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A SURVEY ON UNINHABITED UNDERWATER VEHICLES (UUV)

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ABSTRACT

This work presents the initiation of our underwater robotics research which will be focused on underwater vehicle-manipulator systems. Our aim is to build an underwater vehicle with a robotic manipulator which has a robust system and also can compensate itself under the influence of the hydrodynamic effects. In this paper, overview of the existing underwater vehicle systems, thruster designs, their dynamic models and control architectures are given. The purpose and results of the existing methods in underwater robotics are investigated.

INTRODUCTION

Underwater robotics research has attracted the interest of many researchers over the years. The primary reasons are the need to perform underwater tasks that may be dangerous for a human operator and the need to perform underwater survey tasks that last for longer periods of time. Today, most of the systems that require a certain level of precision and dexterity are built as Remotely Operated Vehicles (ROVs). Whereas, the systems that perform repetitive tasks such as underwater survey tasks are configured as Autonomous Underwater Vehicles (AUVs).

While ROVs use a tethered communication and energy link with a mother ship, AUVs do not require such a connection. Nevertheless, most survey class AUVs maintain acoustic communication with their human operator to transmit vehicle status information and higher-level control signals. The continuous tethered communication enables the ROVs to be teleoperated. The inclusion of the human decision and dexterity enables the system to carry on precision operations in undefined environments which is true for most of the underwater tasks. The addition of a robotic manipulator to an ROV or AUV upgrades the system to an Unmanned Vehicle-Manipulator System (UVMS). As a result of this, the dexterity is increased as the control problems of the system arise.

The authors are initiating a study to challenge the control and stability problems of UVMSs using a teleoperation system setup. The first phase of the research involves a detailed investigation on modeling and control of these systems. This paper presents a survey on underwater vehicle research topics: modeling, fault tolerance in UUVs, control strategies, UVMSs, localization/navigation and communication.

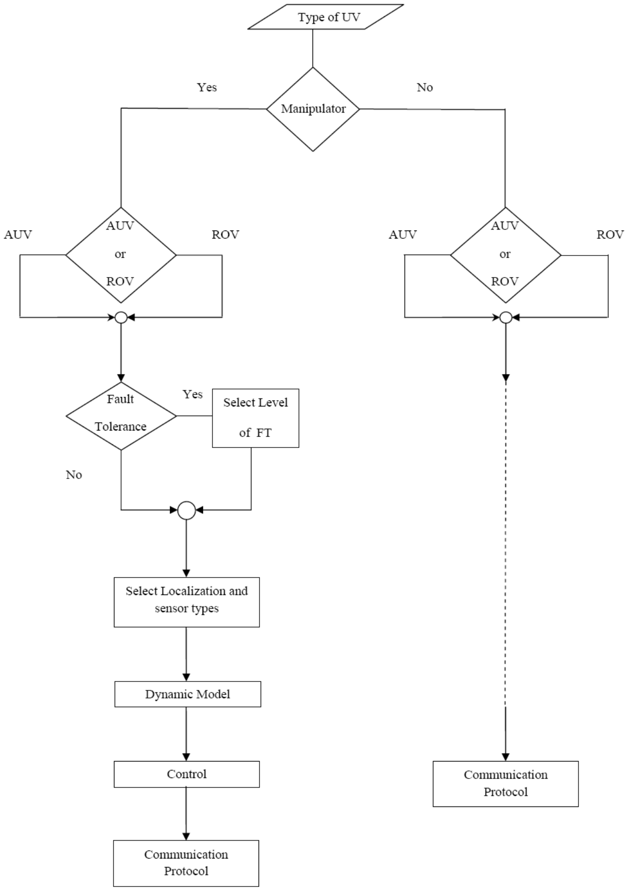

Figure 1. Flowchart of the UUV Design

Figure 1 outlines the design flow of an UUV. Complying with the design criteria, after the first two decisions on inclusion of a manipulator and configuring the system as an AUV or an ROV, the design flow is the same for all UUVs. The designer must investigate the working conditions of the system for possible additions of fault tolerance features. After the selection of sensory information, navigation and localization equipment, dynamic model of the system is developed. The dynamic model also includes the environment model with all the hydrodynamic effects. The ultimate task is then initiated as the control architecture design. This design phase involves simulation studies and the verification of the developed controller and the system in experimental work. As the aim of our work is to have continuous communication for teleoperation, communication protocols and problems (time delays, data losses) remain as an open area of research.

