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Working environments and controller design for unmanned underwater vehicles in offshore aquaculture – A review

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Abstract: In offshore aquaculture especially fish farming, many manual operations such as inspection on the fish net-pen (known as net-cage interchangeably and including the infrastructure to house net-pen) are facing the constraints of labour shortage, safety, productivity and operating costs. To tackle this challenge, unmanned underwater vehicles (UUVs) have been deployed to perform the tasks usually done by humans. Compared to UUVs used in oceanographic research or recreational purpose, UUVs for offshore aquaculture require high maneuverability to operate close to the fish net-pen and the infrastructure (e.g., grid system and mooring lines) in a constrained operational environment. Furthermore, most UUVs rely on the limited onboard power supply without tethered power supply due to the constrained operational environment. Optimal utilization of energy is another issue. This paper discusses the applications of UUVs in offshore aquaculture with a focus on their maneuverability and energy optimality.

Keywords: offshore aquaculture, visual inspection, unmanned underwater vehicles (UUVs), high maneuverability, energy optimality

1. INTRODUCTION

About 71% of the earth's surface is occupied by water and 98% of which is contained in the ocean [1]. With its large coverage, human activities in the ocean date back to a few centuries in terms of transportation, fishing and at a later time, oil & gas industry. Recently offshore aquaculture, a sustainable way of producing ocean products (e.g., offshore fish farming), has been developed in response to the existing limited land inshore, the environmental impact on the local ecosystem near coastal area and conflicting coastal users such as shipping and recreational developments nearshore [2–5]. Stemming from this interest, many new technologies and knowledge of offshore aquaculture especially fish farming including the design and construction of fish net-pen and associated infrastructure, and the application of robotic platforms such as UUVs in fish net-pen inspections and other production processes are recently reported [6–8]. Note: UUV is a general term and it covers autonomous underwater vehicle (AUV) and remotely operated underwater vehicle (ROV). A detailed discussion can be found in [9, 10]. AUVs are deployed for untethered operations in a long range (e.g., environmental monitoring and defence) and ROVs are used for tethered operation in a short range (e.g., net cleaning and underwater photography). UUV, AUV and ROV terms will be used interchangeably whenever necessary not to alter the terms used by the original authors in the following literature review.

Aquaculture holistically defines any farming in the water body such as fish farm, seaweed farm and oyster farm whereas offshore aquaculture has an ambiguity in defining the term [11]. In this paper, offshore aquaculture could refer to aquaculture located off the shore either in the sea or in the open ocean. Being located in the sea or ocean with a harsh environment, the scheduled inspection on the fish net-pen is an unavoidable requirement. According to the site classification by Food and Agriculture Organization of the United Nations in 2009, coastal ($< 0.5km$ from the coast, $\leq 10m$ depth at low tide), off the coast ($0.5 - 3km$ from the coast, $10 - 50m$ depth at low tide) and offshore ($> 2km$ from the coast, $> 50m$ depth) sites encounter wave height (Hs) of $< 1m$, $\leq 3 - 4m$ and $\geq 5m$ with different wind speeds and currents respectively requiring regular to remote and automated operations [6]. These harsh environments impose safety risk on offshore work force and increase the operating cost. To minimize these concerns, UUVs are being deployed, for instance, to conduct visual inspections to detect holes in the fish net-pen and the overall structural integrity. Notably, requirements of daily inspection on fish pen and inspection on grid system, marker buoy lights and mooring lines due to the physical, chemical and biological forces are reported in [6].

The deeper under the water where the inspection work is conducted, the more stringent the required training for the diver is and the more indispensable the professional and expensive gears are. To replace or collaborate with the diver, UUVs can perform the visual inspections more frequently, efficiently and economically. It was reported that a diver needs up to 2 to 3 days to conduct a thorough visual inspection to detect holes in the fish pen of $400m$ circumference: $127m$ diameter and $10m$ depth, whereas a UUV takes only about 4 hours to complete the same task [12].

