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Robust sliding mode control of a mini unmanned underwater vehicle equipped with a new arrangement of water jet propulsions: Simulation and experimental study

Ehsan Zakeri [a,*], Said Farahat [b], Seyed Alireza Moezi [a], Amin Zare [a]

[a] Young Researchers and Elite Club, Shiraz Branch, Islamic Azad University, Shiraz, Iran
[b] Mechanical Engineering, University of Sistan and Baluchestan, Zahedan, Iran

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ABSTRACT

This paper presents dynamical modeling and robust control of a Mini Unmanned Underwater Vehicle (MUUV) equipped with a new arrangement of water jet propulsion. The water jet propulsion includes some advantages comparing with a propeller one, such as, reducing the number of required motors, desired number and arrangement of the propulsions, removing adverse torque and cavitation due to propeller rotation and etc. In order to model the proposed MUUV, the gray box method is used in such a way that the dynamical equation of motion is derived analytically by Euler-Lagrangian method, and then the hydrodynamic coefficients (such as added mass and drag coefficients) are derived by performing some tests in a Computational Fluid Dynamic (CFD) software. The dynamical model is used to simulate the MUUV system and also to design the proposed controllers, which are Feedback Linearization Controller (FLC) and Sliding Mode Controller (SMC). In order to investigate and compare the performance of the MUUV and the applied controllers, three types of tests including a desired signal tracking case and two desired path tracking cases are designed. To do so, a method is presented to obtain the desired signals from a desired path under predetermined conditions. Then, an MUUV prototype is designed and constructed in order to investigate the performance of the proposed water jet propulsions and controllers for regulation and tracking desired signal purpose, experimentally. As it is expected, the simulation and experimental results show better performance of the SMC compared to FLC. Furthermore, the experimental results reveal that the water jet propulsion is implementable to practical prototypes and also can be produced in an industrial level.

1. Introduction

Oceans are one of the main sources of energy and also a balance of the chemical processes for the life cycle. They have important advantages, such as: providing heat and energy, containing hydrocarbons and minerals, moderating weather, the result of which is supplying food sources, and controlling seafood resources, directly. All of these points have motivated human to investigate into the oceans by developing and utilizing new equipment such as Unmanned Underwater Vehicles (UUVs) or robots [1]. Underwater robots have widespread applications in marine industries or rescue such as, inspection, repairing and maintenance of subsea structures, inspection and maintenance of oil pipelines under the sea surface, and etc. [2].

According to the above points, the importance and applications of submarine robots lead to lots of researches on different fields corresponding these robots. These researches include modeling, control and even path planning [3] and [4]. In the field of modeling and investigating the robot motion, Dantas and De Barros studied numerically the effect of near-surface motion of Autonomous Underwater Vehicle (AUV) on its maneuverability [5]. To do so, they used Computational Fluid Dynamics (CFD) and compared their results with real data for validation. The results showed that the use of nonlinear method in CFD is closer to reality, compared with the standard method. In another study, Randeni et al. examined the hydrodynamic reactions of two AUVs having relative motion [6]. To do so, they used CFD; additionally, they proposed a simple model for AUV hydrodynamic forces with relative motion. Finally, comparing the results obtained from CFD modeling and the simple proposed model with real experimental data, they showed that both methods were acceptable, and appropriately accurate.

In the field of control and stability of these robots, Seok suggested an adaptive controller for under actuated underwa-

* Corresponding author.
E-mail address: ehsan8631@gmail.com (E. Zakeri).

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ter vehicles [7]. The design of the controller was performed with assumptions such as asymmetric hydrodynamic coefficients matrix and also uncertainty in damping coefficients taken into account. Simulation results showed that this controller was acceptable. Zhang et al. designed a controller that was robust to uncertainty and disturbance for high-speed vehicles [8]. They used H_∞ and LMI techniques for robustness and proving the stability. Also, for simulation, they derived dynamical equations for a vehicle under super-cavitation conditions. The simulation results showed a good robustness and reasonable performance of the controller. In another research, Xu et al. designed a dynamic Sliding Mode Controller (SMC) for the aim of path tracking in order to be used in under actuated underwater vehicles [9]. To design the controller, the back stepping and sliding mode methods were used and consequently, a controller robust to uncertainty and disturbance was designed. The simulation results indicated a good controller performance.