MODELING

Modeling is the first phase of an UUV design regardless of selecting the UUV as and AUV or an ROV. Design criteria direct the designer whether to include a robotic manipulator to the system or not. At this point, modeling studies initiate. The modeling is investigated in three subsections as the parameter identification, thruster dynamics and the dynamic modeling of the whole system.

Identification

In [1], the authors addressed the problem of experimental identification of finite-dimensional nonlinear dynamical models for open-frame ROVs. And the results show that the development of model-based control techniques for the dynamic positioning of underwater robotic vehicles has been limited by the lack of experimentally validated plant models. In [2], the aim was to demonstrate that the modeling and identification of small underwater vehicles could be achieved at low cost. Identification was done in two steps, Least Squares (LS) and Extended Kalman Filter (EKF). In [3], the authors collected the experimental data for a set of maneuvers which were later reconstructed to give the required vehicle state estimates. Extended Kalman filter was used for this reconstruction. Using a stepwise regression algorithm, hydrodynamic derivative estimates were generated. There were significant differences between some of the hydrodynamic coefficients obtained using system identification and those measured using the planar motion mechanism.

Thruster Dynamics

A new parameter, Critical Incoming Angle (CIA), is introduced in [4]. The incoming angle effects can be dominant while an underwater vehicle changes its direction, or an omni-directional vehicle carries out its task. In [5], two improvements in the finite-dimensional nonlinear dynamical modeling of marine thrusters is reported and tested for two conditions, axial fluid flow and using sinusoidal lift/drag curves by the authors. The trail data concludes that thrusters' models utilizing both enhancements provide a better level of accuracy in both transient and steady-state responses. In [6], the authors developed a nonlinear parametric model of a torque-controlled thruster. They evaluated several compensators using a hybrid simulation which combined an instrumented thruster with a real-time mathematical vehicle model.

Dynamic Modeling

Kane's method is utilized in [7] to develop an n-axis robot arm by using. Four dynamic forces; mass, profile drag, fluid acceleration, and buoyancy are added to the environment model in this work. In [8], the authors claim that hydrodynamic forces can be large and hence have a significant effect on the dynamic performance of underwater manipulation systems. Hydrodynamic forces for a cylindrical single-link arm are investigated in this work. In [9], some techniques which can be used to derive performance prediction and autopilot design are described. These techniques are system identification and predictive method.

FAULT TOLERANCE

Although much work has been produced on fault detection/diagnosis, our aim is to develop systems that can configure a fault-tolerant system in different levels. Thus, the survey is focused on the research that provides a solution as a result of the fault detection.

Fault-tolerant design of a system for the 6 degrees-of-freedom ODIN autonomous underwater vehicle (AUV) is described in [10]. Experiments focused on detection, isolation, and accommodation of thruster and sensor failures. In [11], the authors studied the allocation of thruster forces of an autonomous underwater vehicle under thruster faults. The allocation technique is based on the generalized inverse theory and provides the minimum norm solution to the thruster forces for a particular motion trajectory. The proposed control law allows the AUV to track the desired task - space trajectory with asymptotic reduction of error in case of thruster faults. In [12], the authors presented the software and hardware architectures of their Autonomous Underwater Vehicle Controller (AUVC). AUVC ability to detect failures and select appropriate backup systems to achieve mission was tested in this work.

CONTROL

Current work on the control of the underwater vehicles has been focused on actuation/thruster control, dynamic system control and, control architecture design.