Though there are many advantages of using UUVs in offshore aquaculture as mentioned above, there is much room for the improvement in their maneuverability and energy optimality. Unlike the torpedo-shaped UUV in defense, terrain-aided navigation and underactuated UUV for the recreational purpose, UUVs in offshore aquaculture are mostly in a rectangular or square shaped form factor to take advantage of geometrical symmetry in stabilizing the less used degree of freedom (DoFs) such as pitch and roll or simplifying the overactuated system into a less DoFs for the ease of control complexity by abusing the geometrical symmetry [13–15]. However, low maneuverability in the use of less human intervention for the close-infrastructure operation (e.g., the visual inspection) is simply inadequate given the harsh environmental factors such as current and waves. Moreover, the constrained environment with multiple fish net-pens and mooring lines again calls attention to the requirement of high maneuverability. Short working time and range due to the limited capacity of power supply carried by a UUV is another issue. Use of tethered power supply is not viable in most cases and is thus not a feasible solution. Therefore, how to operate the UUVs in an energy-efficient manner under the power supply's capacity constraint is important.

The remaining part of this paper is structured as follows. Section 2 further explains the application of UUVs in visual inspection in offshore aquaculture, the state of the art of UUV deployment and the future improvement a UUV research could contribute. Section 3 details the state of the art research on achieving high maneuverability and energy-optimal control of a UUV. Finally, Section 4 summarizes the contribution of this paper and suggests the future work.

2. VISUAL INSPECTION

In offshore aquaculture fish farm, visual inspection of the fish net-pen is essential to monitor biofouling which causes net occlusion, deformation, structural fatigue of the fish net-pen and higher disease risk for the fish and reduced water flow causing lower oxygen level essential for fish health [16,17]. Furthermore, it is necessary to detect the holes in the fish net-pen which allow fish escape and these escapes can cause the transfer of disease and interbreeding, resulting in wild fish genetics alteration [18]. Defects in the fish net-pen also allow predators to enter the fish pen.

Conventionally, a diver conducts the visual inspection which is very time consuming. Moreover, labour shortage, safety, productivity and operating costs are the main concerns in the long run [18, 19]. Due to those concerns, UUVs carrying computer vision systems and other sensors are being introduced to minimize or even replace the human intervention in the visual inspection [12, 18, 20]. In addition to visual inspection, UUVs can perform the environmental data (e.g., temperature, salinity and oxygen level) collection from different locations of interest unlike localised stationary sensor which can only collect data in a much more limited range [19].

To conduct the visual inspection of the fish net-pen using a UUV, it is critical to understand the general operational constraints of both fish net-pen (including the infrastructure) and UUVs including water depth, current speed and storm incidence. Different types of fish pen design and the advantages and disadvantages of each design are discussed in [21]. Fish pen designs are categorized into open net cage system and closed containment tank system (e.g., ECO-ARK® AQUACULTURE 4.0 by Aquaculture Centre of Excellence Pte Ltd). Again, open net cage system is sub-categorized into (1) floating flexible cage (e.g., PolarCirkel HDPE Circular cage), (2) floating rigid cage (e.g., Havfarm), (3) semi-submersible flexible cage (e.g., REFA Tension Leg Cage (TLC) design concept), (4) semi-submersible rigid cage (e.g., Ocean Farm 1) and (5) submerged cage (e.g., SADCO-A,D,E Series Underwater Cages) [21].

Different fish pen designs are proposed according to the requirement of the fish farm operators and based on the environmental factors. In addition to the different designs, due to the spatial and temporal differences, biofouling, its growth rate and structural defects of fish net-pen and the infrastructure vary. Structural complexity of fish pen as shown in Fig. 1 requires high maneuverability of the UUV to conduct visual inspection. It also makes a limited onboard power supply more suitable than a tethered power supply as the energy source of the UUV. In other words, high maneuverability and energy-optimality are essential features for UUV to conduct a thorough visual inspection of the fish net-pen in offshore aquaculture.

