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Recent Developments in Modeling and Control of Underwater Robot Manipulator: A Review

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Abstract

Objective: The ocean resources and scientific related research is an attractive research topic. To witness a significant development of an intelligent robotic underwater work system, it is necessary to present various technological advancements in this area in form of technical review. **Methods/Statistical Analysis:** In this direction, authors provide a comprehensive assessment of recent developments of underwater robots and their various control strategies. This review highlights the different control techniques of underwater robots, which have been investigated for overall control of underwater robots. These controls include motion control, trajectory control of end-effect or for the underwater robot manipulators, thrust control and force control. **Finding:** Various control strategies have been developed and employed by researchers such as adaptive control, PID control, Sliding Mode Control (SMC), robust/optimal control, and robust overwhelming control. The literature survey has further emphasized the use of such controllers for motion, thrust and force control in underwater robotic conditions. **Application:** This article will be beneficial for researchers in this area to understand various applications of underwater robots. Another focus of this paper is to provide a candid commentary on modeling and simulation techniques adopted by various researchers in the area of underwater robots.

Keywords: Modeling, Trajectory Control, Thrust Control, Underwater Dynamics, Underwater Robot

1. Introduction

Ocean which covers three fourth of earth surface has been an attractive field for commercial utilization of ocean resources and scientific related research. This has efficiently improved the development of underwater robotic system. In various work assignments in undersea environment like construction, probing and repairing undersea equipment like welding of ships, servicing cables and pipes, salvaging for underwater archeology, and anything else which requires deep sea exploration etc., underwater robot manipulators have a vital role.

Underwater robot Manipulators are immature as compared to those used in on-land systems and therefore, performance of the robot is limited. High technologies have been developed for terrestrial robots. These technologies cannot be directly applied for underwater robots, since such systems have different dynamic characteristics then terrestrial robots. The dynamics of underwater robot manipulators are non-linear in nature because of rigid body coupling and hydrodynamic forces acting on the vehicle. This dynamic behavior is comparable to the well-known rigid body vehicle motion of an aircraft. However, there are a couple of important differences: 1. Underwater robot Manipulators mostly has comparable velocities in three principle directions. 2. The high density of water sets underwater robot manipulators apart from aircraft because of the forces and moments produced by the motion of fluid are significant. The continuous advancement in control, navigation, artificial intelligence, material science, computer, sensor, and communication, has made UVMs attractive in the study of oceans as investigated by[1–3]. Many researchers have modeled and control the different underwater robot manipulators using different

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control strategies broadly divided in five directions i.e., 1. Underwater robot control, 2. Motion control of the underwater robot, 3. Trajectory control of end-effect or for the underwater robot manipulators 4. Thrust control and 5. Force control. The segregation of the papers in these directions has been presented in five sections, which has been started from the next section.

2. Underwater Robot Control

The control related to the underwater robots is considered as control of its path, velocity or force on vehicle or end-effector of underwater robot manipulator. Because of unpredictable external disturbances and non-linearity this issue is very challenging. The different control approaches and schemes like adaptive control, sliding mode control (SMC), robust/optimal control, robust overwhelming controller, Proportional-Integral Derivative control (PID) and many other have been proposed and applied for control of underwater robots. This section covers the approaches and schemes for the control of underwater robots used by the researches from time to time.

In[4,5] have used extension of sliding mode control for control of UV (Underwater Vehicles) in presence of disturbances, nonlinear dynamics and under difficult control-system design problems. In[6] have developed equation for underwater vehicles using Lagrangian framework and by adding inertia for consideration of hydrodynamic underwater conditions. The added inertia provided clear interpretation in case when underwater condition and UV was considered in energy approach point of view. Yuh[7] has presented the dynamics of the untethered vehicle and applied the adaptive control strategy. The adaptive controller provided effective for UV under the influence of unpredictable changes in the dynamics of the UV and its surroundings. For similar conditions[8] have also developed adaptive 6-DOF controller for AUV's (autonomous underwater vehicles). In[9] have applied Newton's equations and Lagrangian formalism by combined framework for vectorial parametrization of inertia, Coriolis, centrifugal, and hydrodynamic added mass forces for UV with 6-DOF.