Actuation/Thruster Control

In [13], a simplified model of a thruster used and a general equation of rigid body motion for an underactuated ROV are discussed. Firstly, the non-linear and the coupling effects on the ROV are derived. Observed steady-state nonlinear behavior of the thruster is used to design a PID controller. In [14], the authors presented experimental results of five different thruster control systems based on on-line neural network (NN) control, off-line NN control, fuzzy control, and adaptive-learning control and PID control. The controllers in this work are tested for the system with and without fins. The fins are shown to change the system hydrodynamics, (i.e. drag force). After the tests, the authors claim that adding fin to the system makes it more stable and increases the hydrodynamic inertia effects.

Dynamic Control

In [15], it is shown that navigation can be achieved in the presence of unknown currents. The navigation algorithm is implemented using an observer and experimental and theoretical works are compared.

The problem of controlling an Autonomous Underwater Vehicle (AUV) in a diving maneuver is discussed in [16]. Both non-adaptive and adaptive techniques are considered to adjust to the changing dynamics and operating conditions.

New computer architecture to enable the vehicle to operate as a network server using acoustic and radio communication links is presented in [17]. Test results showed that the vehicle was capable of automatically controlling its altitude above bottom, its depth, its heading, and cross-track error. The vehicle was designed for accurate navigation in shallow water using an extended Kalman filter and DGPS.

In [18], the authors gave a detailed of the development of ODIN-III as well as the basic algorithm for the framework experimental results for a fine motion control scheme. Controller showed improvement of a fast motion compared to the previous results of ODIN.

In [19], it is claimed that intervention tasks performed by intelligent underwater robots are improved by the increase in their ability to gather, learn and use information about their working environment. In this work, experimentation is done for the real-time embedded Disturbance Compensation Controller (DCC) for small AUVs. The results indicated that it is possible to use underwater vehicles for station-keeping tasks in shallow water with the technology described in this study.

An experimental investigation of model-based controllers for the low-speed maneuvering of fully actuated underwater vehicles is reported in [20]. Experimental results indicated that when fixed model-based controllers that employ incorrect plant model parameters perform worse than PD controllers. While unmodelled thruster saturation significantly degrades the performance of the adaptive controllers, model based controllers performance is about the same as the performance of the PD controllers.

Integration of planning with probabilistic state estimation and execution is described in [21]. The authors were motivated by the need to explore the oceans in a cost-effective fashion using Autonomous Underwater Vehicles (AUVs). This required AUVs to be goal-directed, perceptive, adaptive and robust in the context of dynamic and uncertain conditions. In this work, the authors claimed that using a unified representational and computational framework for estimation, planning, and execution has shown effective for adaptive mission control.

Control Architecture

Four types of control architecture used in AUVs, hierarchal, heterarchical, subsumption, and hybrid architecture, are discussed in [22]. Other than a new sensor-based embedded AUV control system architecture, 25 existing AUVs and 11 AUV control architectures are also briefly presented in this study. In [23], Yuh has published a survey, which is highly cited in UUV publications, about underwater robotic technologies and dynamics, control systems, navigation and sensors, communications, power systems, pressure hulls and fairings, and mechanical manipulators.

Smith presented a disturbed control system for the Ocean Voyager II AUV which is called as LONTalk in [24]. The advantages and disadvantages of using this system are discussed with examples. In [25], the authors developed a new control system which is called sliding control that is said to deal with precise trajectory control easily. Methodology of this system and simulation results are presented in this work. In [26], the authors claim that a multivariable sliding mode autopilot based on state feedback, designed assuming decoupled modeling, is satisfactory for the combined speed, steering, and diving response of a slow speed AUV. The results of the trails indicate that the influence of speed, modeling nonlinearity, uncertainty, and disturbances, can be effectively compensated, even for complex maneuvering.

In [27], the authors described kinematics of an AUV by six state variables and four inputs, and use a Lyapunov-like function to develop a nonlinear tracking control scheme and it effectively made use of the nonholomic nature of the system.

