Euler angles
1	motions in *x*-direction (surge)	X	u	x
2	motions in *x*-direction (sway)	Y	v	y
3	motions in *z*-direction (heave)	Z	w	z
4	rotation about *x*-axis (roll)	K	p	ϕ
5	rotation about y-axis (pitch)	M	q	θ
6	rotation about *z*-axis (yaw)	N	r	ψ

Tab. 1. Notation used for the underwater vehicles.

As a matter of fact, since the motion of the Earth hardly affects the marine vehicles due to their low speeds, this can be considered as a good approximation. As a result of this, an 'earth-fixed reference frame' *XYZ* can be considered to be inertial. This implies the following:

- the position and orientation of the vehicle should be described relative to the inertial reference frame;
- the linear and angular velocities of the vehicle should be expressed in the body-fixed coordinate system.

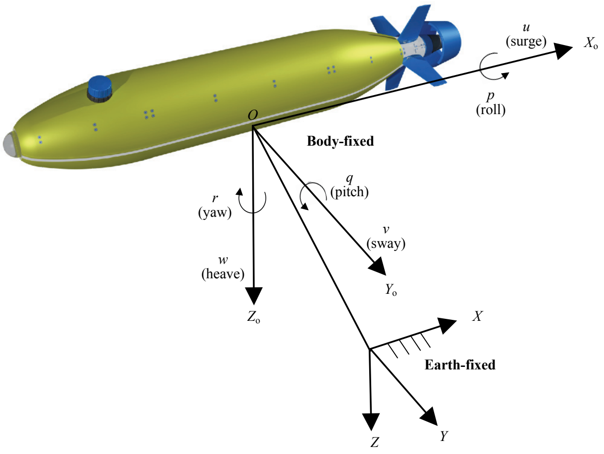


Fig. 3. Body-fixed and earth-fixed reference frames ([21]).

Based on the notation shown in Tab. 1, the general motion of a marine vehicle in 6 DOF can be described by the following vectors [18]:

$$\boldsymbol{\eta} = [\boldsymbol{\eta}_1^T, \boldsymbol{\eta}_2^T]^T \tag{1}$$

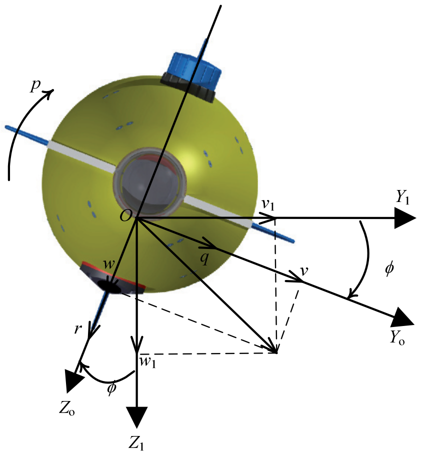
where $\boldsymbol{\eta}_1 = [x, y, z]^T$ and $\boldsymbol{\eta}_2 = [\phi, \theta, \psi]^T$.

$$\boldsymbol{\upsilon} = [\boldsymbol{\upsilon}_1^T, \boldsymbol{\upsilon}_2^T]^T \tag{2}$$

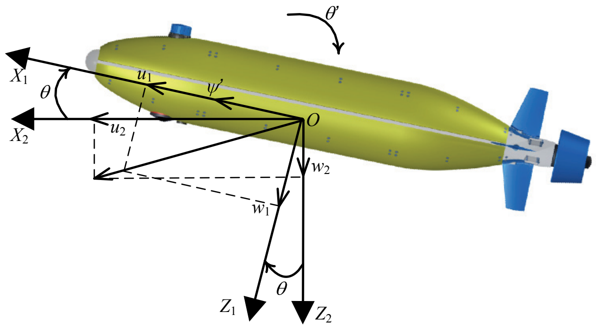
where $\boldsymbol{\upsilon}_1 = [u, v, w]^T$ and $\boldsymbol{\upsilon}_2 = [p, q, r]^T$.

$$\boldsymbol{\tau} = [\boldsymbol{\tau}_1^T, \boldsymbol{\tau}_2^T]^T \tag{3}$$

where $\boldsymbol{\tau}_1 = [X, Y, Z]^T$ and $\boldsymbol{\tau}_2 = [K, M, N]^T$.



