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Three-dimensional optimal path planning for waypoint guidance of an autonomous underwater vehicle

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HIGHLIGHTS

- An optimal 3D path is generated offline for waypoint guidance of an AUV.
- Four objective functions are selected and Pareto-front is found using the NSGA-II.
- A 3D guidance system is used for guidance of the AUV through the optimal paths.
- The dynamic modeling of a novel miniature AUV is derived.
- Heading autopilot and depth controller are designed for the miniature AUV.

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ABSTRACT

In this paper, optimal three-dimensional paths are generated offline for waypoint guidance of a miniature Autonomous Underwater Vehicle (AUV). Having the starting point, the destination point, and the position and dimension of the obstacles, the AUV is intended to systematically plan an optimal path toward the target. The path is defined as a set of waypoints to be passed by the vehicle. Four criteria are considered for evaluation of an optimal path; they are "total length of path", "margin of safety", "smoothness of the planar motion" and "gradient of diving". A set of Pareto-optimal solutions is found where each solution represents an optimal feasible path that cannot be outrun by any other path considering all four criteria. Then, a proposed three-dimensional guidance system is used for guidance of the AUV through selected optimal paths. This system is inspired from the Line-of-Sight (LOS) guidance strategy; the idea is to select the desired depth, presumed proportional to the horizontal distance of the AUV and the target. To develop this guidance strategy, the dynamic modeling of this novel miniature AUV is also derived. The simulation results show that this guidance system efficiently guides the AUV through the optimal paths.

1. Introduction

An Autonomous Underwater Vehicle (AUV) is defined as a vehicle that can perform underwater tasks and missions autonomously, using onboard navigation, guidance, and control systems [1]. With the increase in the reliability and technical abilities of these vehicles further to the operational ranges, now more than ever, the AUV industry is seeing dramatic growth. In addition to scientific underwater exploratory missions, AUVs are also used for military purposes, inspection of underwater structures, as well as are largely utilized in the mining and oil industries such as search for underwater resources [2–7]. The goal in underwater robotics is to create fully self-contained, intelligent, and decision-making AUVs [1]. In order to accomplish that, much research is being carried out worldwide with particular emphasis on autonomy, navigation, object detection, energy sources and information systems [2]. In the recent years, the advances in the field of Navigation, Guidance and Control (NGC) systems have contributed significantly to the progress achieved in the development of autonomous vehicles [8]. Guidance systems have traditionally been designed separately from control systems by adopting simple strategies such as LOS between waypoints and generating the corresponding reference heading [9]. Naeem W. et al. [8] have reviewed some important guidance laws applicable to AUVs including Lyapunov-based guidance, Proportional Navigation Guidance (PNG), and Line-of-Sight (LOS) guidance. Having a suitable guidance strategy, an AUV can accomplish its missions by splitting the path to several waypoints and passing through them toward the goal. Waypoints are some fixed points in environment that an AUV should pass to have a desirable traveling

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toward the destination point. Waypoint guidance, which means guiding the vehicle from one waypoint to the next one, is an important issue for an autonomous vehicle [10]. Considering the next waypoint as a fixed target in each step, typical guidance strategies can be applied for waypoint guidance [10]. However, determining the location of each waypoint to have an optimal path should be considered before waypoint guidance of the vehicle. In fact, a path planning program can be used to find the optimal paths for waypoint guidance of an AUV. Path planning algorithms can be categorized into two classes according to when the path is generated [11]. In the first class, which is called pre-generative path planning, the path would be produced before the mission. On the other hand, in the second class, known as reactive path planning, the path would be generated during the mission as the vehicle proceeds through environment [11]. Global path planning, as a pre-generative path planning strategy, is a technique for finding the best path in the known environment where the starting and the destination points and the position of each obstacle are determined [12]. The typical criteria for evaluation of the optimal path of an AUV have been related to traveling time and safety conditions [11]. Sometimes, total length of path is considered instead of traveling time [13]. Also, in some cases, it is important to plan paths with minimum energy consumption [11]. Smoothness of the trajectory is another factor that has been considered in some studies [13]. Environment modeling and searching method are two important parts of each path planning problem. Free-space method, grid method, and visibility graph method are some suggested methods for environmental modeling [12]. Also, artificial potential field method [14], A* algorithm [15], genetic algorithm [16], and topology method are some suggested methods for solving this constrained optimization problem [12,17]. A case-based reasoning approach to path planning for AUVs is studied in [18] which relies on past experience of the vehicle. Also a Fast Marching (FM)-based approach is proposed in [17] while underwater currents are taken into account and turning radius is considered as a constraint. A hierarchical global path planning approach is proposed for AUVs in [19] based on decomposition of the workspace and finding the best path at each level. Also, electronic chart information is used as a method for environment modeling in [12] and genetic algorithm is used for finding optimal global path.