In [28] the authors worked on the dynamic model of the untethered vehicle, and described an adaptive control strategy for such vehicles. In this work, the robustness of the control system with respect to the nonlinear dynamic behavior and parameter uncertainties is investigated by computer simulation. The results indicated that the use of the adaptive control system can provide acceptable performance of the vehicle in the presence of unpredictable changes in the dynamics of the vehicle and its environment. In [29], the authors designed a Multi-input / Multi-output self tuning control system and the performance of the system is evaluated.

An adaptive Saturated Proportional-Derivative (SP-D) setpoint controller for AUVs is proposed in [30]. It is claimed that the global asymptotic stability can be guaranteed even when the gravity and buoyancy force is uncertain with this type of a controller. In this work, Lyapunov's direct method and LaSalle's invariance principle are used.

A hybrid adaptive control of AUV is investigated in [31]. The authors presented the results for modified direct, indirect, and linear quadratic Gaussian adaptive control in this study. Results concluded that the direct method produced the best results. In [32], the authors introduced a vehicle control system that is capable of learning and adapting to changes in the vehicle dynamics and parameters. This control system is compared with a conventional linear control system in this study.

In [33], the authors described a technique to localize the vehicle through detecting known landmarks using on-board navigation sensors, overcoming uncertainties in vehicle dynamics and its operating environment. Simulations and experiments conducted in this study indicate that the system is capable of controlling the vehicle in six DOF with high accuracy using the estimated position and velocity from the on-board sensor-based navigation system. In [34], the authors presented a six degrees-of-freedom controller for AUVs. The author selected the control law to be adaptive to cope with the dynamic parameters which are mostly uncertain in the underwater environment. The proposed control law adopts quaternion representation for attitude errors, and thus avoids representation singularities that occur when using Euler angles description of the orientation.

An adaptive control of underwater robots with sonar-based position measurements is presented in [35]. In the light of the test results, the control system is shown not to not require any prior information about the system dynamics and yet could provide high performance in the presence of noise and unmodelled dynamics. In [36], another adaptive control law for AUVs and ROVs is introduced which is not using earth-fixed frame nor vehicle-fixed frame. Results indicate that the use of the proposed adaptive action could significantly reduce the tracking error.

In [37], the authors proposed two methods to compensate for the model uncertainties. The first method is an adaptive passivity-based control scheme and second is a hybrid (adaptive and sliding) controller. In this work, the hybrid controller is simulated for the horizontal motion of the Norwegian Experimental Remotely Operated Vehicle (NEROV) and simulation results indicate a satisfactory performance. In [38], the authors investigated the theory and experimental work of the Adaptive plus Disturbance Observer (ADOB) controller for underwater robots. They claim that this controller would be robust under the influence of external disturbance and uncertainties in the system. The result of experiments conducted in this study indicate that the ADOB controller could be listed as promising for underwater robots, especially for the systems with failing PID type controllers.

Yuh has presented the results of recent study on the application of neural network to the underwater robotic vehicle system in [39]. The robustness of the system was investigated against the nonlinear dynamic behavior and the results proposed by computer simulations. According to the simulation results using neural network has increased the autonomy of the vehicle. In [40], the authors introduced learning control approach to underwater robotic vehicle system using neural networks. The simulation tests result concluded that dominant vehicle dynamics are varying with the vehicle velocity and effect of thruster dynamics becomes significant at low velocity in the vehicle control system. Yuh [41], has also presented a learning control system which is using neural networks for underwater robotic vehicles and the system is tested by simulations. The simulation test results indicate that control system is capable of providing an acceptable tracking performance. A direct adaptive neural network control system is designed in [42]. The researchers trained this sytsem on-line by parallel recursive error prediction method and critic equation. In [43], the authors also described a neural network system which can arrange the robot dynamics and controller adaptation in parallel with robot control. In this work, adaptability of the system is investigated under unknown disturbance.