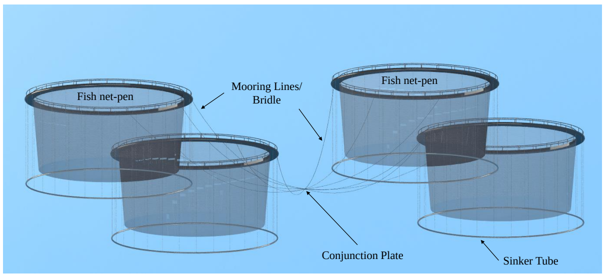

Fig. 1. Simplified illustration of the constrained environment in a floating flexible cage

3. MANEUVERABILITY AND ENERGY-OPTIMALITY OF UUVS

As mentioned previously, to operate a UUV around a constrained environment (fish net-pen) in a fluid medium with the varying environmental parameter (e.g., the underwater current and disturbances) and hydrodynamics parameters such as added mass and damping effects, the UUV needs to possess high maneuverability and energy-optimality.

To achieve high maneuverability, a rectangular or square- shaped UUV can be equipped with six or more thrusters (commonly with eight thrusters) as shown in Fig. 2. A generic 6-DoFs nonlinear dynamic model as shown in Equation 1 can be derived using Newton-Euler method. To set up the reference frame to describe the dynamic model, the North-East-Down (NED) reference frame and the Society of Naval Architects and Marine

Engineers (SNAME) nomenclature as shown in Fig. 2 & Fig. 3 are adopted [22, 23].

$$M\dot{\nu}+C(\nu)\nu+D(\nu)\nu+g(\eta) = \tau(\triangleq Bu)+\tau_{current} \quad (1)$$

where $\nu = \{u, v, w, p, q, r\} \in \mathbb{R}^6$ is the linear (in $\{x_b, y_b, z_b\}$ axis) and angular (around $\{x_b, y_b, z_b\}$ axis) velocity vector, $\eta = \{x, y, z, \phi, \theta, \psi\} \in \mathbb{R}^6$ the linear (in $\{x_n, y_n, z_n\}$ axis) and angular (around $\{x_n, y_n, z_n\}$ axis) position (Euler angles) vector, $M \in \mathbb{R}^{6\times6}$ inertia matrix, $C(\nu) \in \mathbb{R}^{6\times6}$ the Coriolis-Centripetal acceleration matrix, $D(\nu) \in \mathbb{R}^{6\times6}$ the linear and quadratic damping matrix, $g(\eta) \in \mathbb{R}^6$ the vector characterizing gravitational force, buoyancy and the resulting restoring forces and moments, $\tau_{current} \in \mathbb{R}^6$ the constant disturbance contributed by the ocean current, $\tau \in \mathbb{R}^6$ the resultant thrust vector, $B \in \mathbb{R}^{6\times8}$ the thruster control matrix (TCM), $u \in \mathbb{R}^8$ the input vector. Note: $u(\subset \nu) \in \mathbb{R} \neq u \in \mathbb{R}^8$ (This is purely a name collision between SNAME nomenclature and control terminology.) To be consistent with both, it is appropriate to keep the use of "u" with a compatible dimension wherever necessary.

The 6-DoFs UUV is over-actuated with eight thrusters, $u \in \mathbb{R}^8$, and thruster control matrix (TCM), $B \in \mathbb{R}^{6\times8}$ is a rectangular matrix. Using pseudo-inverse, TCM can be manipulated to map τ and u to each other. As the generic 6-DoFs nonlinear dynamic model only consists of linear and angular velocity vector, $\nu \in \mathbb{R}^6$, as the state, there needs a conversion to include linear and angular position vector, $\eta \in \mathbb{R}^6$, such that the UUV's nonlinear state space model becomes $\dot{x} = f(x(t), u(t), t) \in \mathbb{R}^{12}$, $x = [\eta\ \nu]^T$.