(a)



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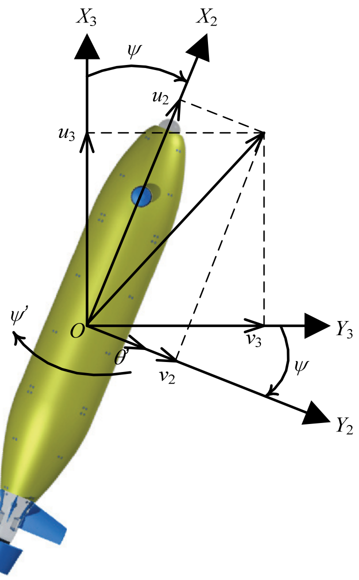
b)



(c)

Fig. 4. Rotation sequence according to the *xyz*-convention
(a) Rotation over roll angle ϕ about X_1 ($u_1 = u_2$)
(b) Rotation over pitch angle θ about Y_2 ($v_2 = v_1$)
(c) Rotation over heading angle ψ about Z_3 ($w_3 = w_2$).

Throughout (1)-(3), $\boldsymbol{\eta}$ denotes the position and orientation vector with coordinates in the earth-fixed frame; $\boldsymbol{\upsilon}$ denotes the linear and angular velocity vector with coordinates in the body-fixed frame; and finally $\boldsymbol{\tau}$ describes the forces and moments acting on the vehicle in the body-fixed frame.

The rotation sequence according to the *xyz*-convention showing both the linear (u, v, w) and angular (p, q, r) velocities, is depicted in Fig. 4.

4.2 Stability of UUVs

Stability of an underwater vehicle can be defined as "the ability of returning to an equilibrium state of motion after a disturbance without any corrective action, such as use of thruster power or control surfaces" [18]. Hence, maneuverability can be defined as the capability of the vehicle to carry out specific maneuvers.

At this point, the following issue about the stability shall be emphasized: Excessive stability implies very high control effort; whereas it would be easy to control a marginally stable vehicle. Consequently, there exists a compromise between stability and maneuverability, which should be carefully considered throughout the design of a UUV.

Furthermore, it makes sense to distinguish between controls-fixed (open-loop) and controls-free (closed-loop) stability. The essential difference between these terms can be stated as follows [18]:

- Open-loop stability implies investigating the vehicle's stability when the control surfaces are fixed, and when the thrust from all the thrusters is constant.
- Closed-loop stability refers to the case when both the control surfaces and the thruster power are allowed to vary.

This implies that the dynamics of the control system must also be considered in the stability analysis.

4.3 Techniques for Motion Control of UUVs

In the presence of environmental disturbances, improved robustness and performance for an underwater vehicle can be achieved using closed-loop control system of PID-type (proportional, derivative and integral) instead of an open-loop control scheme. In closed-loop control approach, sensor and navigation data are used for feedback. Using a series of controllers of PID-type, where each controller is designed for the control of one DOF, is a well-known practice for the conventional autopilot design of UUVs.

Traditionally, PID controllers used to be applied for the ROV systems. However, most ROV systems for offshore applications used only simple P- and PI-controllers, since derivative action was very sensitive to measurement noise, and it was difficult to measure (and to estimate) the velocity vector. It should be noted that the use of the PID algorithm for control does not guarantee the optimal control of the system or system stability, since the system to be controlled shows highly nonlinear behavior for the underwater vehicle case.

In the early 1990s, decoupled control design approach was mainly applied to the UUV control problem [23]. In such studies, the main approach was to decouple the 6 DOF linear equations of motion into three non-interacting (or loosely interacting) subsystems for speed control, steering and diving. Several closed-loop PID-controllers were used for each of the subsystems in [24].

The basic tasks in AUVs are depth and steering control. Numerous control strategies have been adopted; certainly, all of them have advantages and disadvantages. It is possible to classify the algorithms into two main groups: Linear and Nonlinear [19].

1) Linear methods: They are designed by using a vehicle's linear model, identified in a specific behavior case (nominal forward speed, angle of attack, etc.). These methods enable to control a vehicle easily, but they work in specific conditions and model nonlinearities are not considered. The PID-based methods mentioned in the previous paragraphs also fall into this category, since the mathematical operators applied in these methods (e.g. proportion, integration, differentiation) are linear. An example for the application of PID control to the underwater vehicles is [25]. A modified PD, namely the 'decoupled PD set-point controller' for UUVs is presented in [26].

Another approach falling into the linear control category is the Linear-Quadratic-Gaussian (LQG) method, which is suitable for uncertain linear systems disturbed by:

- additive white Gaussian noise,
- incomplete state information (i.e. not all the state variables are measured and available for feedback),

where the available state information is also disturbed by additive white Gaussian noise and quadratic costs. This method was applied to the underwater vehicle control problem in [27].

2) Nonlinear methods: In the literature, the nonlinear control methods have been applied for particular problems and specific unmanned vehicles developed throughout various research projects. Among those, one of the most commonly used methodologies is the Sliding Mode Control (SMC), a robust control scheme in case of parameter uncertainties.