Energy methods have been applied by[10] for designing control laws for stability of UV while in motion. The principal technical challenges have been examined by[11] and have also provided new technology for commercial URV. An adaptive control scheme has been used by[12] to achieve transparency and stability for a teleoperation of an underwater manipulator. For unmanned UV, a lumped parameter has been modeled by[13]. It has also been shown that hydrodynamic coefficient has effective effect on the performance of AUV. In[2] have presented a non-regressor adaptive controller for motion control of an URV. Algorithm for adaptive controller has ability to estimate the control gains, which has been defined by the bounded constants. The divines and steering maneuvers[14] have assessed the hydrodynamic coefficients. This has been done by developing the controller with sliding mode observer and an extended Kalman filter. There is further by optimized Unscented Kalman Filter (UKF) Via a Radial Basis Function (RBF) for autonomous robot have been done by[15] for implementing novel method of Simultaneous Localization and Mapping (SLAM). Following the past developments[16], modeled 3D kinematics and dynamics of rigid body moment in fluid environment. The model was matrix-based and the effect of hydrodynamic equations on movement in fluid environment was studied. An adaptive controller scheme has been proposed by [17]based on existing parameter-adaptation schemes. Fewer control efforts has been used to obtain good transient performance of tracking errors. To achieve robustness to external disturbance and uncertainty effecting AUR[18] have provided adaptive plus disturbance observer (ADOB) controller. The controller has been examined experimentally by comparing with PID and PID plus DOB controller.A dynamic model for undulatory locomotion have been proposed by[19] to study the swimming mechanism of a developed bionic robot tuna by solving the established dynamic equations and efficiency formula. In this analysis, the swimming velocity and propulsive efficiency of the bionic robot tuna have been obtained numerically. Biomimetic fish robot has been designed by[20] using piezo ceramic actuators. The performance of fish robot has been further studied by considering artificial caudal fins. An analytical optimization approach has been developed by[21] to study model of 4 links caragiform fish robot. The combined effect of Genetic Algorithm (GA) and Hill Climbing Algorithm (HCA) has been analyzed for maximum velocity with which fish robot can travel. Author in[22] developed an underwater acoustic modem to control UV with wireless controller. The controller has been implementing on terrestrial wireless sensor network to analysis its efficiency. An octopus's anatomy based UR has been purposed by[23]. With four longitudinal and four radial muscles a 3D dynamic modeling has been performed. In[24] the study of swimming motion has been carried out of a squid-like robot with two undulated side fins. Space discretization has been done with finite analytical method and time discretization has been performed with Euler implicit scheme. Further PISO algorithm has been developed and implemented for velocity pressure coupling. In[25] have developed on-board PC with Windows XP OS for MUUV. The mathematical model has been prepared on bases of which control algorithm and system designing was done. Further hardware implementation and experimentation has been done. In[26] has implemented swarm network communication for AUVs which has been used to transfer the data, to communicate with one another to perform tasks such as navigating multi-path trajectory. The spherical shape structural design of the SUR-II has been purposed by[27]. It was able to with stand outstanding shock and was flexibly. For collection of data and control of motion this master–slave structure has been tested. CISCREA (semi-AUV) with low speed has been modeled by[28], having complex shape structure. The robust control has been achieved with stable controlled synthesis. In[29] described the BUSCAMOS-Oil monitoring system. This system has been created by combining autonomous surface vessel with UV. The controller modeled was based on bio-inspired neural networks. The algorithm of neural network was for avoiding obstacle and self-organization directional mapping. All such strategies have been useful and beneficial in this area of research.

3. Motion Control of the Underwater Robots

Another significant issue in underwater robots is its motion control. In this regard different researchers have developed and proposed various controllers which take care of the type of underwater robots and its environmental conditions. In this section, such studies have been presented in detail.

A self-tuned and linear feedback controller has been developed[30], which does not involve complex design procedures or vast on-line computations. A comparison of three controllers on UV has been performed by[31]. The three controllers are linear Proportional Derivative (PD) controller, a partial model-based compensation, and the nonlinear robust feed- back. On the basics of sliding mode approach[32–34] developed an adaptive controller for the tracking of UVMS. Dynamic modeling and Lyapunov-like analysis has been performed by considering fixed-body and joint-space coordinates for reducing errors. To reduce the total hydrodynamic forces on the AUVMS[35] have proposed a motion coordination algorithm. Resolution of kinematic redundancy of AUVMS has also been considered at the acceleration level to include system dynamics in algorithm.

In[36] have addressed the trajectory tracking problem for the low-speed directional of fully actuated UV. The demonstration with numerical simulations has been studied for wide range of operating conditions. The study for stability has been carried out by using linear Proportional-Derivative (PD) control and adaptive model-based controllers. The stability investigation of AUVs has been conducted by[37,38] for real-time optimization of motion planning. The proposed novel robust trajectory based controller performed satisfactorily in uncertain conditions encountered by AUV. In[39] have designed an autonomous underwater move-in-mud robot and analyzed measurement principle using Kalman filter to enhance the accuracy. To perform different tasks assigned to AUV, motion controller which is able to control position and speed has been developed and applied.