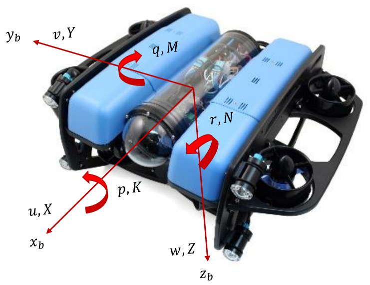

Fig. 2. BlueROV2 Heavy Configuration (eight thrusters) with SNAME nomenclature. Photo courtesy of BlueRobotics.

To choose a suitable UUV to conduct a visual inspection of a fish net-pen, it is critical to cross-check its specifications such as rated depth, nominal & maximum surge velocity and other velocities, thrust and torque limitations at and around each axis against the operational constraints of the fish farm discussed previously. Moreover, a feasible operating time of the UUV can be estimated from the limited capacity of the onboard power supply (e.g., battery).

The previous discussion on a 6-DoFs nonlinear UUV model to achieve high maneuverability leads to how it should be controlled so that it completes the visual inspection task in an allowable fixed duration of time in an energy-efficient manner, given the limited capacity of the onboard power supply. In other words, the controller design can be formulated as the one to solve energy-optimal

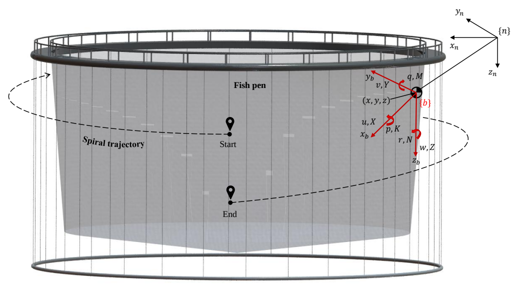

Fig. 3. Illustration of a fish net-pen with a spiral trajectory for a UUV to perform a visual inspection. The body frame {b} of UUV is defined at its center of mass and the SNAME nomenclatures are expressed at the relevant axes. The pose (position and orientation) of UUV is expressed in the NED frame {n}.

finite-horizon constrained optimization problem. Generally, it can be described as shown in Equation 2.

$$\begin{aligned} \min_{u(.) \in \mathcal{U}_{admissible}[t_o, t_f]} \quad & J(x(t), u(t), t) = J(t_f) + \\ & \int_{t_0}^{t_f} [\alpha J_T + (1-\alpha) J_E] dt, \qquad (2) \\ \text{subject to} \quad & \dot{x} = f(x(t), u(t), t), \\ & x_{min} \leq x \leq x_{max}, \\ & u_{min} \leq u \leq u_{max}. \end{aligned}$$

where $J(x(t), u(t), t)$ is the performance index, $J(t_f)$ is the terminal cost, J_T is the tracking cost, J_E is the energy cost, $0 \leq \alpha \leq 1$ is the weighting variable, $t \in [t_0, t_f]$ is the total operating time, t_0 is the initial time, and t_f is the final time. (Note: indeed, J_E is the power term but named as energy in this paper for the ease of energy-optimal description with the abuse of naming.)

Control strategies for UUVs are usually developed from their dynamic model [24, 25]. Nonlinear systems exhibit much richer behaviours than linear systems which make the controller design more challenging. Though there are a few standard and systematic procedures for designing nonlinear controllers, a set of design tools such as those based on Lyapunov stability theory can be applied to develop the controller for a specific type of system [26, 27]. In some situations, such as UUV operating in a small range near a fixed point, the dynamic model can be linearized around that point, providing an advantage of applying well established control methods for linear systems [28, 29]. However, the resulting linear controller likely has poor performance if the UUV's operational range exceeds its limit.