In [44], a neuro-fuzzy controller for autonomous underwater vehicles (AUVs) is described. The authors claimed that the advantage of modified fuzzy membership function-based neural networks (FMFNN) is combining the fuzzy logic and neural networks. Compared to other control methods, the proposed FMFNN control algorithm said to never require any information on systems, off-line learning procedures, and human intervention to adjust parameters. Computer simulations for this work are conducted and result indicated that the proposed FMFNN controller for an unknown dynamic system produces acceptable performance compared to other real-time, self-tuning controllers. In [45], the authors present the utilization of a self adaptive neuro-fuzzy controller as a feedforward controller and in mean time PD control as a feedback controller in controlling an AUV. In [46], a new design for fuzzy logic controller is proposed. In the study changes in UUV depth, regulates pitch are simulated and observed.

UNDERWATER VEHICLE-MANIPULATOR SYSTEM (UVMS)

The control of UVMSs can be investigated as pure motion control and interaction control architectures. In order to deploy a force-reflecting bilateral teleoperation system, interaction control architecture is our main area of interest.

Dynamic Motion Control of UVMSs

The problem of redundancy resolution and motion coordination between the vehicle and the manipulator in UVMSs are addressed in [47]. In this study, a task-priority inverse kinematics approach to redundancy resolution is merged with a fuzzy technique in coordination of the vehicle-arm. Researcher conducted simulation studies on a 9-dofs UVMS. In [48], a robust control scheme using a multilayer neural network with the error back propagation learning algorithm is proposed. The proposed controller is employed in the control of a robot manipulator operating under the sea which has large uncertainties such as the buoyancy, the drag force, wave effects, currents, and the added mass/moment of inertia. Simulation test results indicated that the control scheme could with the unexpected large uncertainties. In [49], the adaptive passivity-based control scheme is formulated in an augmented task-space where both the underwater vehicle and the end-effector have 6 degrees of freedom.

A tele-robotic control system has been developed for a subsea manipulator as part of the ARM (Automated Remote Manipulation) project in [50]. The ability of the ARM System is that it conducts tasks, previously thought to require divers, allows for the greater use of ROVs in current fields with considerable economic savings. In [51], the authors presented a new method to analyze dynamics of underwater robot manipulators. In the proposed method, hydrodynamic terms such as added mass, drag and buoyancy in dynamics of underwater robots are obtained by iterative learning control and time-scale transformation. In [52], the authors developed highly-accurate model of the hydrodynamic interaction forces, and implemented a coordinated arm/vehicle control strategy. Under this model-based approach, interaction forces acting on the vehicle due to arm motion were predicted and fed forward into the vehicle control system. Using this method, vehicle station-keeping capability was greatly enhanced. Tracking errors and settling times for the manipulator end point were reduced significantly.

Interaction Control of UVMSs

Two control schemes, extended hybrid control and extended impedance control, for compliant motion control of redundant manipulators in [53]. The experimental results have validated the two control schemes and demonstrated that the redundancy can be effectively utilized to optimize various objective functions. In [54], method of actively controlling the apparent stiffness of a manipulator end effector was presented. The approach allows the programmer to specify the three translational and three rotational stiffness of a frame located arbitrarily in hand coordinates. The stiffness control approach to force control in a manipulator system has been shown to be a useful and effective means of effecting force control in assembly tasks.

In [55], the authors presented a force control strategy for a robot floating on the water. The control strategy reduces the number of vehicle actuators required for the force control by utilizing the restoring force/moment applied to the vehicle. In [56], the authors defined a proper metric in joint space. Minimal parameterization of motion and force controlled subspaces as wel1 as the null motion component is realized. With this formulation, control of both motion/force and internal motion of redundant manipulator could be achieved utilizing a new hybrid impedance control method with inertial decoupling of each space. In [57], the authors presented a spatial impedance control with redundancy resolution. In order to ensure geometric task consistency, the rotational part of the stiffness is described in terms of a unit quaternion. The dynamically consistent pseudoinverse of the manipulator Jacobian is adopted to decouple the dynamics of the end-effector motion from the null-space motion. Redundancy is exploited to stabilize null-space joint velocities and optimize an additional task function.