Even though SMC is a nonlinear control method, several studies (such as [24] and [28]) still assume linear vehicle model in the nominal control. Another example of SMC using a simplified nonlinear vehicle model for the nominal control is presented in [29]. The main drawback of SMC is the chattering effect, which can excite un-modeled high frequency modes. These modes degrade the performance of the system, and may even lead to instability. Chattering also leads to high wear of fins and increase electrical power consumption (Recently, a chattering-free SMC is proposed for the trajectory control of ROVs in [30]).

Later, other approaches, which use full nonlinear model, have been proposed. Particularly in [19], Lyapunov and back stepping techniques are used. In [31], PI-type task functions enabling a conventional Lyapunov-based guidance system to counteract the effects both of un-modeled, i.e., unmeasured kinematic interactions between a UUV and the environment, and of bias in velocity measurements, is introduced. An adaptive nonlinear controller based on traditional back stepping method for diving control of an AUV is presented in [32]. In [19], a method called Higher Order Sliding Mode (HOSM) is implemented in order to avoid the chattering problem and to improve control performance. A nonlinear output-feedback control technique based on the HOSM approach is applied to the motion control problem for an underwater vehicle prototype that is equipped with a special propulsion system based on hydro-jets with variable-section nozzles and the results are presented in [33].

Due to the challenging nature of the underwater vehicle control problem, researchers have been continuing to pursue (general or ad-hoc) novel approaches for the solution throughout the last and the current decades. Regarding their strength and robustness, recent studies have concentrated on intelligent and/or adaptive control methods. State of the art publications on this topic apply neural network based, fuzzy reasoning oriented, even the hybrids of these methods.

Due to their capability of estimating various mathematical functions, including highly nonlinear functions, neural networks are powerful tools. Furthermore, in many cases, such networks can be trained to adapt to changing input-output relationships. Hence, neural networks may have a great potential in control systems for nonlinear and unknown systems, such as AUVs [34].

In addition to handling nonlinearity, several other properties of the neural networks make them suitable for control purposes [34]:

- Parallel structure: The parallel structure of neural networks, which facilitates the construction of parallel implementation of control systems, yields robust and fast processing systems.
- Applicability to hardware implementation: Neural networks can easily be implemented in hardware. A number of integrated circuits (ICs) implementing artificial neural networks (ANNs) are available in the market.
- Multivariable nature: Their potential ability to correctly map functions with many inputs and outputs make neural networks interesting for the control of multivariable systems.

Several different neural network controller schemes have been suggested and implemented in the past [34], some of which have been particularly applied to the underwater vehicle control problem:

1. Identification and modeling:
   (a) Forward Modeling;
   (b) Direct Inverse Modeling; and
   (c) Indirect Inverse Modeling.
2. Direct control:
   (a) Supervised Control;
   (b) Direct Inverse Control;
   (c) Model Reference Control;
   (d) Critic Control;
   (e) Internal Model Control; and
   (f) Predictive Control.

Offline learning method has been a simple but a common way of implementing control systems utilizing neural networks. Since the neural network controller is first trained prior to use (analogous to tuning of a conventional controller), the speed of the resulting network is generally considered to be high enough. During runtime, no weight adjustments take place and the response of the controller is rapid. However, the resulting controller is not adaptive, and hence inaccuracies in the network weights or changes in system parameters are likely to result in poor performance of the controller system.

Continuously updating the neural network weights while the controller is in use, is a very powerful alternative to offline training. In adaptive (or online trained) neural network controllers, initially a measure of the system performance is set up, and the controller weights are adjusted in a manner that improves this performance, generally through minimizing some output error. The main challenges of this approach are calculating the optimal weight changes from the system input and output as well as the reference trajectory for the system and ensuring the stability.

In the literature, it is observed that most of the network controllers designed for AUVs are direct controllers constituting the main part of the control system. Offline trained, non-adaptive AUV neural network controllers are presented in [35, 36], and online controllers are proposed in [37-43].

In order to have effective robust controllers for various applications, fuzzy logic controllers are being developed and used. It is logical to design a fuzzy controller, if the dynamics of the controlled system is fully known. For motion control of underwater vehicles, fuzzy logic control has been applied in [44-46], and the sliding mode fuzzy logic control has been applied in [47, 48].

5. A UUV System Architecture Proposal

As a developer team for all types of UUVs (i.e. ROVs, AUVs, SSRs), our research group has so far developed a hardware/software infrastructure in order to achieve an underwater vehicle product line in a rapid manner.