A general mathematical modeling has been provided for simulation and control of UV by[40]. The model purposed has been based on 6-DOF non-linear equations of motion and they further demonstrated the stability by Lyapunov function. The time delay controller has been applied to UIR for nuclear reactor by taking care of trajectory control problems[41]. On rudder UUV a nonlinear input-sate feedback control has been purposed by[42,43]. The controller has been applied to track trajectory on horizontal plane. In[44] discussed the motion control methods for a bionic UR with two undulating fins and applied reinforcement learning to actual robot control, by developing a Supervised Neural Q Learning (SNQL) algorithm. Ismail and Dunnigan[45] have presented a novel control law for an AUV. The stability analysis has been done by using Lyapunov approach and the desired position has been specified as a boundary through define point and region control problem. In[46] have analyzed asynchronous and susceptible raw data from the sensors to outliers in shallow water environment. The detailed sensor analysis based on experimental data gathered in shallow water has been done and further simple sensor fusion algorithm has been generated accordingly.

In[47] have proposed a combination of MAUV dynamic task assignment and path planning algorithm by using the combination of SOM neural network and a novel velocity synthesis approach. An algorithm has been applied to

AUV, to identify the shortest path in the presence of the uncertain current environment and dynamic tasks. In[48] have presented a hybrid baseline navigation method for AUV. The states of the source ship, floating transponder and AUV have been estimated by using combination of extended Kalman filter formulation, the broadcasted kinematic information and acoustic ranges. In[49] developed an on-line dynamic path re-planning system for an AUV to allow it to work efficiently in a spatiotemporal, messy, and uncertain environment. In[50] have shown that optimal one-step-ahead exploration strategy which were based on a transformed optimization conditions with the Cognitive Adaptive Optimization (CAO) can lead to highly efficient solutions for the multi-AXV exploration. Direction finding of an AUV near the free surface has been taken care by[51]. The control system developed for this has taken as uncertain terms like wave disturbance and unmodeled hydrodynamics. The technique for navigating robotic fish has been purposed by[52]. The technique consists of flow sensing and optimized propulsion with controllable mechanism. In[53] explored the target trajectory in noisy measurements on basics of Unscented Kalman Filter (UKF). To perform glider motions in 3D multiple underwater gliders have been developed by[54]. The active transmission has been achieved by own-ship intercept sonar for finding targets in fluid[55]. All above studies have given a direction for the motion control of underwater robots. Next section will highlight the trajectory control of end-effector for the underwater robot manipulators.

4. Trajectory Control of End-effector for Underwater Robot Manipulators

The intelligent robot should have manipulating capability and able to follow right trajectory. This makes control of end-effector trajectory a very important aspect for underwater robot manipulation. The archival literatures available for modeling and control of end-effector trajectory related to of UWR are discussed in this section.

Optimal trajectories for UV have been computed optimal control and have avoided collision by using a numerical solution[56]. The hydrodynamic between arm and UV poses significant challenge in its control. In this regard[57] studied interaction behavior between an arm and UV by considering rolls and yaw motion of UV for two seconds. In[58] applied the neural network structure of the fuzzy CMAC to enhance fine performance on non-anthropomorphic UR hand.The active and slave arms of free floating dual arm robot have been mapped while in motion by[59] with minimum disturbance of the base. Extending the scope of control, theoretical description of hydrodynamic forces pertaining to added mass effects, buoyancy and gravity, linear and quadratic damping effects have been modeled through bond graph modeling for 3 DOF underwater robot by[60] for end-effector control. In[61] has designed controller for the control of trajectory of UM mounted on AUV. The modeling has been done using bond graph technique. The effect of hydrodynamics has also been considered. The controller designed was based on PD and has been further applied on 2-DOF on-board AUV manipulator. In[62] have presented a new four-bar linkage underwater manipulator design. In[63] have investigated the dynamic modeling with motion planning and control of UVM multibody by using Newton–Euler recursive algorithm. Using this algorithm, coordinate motions between AUV and manipulator have been realized by controlling the restoring forces and by saving the electric power. Besides these studies several other researchers have been attempted for thrust control of underwater vehicles, which has been presented in next section.