In this study, optimal path planning for waypoint guidance of an AUV is considered. Before this work, a heading autopilot and a two dimensional guidance system are developed for a designed miniature AUV [20] and also Fuzzy Logic is used for improvement of the guidance system [21]. Offline path planning is also carried out for a special biomimetic AUV [22]. In this work, three-dimensional optimal path planning for the designed miniature AUV is investigated and a set of optimal paths is determined that includes some waypoints to be passed. For evaluation of an optimal path, four main criteria are considered: "total length of path", "margin of safety", "smoothness of the planar motion" and "gradient of diving". The multi-objective genetic algorithm (NSGA II) is used for finding a set of optimal solutions. Also, a proposed three-dimensional guidance strategy is used for waypoint tracking of the AUV. This guidance system is inspired from LOS guidance strategy and is based on the idea of selecting the desired depth proportional to horizontal distance of the AUV and the target. The simulation results show that, using this strategy, the AUV can efficiently pass through the optimal paths.

2. AUV modeling

This paper is developed based on the characteristics of a designed miniature autonomous underwater vehicle. This underwater vehicle has many advantages compared with regular AUVs because of its small size and low cost. Furthermore, this vehicle is designed to have three independent actuators in surge, heave, and yaw directions; consequently, it is more maneuverable than other AUVs. This miniature AUV is about 40 cm in length and 10 cm in diameter. It has a cylindrical shape which is very typical for underwater vehicles. The head of the AUV is elliptical and the tail is conical. These elements are selected to reduce the drag forces (Fig. 1).

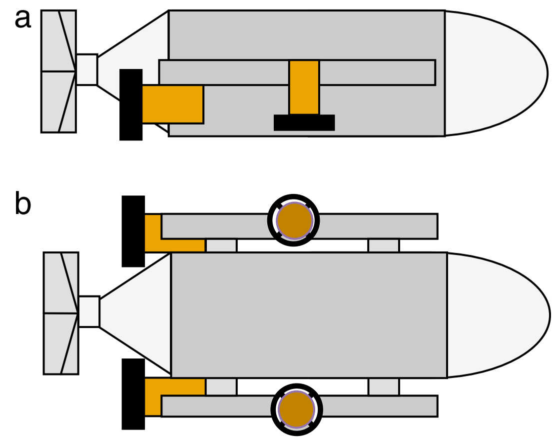

Fig. 1. Miniature Autonomous Underwater Vehicle; (a) lateral view; (b) top view.

For this AUV, the propulsion is achieved by a central thruster as shown in Fig. 1. Also, two lateral waterproof motors with propellers are mounted just behind the centerline to provide yaw control. In addition, two motors are mounted vertically to control the depth of the vehicle. Roll and pitch are controlled by mounting the majority of the weight at the bottom of the AUV. Passively controlled, the vehicle can resist external disturbances. Moreover, because of the designed mechanisms for motions in heave and yaw directions, the vehicle does not need to have roll and pitch motions to go up and down and to turn left and right; so, it always maintains in a horizontal posture. This horizontal posture results in simplification of the mathematical model of the AUV.

The general dynamic model of an AUV could be derived from the Newton–Euler equations of motion. This 6-DOF nonlinear equation is expressed as [2,23,24]

$$M\dot{V} + C(V)V + D(V)V + g = \tau + g_0 + W_e \quad (1)$$

where

$$V = \begin{bmatrix} u \\ v \\ w \\ p \\ q \\ r \end{bmatrix}$$

in which u, v, w, p, q, and r denotes surge, sway, heave, roll, pitch, and yaw velocities, respectively, and dot $(\dot{\ })$ represents differentiation with respect to time. Also, we have

M	system inertia matrix
$C(V)$	Coriolis–centripetal matrix
$D(V)$	damping matrix
g	vector of gravitational/buoyancy forces and moments
g_0	vector used for pre-trimming (ballast control)
τ	vector of control inputs
W_e	vector of environmental disturbances (wind, waves, and currents).

It is assumed that the origin O coincides with the CG of the vehicle, so the system inertia matrix would be represented as

$$M = \begin{bmatrix} m\boldsymbol{I}_{3\times3} & \boldsymbol{0}_{3\times3} \\ \boldsymbol{0}_{3\times3} & \boldsymbol{I}_o \end{bmatrix}$$