The system architecture together with the relevant subsystems is illustrated in Fig. 5. The hardware infrastructure relies on PC/104 architecture together with the generic navigation sensor setup described in Section 2, and illustrated in Fig. 1. The power need of this hardware setup (the electronics of the UUV, but not the thrusters) is supplied by the fuel cell, which is another area of expertise of our research group.

Our software infrastructure proposal is detailed in the upcoming paragraphs. Algorithmically speaking, for the navigation solution, our preference and experience is on the EKF formulation. For control purposes, our current experience addresses the type-1 fuzzy logic based SMC.

In Fig. 6, our software architecture proposal, which is a multi-tier structure compatible with Open Systems Architecture, is illustrated. Being hierarchical, it constitutes the main element of a distributed data processing system.

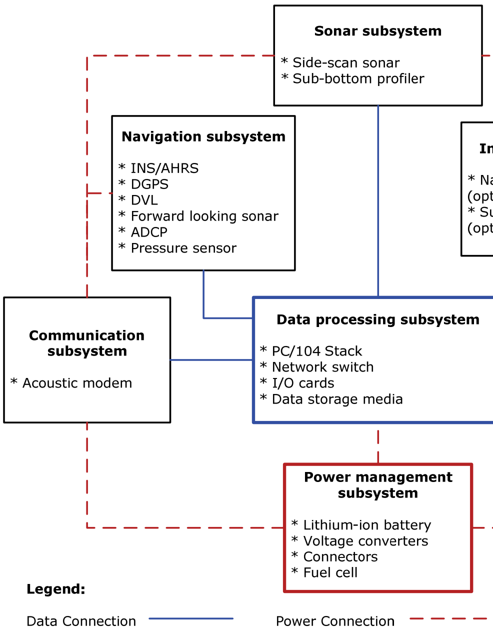


Fig. 5. Our UUV system architecture proposal.

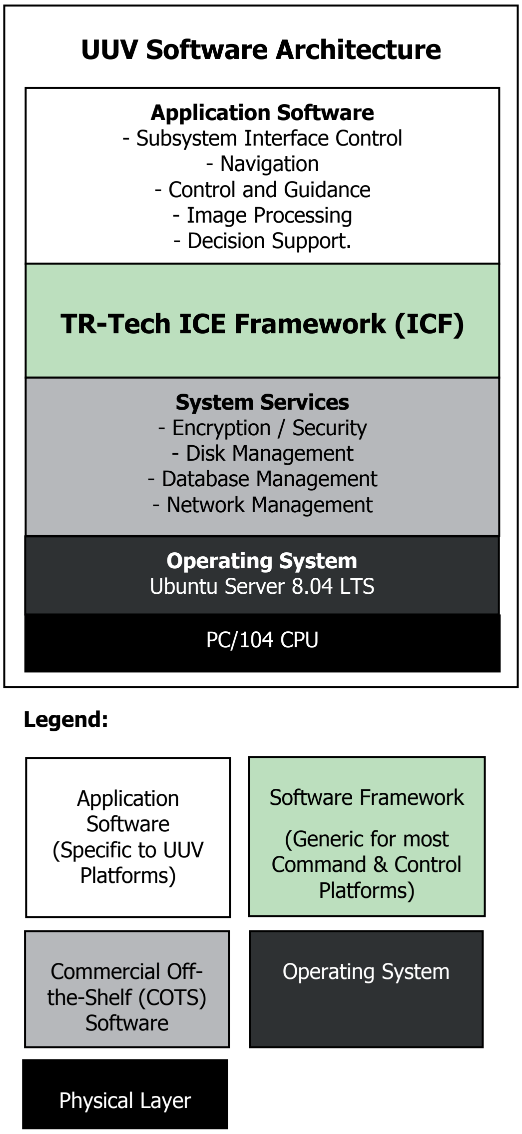


Fig. 6. Our UUV software architecture proposal.

The layers can be listed from bottom to up as:

1. Physical Layer: PC/104 CPU [49].
2. Operating System: Ubuntu 8.04 LTS [50], which is an embedded Linux distribution.
3. System Services: Commercial Off-the-Shelf (COTS) software for utilities such as encryption/security, disk management, database management, network management.
4. TR-Tech Internet Communications Engine (ICE) Framework: A generic set of services, utilities, libraries, which are required for any type of Command and Control platform implementation.
5. Application Software: The applications which are specifically required for a UUV platform implementation

where the structure of the TR-Tech (ICE) Software Framework (the so-called TR-Tech ICF) is illustrated in Fig. 7.