LOCALIZATION/NAVIGATION

Most conventional systems have to use a GPS system to localization purposes where they have to go up to the surface after some period of navigation. Some recent research activities have focused on developing new sensory systems and strategies to cancel this type of a procedure. The following are some examples to these efforts.

At Florida Atlantic University, the researchers [58] designed and developed an enhanced inertial navigation system that is to be integrated into the Morpheus autonomous underwater vehicle. A complementary filter was implemented to provide a much smoother and stable attitude estimate. The results show that the filtering performance can be considered acceptable when the error autocorrelation function falls within a tolerable limit. In [59], the authors introduced a new methodology for the design of multi-rate navigation systems for underwater vehicles. The design technique proposed borrows from Kalman filtering theory and leads naturally to multi-rate complementary filtering structures, the performance of which can be assessed using a frequency-like domain interpretation.

In [60], the authors combined a database which contains sonargrammetric, terrain matching, and image registration information with the standard navigation with the standard navigation instrument suite. The accuracy of positional estimates could be maintained over a longer duration. As a result of this adaptive calibration, it is discussed that it is no longer necessary to go up to the surface to get new position from GPS. In [61], the authors provided a navigation method of an (AUV) for photo mosaicing of shallow vent areas where bubbles are spouting. Simultaneously, this method estimates the position of the AUV and the landmarks, such as bubble plumes and artificial sonar reflectors. This method was implemented on the testbed AUV "Tri-Dog 1" and an experiment was carried out in test tank.

In [62], the authors addressed the issue of estimating underwater vehicle trajectories using gyro-Doppler (body-fixed velocities) and acoustic positioning signals (earth-fixed positions). In [63], the authors proposed a scheme called Scalable Localization scheme with Mobility Prediction (SLMP) by utilizing the predictable mobility patterns of underwater objects for underwater sensor networks. In SLMP, localization is performed in a hierarchical way, and the whole localization process is divided into two parts: anchor node localization and ordinary node localization. During the localization process, every node predicts its future mobility pattern according to its past known location information, and it can estimate its future location based on its predicted mobility pattern.

DUAL COMMUNICATION

Communication is required for both AUVs and ROVs. AUVs use the communication as a heartbeat signal or when they report to the base. A communication protocol becomes necessary for more than one AUV systems cooperating to accomplish a task. However, the communications line is vital for ROVs. All the actions of the ROVs are controlled or monitored by the operator on a mother ship through a communications line. The researchers are working on new communication methods to take place of the tethered systems.

In [64], the authors are proposed a new acoustic modem which is able to provide data processing rates of at least 80Mflops while being sufficient compact for hand development and having low power consumption. In this work, hardware and software architecture of this new modem is presented. In [65], the authors investigated the communication of two AUVs and those AUVs were able to communicate each other by using acoustic modems while performing a simple task and the experiments show the success of the application.

In [66], the authors described an underwater sensor network with dual communication and support for sensing and mobility. The nodes in the system are connected acoustically for broadcast communication. Experiments show that acoustic modem developed in this work is a capable and usable platform for water applications in shallow waters at depths less than 100m. In [67], the authors described a communications and control framework to support the use of underwater acoustic networks and sample application scenarios for single and multi-AUV operation. In [68], the authors described different methods for underwater communication. Fiber optic underwater communication is presented, moreover, they provided an innovative solution of using radio modems.

CONCLUSIONS

This work provided a survey of the technologies used in designing UUVs. A flowchart of the design procedure is given to lead and direct the engineers to build such a system. Aligned with this flowchart, the past work on each step of the design process is presented to inform the design engineer on the recent advances in this field of technology.

Our first aim in the Robotics Laboratory of Izmir Institute of Technology is to build a platform that can stabilize in six degree-of-freedom under the influence of uncertain conditions at a certain depth. This requires sophisticated controllers such as adaptive, neural network and fuzzy logic controllers as reviewed in the Controller section to cope with the uncertainties. The thruster design is another factor in the efficient control of the system. Therefore, our focus is on thruster and controller design for our future work. The addition of an arm to the stabilized platform will be the next step in developing a UVM.

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