Computers and Electrical Engineering 000 (2018) 1–20

Contents lists available at ScienceDirect

Computers and Electrical Engineering

journal homepage: www.elsevier.com/locate/compeleceng

A hierarchal planning framework for AUV mission management in a spatiotemporal varying ocean[☆]

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ARTICLE INFO

Article history:
Received 19 April 2017
Revised 18 December 2017
Accepted 20 December 2017
Available online xxx

Keywords:
Mission planning
Autonomous underwater vehicle
Spatiotemporal ocean
Biogeography-based optimization
Mission timing
Situational awareness

ABSTRACT

This paper provides a hierarchical dynamic mission planning framework for an AUV to accomplish task-assign process in a restricted time operating in uncertain undersea environment. A high-level reactive mission planner is developed for task priority assignment, guiding the vehicle toward a target of interest, and managing on-time mission completion. A low-level motion planner is also developed to handle unexpected changes of the dynamic terrain by re-generating optimal trajectories. The mission planner reactively rearranges the tasks based on mission/terrain updates. As a result, the vehicle is able to undertake the maximum number of tasks with certain degree of maneuverability having situational awareness of the operating field. The Biogeography-Based Optimization (BBO) algorithm is used as the computational engine of the framework in both mission and motion planners. The simulations results indicate the significant potential of the proposed hierarchical framework in providing efficient solutions for mission success and its applicability for real-time implementation.

1. Introduction

Autonomous operation of Autonomous Underwater vehicles (AUVs) in a vast, unfamiliar and dynamic underwater environment is a complicated process, especially when the AUV is obligated to react to environment changes, where usually a-priory information is not available. Recent advancements in sensor technology and embedded computer systems has opened new possibilities in underwater path planning and made AUVs more capable for handling complicated long-range missions. However, there still exist major challenges for this class of the vehicle, where the surrounding environment has a complex spatiotemporal variability and uncertainty. Ocean current variability affect vehicle's motion, for example it can perturb its safety by pushing that to an undesired direction. Consequently, this variability can also have a profound impact on vehicle's battery usage and its mission duration. The robustness of a vehicle's path planning to this strong environment variability is a key element to its safety and mission performance. Thus, robustness of the trajectory planning to current variability and terrain uncertainties is essential to mission success and AUV safe deployment.

☆ Reviews processed and recommended for publication to the Editor-in-Chief by Associate Editor Dr. A. Chaudhary.

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https://doi.org/10.1016/j.compeleceng.2017.12.035
0045-7906/© 2017 Published by Elsevier Ltd.

On the other hand, an AUV should carry out complex tasks in a limited time interval. However, existing AUVs have limited battery capacity and restricted endurance, so they should be capable of managing mission time. Obviously, a single AUV is not able to meet all specified tasks in a single mission with limited time and energy, so the vehicle has to effectively manage its resources to perform effective persistent deployment in longer missions without human interaction. In this respect, time management is a fundamental requirement toward mission success that tightly depends on the optimality of the selected tasks between start and destination point in a graph-like operation terrain. Hence, design of an efficient mission planning framework considering vehicle's availabilities and capabilities is essential requirement for maximizing mission productivity. Many efforts have been devoted in recent years for enhancing an AUV's capability in robust motion planning and efficient task assignment. Although some improvement have been achieved in other autonomous systems; there are still many challenges to achieve a satisfactory level of intelligence and robustness for AUV in this regard.

