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A survey on path planning for persistent autonomy of autonomous underwater vehicles

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ABSTRACT

Recently, there has been growing interest in developing Autonomous Underwater Vehicle (AUV) to operate for longer mission durations as well as with higher levels of autonomy. This paper describes the current state of the art in methodologies to enable long range AUVs and provides a detailed literature review of some existing AUVs characterizing their operation endurance. Path planning is identified as the core and crucial components to improve AUV persistence. The aims of path optimization, path re-planning adapting to the dynamic environments, and cooperative path planning of multiple AUVs have received much attention from the research community. This paper presents a review of the main research works focusing on these three technology areas. The main objective of this paper is to present a comprehensive survey of shape and properties of the path and optimization techniques for path planning. These techniques and algorithms have been classified into different classes and their assumptions and drawbacks have been discussed. Finally, the paper discusses the AUV literature in general and highlights challenges that need to be addressed in developing AUVs with advanced autonomy and capable of operating for longer mission durations.

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1. Introduction

Autonomous Underwater Vehicles (AUVs) are a class of submerged marine robots using various enabling technologies to navigate and perform various tasks. AUVs have a variety of military, scientific research and commercial applications (Westwood, 2010). Military applications include surveillance and reconnaissance, anti-submarine warfare, payload delivery, time-critical strike, harbor protection etc., AUVs are useful for oceanography, littoral ocean floor mapping, water profile sampling and other types of scientific research, AUVs are also increasingly used in the oil and gas market, due to their capability to operate very close to the seabed or in close proximity to industrial structures like those used by offshore industries.

However, the actual autonomy of contemporary AUVs is limited in many ways restricting their potential uses. Further advances in AUV autonomy will enable new operations, such as executing very long endurance missions with a minimum of supervision in unknown, dynamic and hostile environments.

The level of autonomy achieved by AUVs is chiefly determined by their performance in path planning and re-planning. A path planner should be capable of finding a trajectory that safely leads the AUV from its initial or current position to its destination and optimize a certain objective function, such as time or energy consumption. The environment usually contain time-varying currents and obstacles which might not be fully characterized at the start of a mission. Obstacles may be detected as the AUV moves through the environment, rendezvous location may change over time. A special case of non-stationary rendezvous target, such as a surface vehicle, may have moved during the operation. The path planner should thus have the capability to adapt to changing ocean environment, mission goals and system status.

1.1. Motivations

Many of current AUV applications consume much time lasting from days to weeks, and cover large areas of hundreds to thousands of square kilometers. Oceanographic processes, such as currents show great variability over such large expanses and will evolve over such durations. In most existing applications, AUVs are typically deployed from surface vessels with support personnel for deployment, piloting and recovery. During the course of the mission, the support vessel will shadow the AUV and provide much of the higher level decision making processes needed to deal with changes of oceanographic processes. The cost of keeping the support vessel on standby is generally by far the most significant component of the mission cost (Furlong et al., 2012). Recently, there has been growing interest in developing long range AUVs with increased autonomy to conduct science missions over longer periods without supervision (Hobson et al., 2012), thereby reducing mission costs and extending their applicability.

Two developments have been explored to increase the range and endurance of the long-range AUV. The first development is to increase the vehicle storage density-which indicates the capability to store more energy and sensors per unit volume. The second development is to increase the efficiency of the vehicle. These developments are illustrated in Fig. 1.

Compact battery technology capable of storing more electricity is one way to increase the vehicle storage density and capability. Most AUVs in use today are powered by rechargeable batteries, such as lithium ion, lithium polymer, nickel metal hydride etc. Some vehicles use primary batteries which provide perhaps twice the endurance, but at a substantial extra cost per mission. A few of the larger vehicles are powered by aluminum based semi-fuel cells, however, these require substantial maintenance, require expensive refills and produce waste product that must be handled safely. An emerging trend is to combine different battery and power systems with super-capacitors (Abu Sharkh and Griffiths, 2002; Hasvold et al., 2006). Another way to increase the vehicle's storage density capacity is to decrease the payload size (Taylor and Wilby, 2011), application of nanotechnology for developing sensor equipment holds potential to develop highly sophisticated underwater vehicles with reduced payload sizes and power consumption.

Research to increase the efficiency of the AUVs can be categorised along three directions. One direction is looking at reducing the AUV power consumption, including both propulsion power and hotel load (Hobson et al., 2012). Power for most AUVs is generated from power stored in on-board batteries. Propulsion power can be reduced through more efficient motion. Hotel load is defined as the power for on-board instrumentation, guidance, computers and communication devices, and has steadily reduced through advancements in electronic systems. A second direction is looking at acheving advances in mechanical design, particularly the vehicle profile and surface design to reduce vehicle drag (Joung et al., 2009; 2012). A good example of this category is Tethys, its hull, motor and propeller were computer designed and tested to minimize drag and maximize efficiency of propulsion. The third major direction is increase the autonomy of vehicle (Hobson et al., 2012). Mission scheduling and path planning hold tremendous potential to enable long range operations. A vehicle could be launched from shore where upon a path planning system could be used to generate a trajectory that exploits the ocean energy taking use of the favorable currents to propel the vehicle, and lead the vehicle to a remote work site, perform a survey, and then return to shore completely on its own. This will greatly diminish the costs for AUV operations since there is no need for a support vessel and vehicle operations can be monitored on-shore, thereby enhancing the affordability of AUVs to science and industry.

The rest of the paper is organized as follows: Section 2 lists some existing AUVs categorize them into three classes based on their operation endurance. Section 3 introduces the AUV path planning problem, including the aims of path optimization, online path re-planning, and cooperative path planning of multiple AUVs. Sections 4 and 5 provide a comprehensive survey of major works focusing on shape and properties of the path and optimization

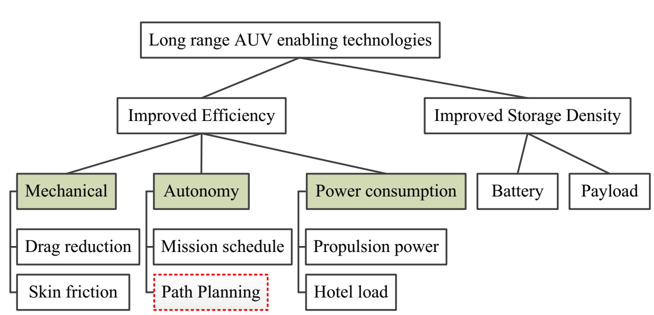

Fig. 1. Methodologies to enable long range AUVs.