5. Thrust Control

Thrust control has significant role for the stability of underwater robot manipulator. This interesting and challenging area attracts the researchers. Time to time researches have shown their interest in this area which is reported in this section. In[64,65] have reported the comparative experiments between model-based control algorithms and conventional thrust control algorithms by applying for control of conventional bladed propeller marine thruster. The model has been purposed by[66] for speed of response depending on instructed thrust level. The modeling involved non-linear parametric model for control of torque with sluggish non-linear filter behavior of thrust. The finite-dimensional nonlinear dynamical model of marine thrusters has been improved by[67]. The first improvement was to include consequence of rotational fluid velocity along with inertia on thrust behavior and further improvement was to determine non-sinusoidal lift/drag. Lumped parameter scheme based identification has been applied separately to estimate drag and thruster installation coefficient[13]. This has been done by considering role of propeller-hull and propeller-propeller for open frame UUV-ROMEO.

In[68] have proposed a new strategy for allocating fault-accommodation on thruster forces of AUV and presented a framework that exploit the consideration of thruster fault while in operating condition. The thrust has effect of Strouhal number, the Froude number, the Reynolds number, and the power consumption when its study has to be done specially for biomimetic fish robot. In this regard[20] have proposed a biomimetic fish robot with piezo ceramic actuator and further studied the role of artificial caudal fins on the fish robot's. In[69] have presented the navigation of underwater 6 DOF REMO Robot. Due to the parallel platform the UR, the kinematic properties have permitted vector formation of thrust forces to permit maneuverability, flexibility, and holonomic abilities for navigation and positioning. The control of thruster used in longitudinal propulsion has been compared by using PID, sliding and fuzzy controllers for MUUV[25]. In[70] have proposed a novel UR which employed a spherical hull and water-jet-based thrusters. The mechanical structure and electrical system part of the UR has been discussed in detail. Further by[27] water-jet-based thrusters has been used for 4-DOF underwater motion of the SUR-II spherical UR. The PD controller has been implement to control the water-jet thrusters for underwater motion and further output data has been calibrated by using Kalman filter. The torque and force control is one of the significant issues in underwater robot manipulators, which has been discussed in next sections.

6. Force Control

The interaction of URMS with the environment is challenging due to uncertainty in the model knowledge, hydrodynamic, kinematic redundancy of the URMS and unpredictable underwater disturbances. Number of researchers has proposed and implemented different strategies for force/impedance control applied on underwater robots or vehicles. All significant and important literature has been reviewed in this section. In[71] have investigated effectiveness of impedance controller on UVMs through simulation. In[72–75] has presented an external force controller model for UVMS which does not need any dynamic compensation by using an explicit force control scheme. Further in underwater conditions the loss of interaction because of UV movement has also been considered. The study of AQUA, an underwater hexapod robot was characterized for the forces produced due to the paddle's oscillation by[76]. Experiment has been done by creating model which predicts the force produced both by paddle oscillation and flexible fins. In[77] have presented the concept of crabster i.e., closed-form dynamic equations based on L-E formulation. The concept has been used for the modeling of drag and lift forces acting on the legs of UR. In shallow water working of underwater vehicle most likely gets disturbed by the strong surge which produces hydrodynamic forces. In[78] have developed the second order wave drift force model which takes care of UV in shallow water. The proposed controller is for three dimensional disturbances due to wave forces. Along with PID and fuzzy compensator, least square multi order data fitting polynomial prediction has been used for this application. In[79] have implemented successfully Multiple Impedance Control (MIC) and AOM method for explicit dynamic model of a dual arm UVM which showed a better tracking error in case of collision with environment. In[80] have developed a scheme for disturbance compensation of a mobile dual-arm UR. This has been done by deriving internal torque, using redundant parallel mechanism theory. All these research work has given a direction for force control of underwater robots.

7. Conclusions

Research from around the world has been attracted in the field of underwater robots. Different types of UR/UV have been controlled, by applying different control strategies, accordingly the review has been done. The review may be concluded as follows.

- Several researchers have modeled and control the underwater robots and vehicles using different control strategies like adaptive controller, model-based controllers, PD, PID, Sliding mode, etc.
- The techniques of control of underwater robots has been described by researchers for overall control of underwater robots, motion control, trajectory control of underwater robot manipulator, thrust control and force control. Now, there is a choice for the researchers to adopt proper techniques in the field of control of underwater robot or vehicles.
- The main emphasis is to provide information about the modeling and control approaches adopted by various researchers in the field of underwater robots. The review shows that limited research has been carried out for the control of flexible link underwater robot manipulator.

- In most of cases, model interaction with underwater environment has not been considered while performing tasks.
- There is a need to investigate the modeling strategy to incorporate possibility of flexible link for underwater manipulator to perform different tasks while interaction with underwater environment.
- Attempts are still required to elucidate the exposure response relationship for the assessment of unknown forces produced in underwater conditions. Theoretical and algorithmic developments should be continuing to be made in development of new types of underwater robot manipulators or vehicles.

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