As presented earlier in describing the constrained environment for the UUV and infeasibility of the tethered power supply in most of the area, energy-optimal control is essential for the UUV operating in offshore aquaculture due to its limited onboard power supply. An energy-optimal depth tracking control of a linearized dynamic model of AUV using model predictive control (MPC) framework, incorporated with a quadratic energy cost function was presented in [29]. In 1992, the offline open-loop trajectory generation of a UUV by transforming the optimal control problem with the nonquadratic performance index of thrust force into nonlinear programming (NLP) problem, solved by direct shooting (discretization of control variables and transformation of optimal control problem into a finite-dimensional nonlinear programming problem) was reported in [30]. A nonlinear robust Model Predictive Control (NRMPC), optimized by A* algorithm of a torpedo-shaped AUV in which a simplified kinematic model was applied, and uncertainties resulted from the ocean current prediction was modelled with the Regional Ocean Modelling System (ROMS) was presented in [31]. In this NRMPC, the optimal control objective function was determined by the factors including the hotel load (the electrical load, consumed by all the systems except propulsion) of the AUV, the energy consumption related to inertia and drag forces and the estimated remaining energy. A sub-optimal energy solution of a torpedo-shaped 6-DoFs AUV using sliding mode control (SMC) where the system output was treated as a part of the cost function of a linear quadratic regulator (LQR) was detailed in [32]. A four sequel of energy-optimal control of a long rectangular-shaped 4-DoFs AUV using power consumption model of the thrusters were presented in [33–36]. Energy optimization was formulated as static and dynamic surge motion optimization (except the 3rd paper) through: (i) the comparison of tracking MPC (TMPC), energy-optimal MPC (EO-MPC) and real-time EO-MPC (RTEO-MPC) with direct collocation (DC) as the baseline, (ii) the design of energy-optimal economic MPC (EO-EMPC) by combining the horizontal motion and the energy-to-go (beyond the finite-prediction horizon to the final goal) in economic MPC (EMPC) in which the objective function is directly related to the energy consumption over the remaining trajectory instead of state tracking errors normally found in a standard MPC, (iii) the incorporation of energy optimization and uncertainty due to ocean currents to produce robust energy-optimal line-of-sight (LOS) MPC (ELOS-MPC) in which LOS is a guidance system to calculate the deviation of the UUV from the path between the previous and next waypoints, and (iv) the reintroduction of energy-optimal EMPC (EO-EMPC) with time constraints, more details in LOS and different constant current flows. Across four sequels, heave and pitch are decoupled from surge and yaw and are controlled by proportional-integral-derivative (PID) control to reduce the computational complexity.

Almost all the energy-optimal control schemes presented above were only validated in a simulated environment without experimental results to the best of our knowledge. Although there were some literature with experimental results, they were not targeted for energy-optimality and test sites were ideal like salt water tank or pool [24, 37, 38]. Sea trials were reported in [18, 39, 40] but the control schemes were not energy-optimal. Alternatively, some literature with experimental results covered only the visual inspection/ inspection-related part and excluded the control experiments or briefly explained the control scheme as a part of the experiment [12,20,41]. In addition, most of them were reported on underactuated systems which have poor maneuverability in the constrained environment such as fish net-pen visual inspection for which a UUV requires high maneuverability for path tracking around the fish net-pen to capture a stable visual feedback while rejecting the environmental disturbances. From the analysis and synthesis of the literature presented, it can be observed that the visual inspection of fish net-pen in offshore aquaculture, the deployment of UUVs in the constrained environment, high maneuverability and energy-optimality were sectorially reported by many researchers and this paper highlights the importance of a holistic approach to tackle an existing industrial problem while considering all the operational constraints. Therefore, there is a need for further investigation on the energy-optimal control of highly maneuverable UUVs for the visual inspection of fish net-pen in offshore aquaculture.

4. CONCLUSION

This paper reviews the applications of UUVs in offshore aquaculture with a focus on the controller design to achieve an UUV's maneuverability and energy optimality required in their missions (e.g., visual inspection of fish net-pen). The constraints in the UUV's working environment and their effects on the controller are discussed. Typical control schemes which have the potential to be implemented in practice are presented. The future work includes further exploration on energy-optimal control of highly maneuverable UUVs in simulation and experiments and the extension of the energy-optimal controller on robustness and stability analysis. The research outcome could potentially impact any general close-infrastructure inspection in other fields such as offshore renewable energy farm and oceanographic research.

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