AUVs capabilities in handling mission objectives are directly influenced by routing and task arrangement system performance. The main issue that should be covered by route planning system is to direct vehicle(s) to its destination in a network while providing efficient maneuver and optimizing travel time. An integrated mission task assignment and routing strategy is proposed in [1] to serve the AUVs routing problem in order to deliver customized sensor packages to mission targets at scattered positions, while minimising total energy cost in the presence of ocean currents. The AUV routing problem is investigated with a Double Traveling Salesman Problem with Multiple Stacks (DTSPMS) for a single-vehicle pickup-and-delivery problem by minimizing the total routing cost [2]. A large scale route planning and task assignment joint problem related to the AUV activity has been investigated in [3] by transforming the problem space into a NP-hard graph context and using the heuristic search nature of Genetic Algorithm (GA) and Particle Swarm Optimization (PSO) to find the best waypoints and their corresponding tasks. Later on, the same concept is extended by MahmoudZadeh et al., to AUV routing in a semi-dynamic network, while performance of the BBO and PSO algorithm is tested on single vehicle's routing approach [4]. Growth of the graph complexity, or in general, enlargement of the search space increases the computational burden that is often a problematic issue with deterministic methods such as mixed integer linear programming (MILP) proposed by Yilmaz et al., for governing multiple AUVs [5]. In terms of task assignment, many typical AUV missions are limited to executing a list of pre-programmed instructions and completing a predefined sequences of tasks. The majority of the mentioned researches particularly focuses on task and target assignment and time scheduling problems without considering requirements for vehicle's safe deployment or quality of its motion in presence of environmental disturbances. A vehicle's safe and confident deployment is a critical issue that should be taken into consideration at all stages of a mission in a vast and uncertain environment. Some of the existing AUV trajectory/path planning approaches are discussed as follows, which are more concentrated on vehicles deployment encountering dynamicity of the operating environment.

Various strategies have been developed and applied to the AUV path-planning problem in recent years. The well-known direct method of optimal control theory, called inverse dynamics in the virtual domain (IDVD) method, was employed to develop and test a real-time trajectory generator for realization on board of an AUV [6,7]. A sliding wave front expansion algorithm applying continuous optimization techniques has been presented by Soulignac for AUVs path planning in presence of strong current fields [8]. Jan et al., investigated higher geometry maze routing algorithm for optimal path planning and navigating a mobile rectangular robot among obstacles [9]. Nevertheless, this strategy may not be appropriate for AUV dynamic environments where the current field changes continuously during the mission. Earlier proposed methods [8,9] are capable of providing optimum path planning for AUV using previous information for re-planning process, which is computationally reasonable in generating accurate local trajectories; however, they modelled the environment as a 2D space, which is inefficient for application of the AUVs, as a 2D representation of a marine environment doesn't sufficiently embody all the information of a 3D ocean environment and the vehicle's six degree of freedom. The evolution-based strategies like Differential Evolution (DE) [10], GA [11] and PSO [12] are another approach that has been applied successfully to the path planning problem and are fast enough to satisfy time restrictions of the real-time applications. A real-time online evolution based path planner was developed for AUV rendezvous path planning in a cluttered variable environment, in which the performance of four evolutionary algorithms of Firefly Algorithm (FA), BBO, DE, and PSO is tested and compared in different scenarios [13]. A Quantum-based PSO (QPSO) was applied by Fu et al. [14], for unmanned aerial vehicle's path planning, in which only the off-line path planning in a static known environment was implemented. However, the off-line planning cannot sufficiently cover the dynamicity and uncertainty of underwater environment. Although various path planning techniques have been suggested for autonomous vehicles, AUV-oriented applications still have several difficulties when operating across a large-scale geographical area. The recent investigations on path planning that incorporate variability of the environment have assumed that planning is carried out with perfect knowledge of probable future changes of the environment [15,16], while in the reality, accurate prediction of the environmental events (such as currents or obstacles state variations) is impractical specially in longer operations. Even though available ocean predictive approaches operate reasonably well in small scales and over short time periods, they produce insufficient accuracy to current prediction over long time periods in larger scales, specifically in cases with lower information resolution [17]. Moreover, current variations over time can affect moving obstacles (or waypoints in some cases) and drift them across a vehicle's trajectory; therefore, the planned trajectory may change and become invalid or inefficient. Proper estimation of the events in such a dynamic uncertain terrain in long range operations, outside the vehicle's sensor coverage, is impractical and unreliable. This becomes even more challenging for re-planning process, when a large data load of variation of whole terrain condition should be computed repeatedly. Hence, using such an estimation methods is computationally inefficient and unnecessary as only awareness of environmental changes in vicinity of the vehicle is sufficient for performing a prompt reaction. As mentioned earlier, the path planning