In general, design and construction of UUVs include three main sections; physical or mechanical section, electrical and electronical (hardware and software) section and finally, designing a convenient and efficient controller. The design of physical and mechanical parts of UUV includes, the appearance of the main body (which must possess some important properties such as low drag coefficient, resistance to pressure and corrosion, proper location of center of mass and volume and etc. [2]), type and arrangement of propulsions (which is very important because it is usually considered as system input that shows the controllability of the UUV's). Electrical and electronical section of UUV includes electrical motors or propulsions, various necessary sensors, camera for monitoring underwater space, electronic circuits, microcontrollers and also a proper software to control, monitor and communicate with the UUV. Designing or determining a convenient and efficient controller is very important because these vehicles are guided by remote operator (Remotely Operated Vehicle (ROV) or autonomous (Autonomous Underwater Vehicle (AUV)). Therefore, the applied controller must be robust against uncertainties or disturbances in order to guarantee the stability of the UUV position and states.

Dynamic modeling of a UUV is of special importance, because this is a prerequisite of UUV simulation and also designing model-based controllers; therefore, the more accurate the dynamical equations are, the closer to reality the simulation is and the more efficient the controller is. Therefore, so many researches have worked on modeling and deriving dynamical equations of UUVs motion. Modeling of a UUV is usually performed by three different techniques:

1. Considering the UUV system as a black box and finding a proper UUV model. This method is mostly used when the dynamical equations of the UUV system or part of it cannot be derived analytically or they are very complex. To overcome these problems, the system is considered as a black box, and then, by using various methods, of which the most common ones are the intelligent methods, the system is identified and modeled, such as modeling of an ROV using artificial neural networks [10] or modeling an AUV using improved fuzzy neural network [11].
2. Considering the UUV system as a gray box, which means that an analytical model is derived, and then unknown parameters are obtained by using system identification techniques. This method is the most common one, because modeling of UUV as a solid body and without considering hydrodynamic forces is possible, while modeling hydrodynamic forces are not and their parameters are usually estimated by numerical methods or experimental (CFD [12] or experiment [13]).
3. Analytical modeling of the system by means of kinematic, dynamic, robotic and fluid dynamics methods. This type of modeling is not accomplished as much, because there are many complexities and difficulties in analytically modeling of hydrodynamic forces of the UUVs with irregular body shapes.

As mentioned before, designing an efficient controller is of great importance for UUVs, because of the remote control issue. Many researches have focused on designing and applying various control methods on UUVs. These researches include three main types of controllers, as follows:

1. Applying model-based controller on the UUVs such as back stepping or sliding mode [14].
2. Applying non-model-based or intelligent controllers on the UUVs, such as optimal PID [15] or fuzzy logic [16] and neuro-fuzzy controller [17].
3. Appling hybrid model-based intelligent controllers on the UUVs, such as adaptive fuzzy sliding mode [18].

This paper presents the design of a mini UUV (MUUV) with a new arrangement of water jet propulsion including dynamical model of the proposed MUUV in order to be used in simulation and designing of controllers, and finally, design and construction of a prototype of the proposed UUV, which is a mini Unmanned Underwater Vehicles with a new Water Jet propulsion arrangement (mini UUV-WJ) named as "mUUV-WJ-1" in the present work, to show practical applicability of this idea.

The advantages of using a proper arrangement of water jet propulsions are listed as below [19]:

- **Reducing the number of required motors:**

At least six motors with propeller are required to control the UUV in its six degrees of freedom, whereas by using water jet propulsions just one or maximum two water pumps are required in order to provide the necessary pressure. So any number of required propulsion in the form of water jet can be branched from the pressured water vessel and guided to the desired place by hose. However, a control valve is needed to adjust the output water flow of each branch.

- **Removing adverse torque and cavitation due to propeller rotation:**

The water jet propulsion just produces axial force without any adverse torque and also no cavitation is produced due to the rotation of blades [21].

- **Fast response:**

The response of the water jet flow and its corresponding force regarding the input command is very fast, comparing with the propeller type, because it is adjusted by control valves.

- **Better hydrodynamic shape:**

The propeller and its driving motor are usually considered as a disadvantage for hydrodynamic shape of the UUV body.

- **More efficient comparing with rotating propeller propulsion:**

Unlike the propeller propulsion, the water jet propulsion can generate the required force at high speed motion [21].

- **Lower cost:**

In general, the use of a water jet instead of a motor with propeller is more expensive; however, if a suitable arrangement of