The layers constituting the framework can be described as follows:

1. ZeroC ICE [51]: ICE is known and considered as the new generation distributed data processing middleware (i.e. the new generation CORBA). It is a very effective and light-weight communications middleware implementation, which is developed by ZeroC and distributed with GPL (GNU Public License).

2. Boost C++ Library [52] (Component Infrastructure): Boost, which has been initiated by the efforts of the C++ Standards Committee Library Working Group, is currently one of the most respected and most widely used/participated (in the orders of thousands of C++ programmers) C++ library projects. It constitutes the component services layer of the TR-Tech ICF.

3. Intel Open Source Computer Vision (OpenCV) Library [53]: It is a computer vision and real-time image processing library, which has been developed in C/C++, and distributed with Berkeley Software Distribution (BSL) license.

4. GEOTRANS [54]: This is a library performing various conversion operations among numerous geographic coordinate systems, projection systems and datum sets. It has been developed by the National Geospatial-Intelligence Agency.

5. Interface Pattern Infrastructure: This layer is nothing but the pattern (e.g. remote procedure calls (RPCs), publish/subscribe services, multicast /broadcast services, socket services, etc.) implementations, which provide the communication of the distributed components on the distributed computing environment.

6. Domain Infrastructure: These services are various manager components, which are executed as daemons at the system. The major components are RS-232, RS-485 hardware adapters, alarm and event manager, configuration and adaptation manager.

7. System Management Infrastructure: These services are also various manager components, which are executed as daemons at the system. The major components are system manager, software health manager, checkpoint/recovery, load manager, backup manager, log manager.

6. Conclusion

Unmanned Underwater Vehicles (UUVs) will preserve their popularity both in civilian and military purposes. Advances in propulsion and energy storage technology will increase the endurance of these vehicles. In addition to this, as long as the processing powers will increase, it will be possible to implement more advanced navigation (e.g. geophysical) and control (e.g. online-training based and soft computing oriented) solutions on these platforms.

Moreover, the expectations from these devices are evolving day-by-day towards the execution of more coordinated operations. More complicated formation schemes will be pursued in order to accomplish more complicated cooperative missions.

Multi-tiered software architectures are becoming de-fact standard in the defense industry for realization of the C4ISR (Command, Control, Communications Computer, Information, Surveillance and Reconnaissance) systems. Naturally, unmanned platforms, and hence UUVs will get advantage of such implementations. Several considerations arise for the realization of such architectures in the unmanned platforms. In order to achieve rapid development and broad maintenance capabilities, robust open source components shall be identified. Certainly, the robustness of these components will also be critical regarding the run time performance of these mission critical vehicles.

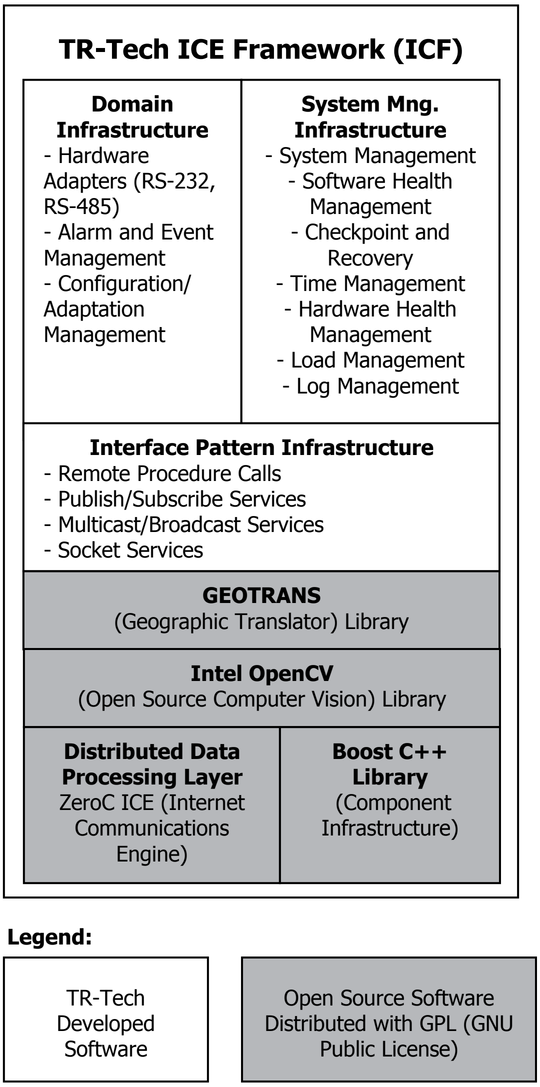


Fig. 7. Our software framework. It should be noted that the framework is designed generically for most Command & Control applications.

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