Modeling Underwater Structures

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ABSTRACT

For systems to become truly autonomous it is necessary that they be able to interact with complex real-world environments. In this article we investigate techniques and technologies to address the problem of the acquisition and representation of complex environments such as those found underwater. The underwater environment presents many challenges for robotic sensing including highly variable lighting and the presence of dynamic objects such as fish and suspended particulate matter. The dynamic six-degree-of-freedom nature of the environment presents further challenges due to unpredictable external forces such as current and surge. In order to address the complexities of the underwater environment we have developed a stereo vision-inertial sensing device that has been successfully deployed to reconstruct complex 3-D structures in both the aquatic and terrestrial domains. The sensor combines 3-D information, obtained using stereo vision, with 3DOF inertial data to construct 3-D models of the environment. Semiautomatic tools have been developed to aid in the conversion of these representations into semantically relevant primitives suitable for later processing. Reconstruction and segmentation of underwater structures obtained with the sensor are presented.

Keywords: autonomous robots; modeling; sensing

INTRODUCTION

Intelligent machines must interact with their world. Such machines must be able to construct internal representations of their environment, reason about these representations, and then move purposefully within their environment using these representations. Building internal representations of the external world and reasoning about them is also a key goal of the field of cognitive informatics (Wang, 2003). However, in spite of decades of advances in mobility and sensing and reasoning algorithms, building fully autonomous machines remain an elusive goal. Achieving full autonomy requires systems that are sufficiently robust such that they can deal with the vagaries of complex environments and external effects that are difficult or impossible to model, and have the ability to reason...
with representations of complex structures and events. Although there have been many advances in terms of autonomous systems, much of the ongoing research concentrates on the development of robots that operate in “clean” research labs that do not present the full complexity of the outside world. Research that has addressed robots in the field typically assumes that the problem is constrained to a plane or that there is a preferred orientation with respect to gravity. Here we explore what is perhaps the most difficult external environment: underwater. The underwater environment presents numerous challenges for the design of visually guided robots, yet it is these constraints and challenges that make this environment almost ideal for the development and evaluation of robotic sensing technologies. The underwater medium limits robot-human communication to low-bandwidth mechanisms such as an acoustic modem or visual markers (e.g., Dudek et al., 2007; Sattar, Bourque, Giguere, & Dudek, 2007) and thus underwater robots must present a higher degree of autonomy than that required in the terrestrial domain. Failures that are minor for terrestrial vehicles can be catastrophic for vehicles operating underwater. These devices must cope with the realities of six-degrees-of-freedom (6DOF) motion in highly unstructured environments. In addition, unknown external forces such as currents act upon the vehicle, and sensing is complicated by fish and suspended particulate matter (aquatic snow).

Because of these complexities, the underwater environment provides a vast range of applications for which the reconstruction of complex 3-D structures is desired. For example, a sensor capable of autonomously reconstructing a 3-D model of a ship’s hull would enable the inspection and analysis of its structural integrity and the search for malicious payloads (Negahdaripour & Firoozfam, 2006). Similarly, a 3-D model of a ship wreck could aid in determining the cause of the event. In addition to man-made structures there is a significant need for the analysis of natural structures, such as coral reefs. Coral reefs are important for the global underwater ecosystem. They provide both shelter and nutrition for many species of aquatic life. Reefs are composed of extremely fragile organisms that can be destroyed by slight changes in water temperature, salinity, and pollution. One metric for establishing the health of the reef is to monitor its size with respect to time. Manually measuring reef size is an error-prone and time-consuming effort. Divers swim along the transect and use video to record the reef. Random samplings are then made of these videos to estimate various reef populations (Aronson, Edmunds, Precht, Swanson, & Levitan, 1994). Although it is well known that such analysis introduces systematic biases into the recorded data due to perspective distortions and other factors (Porter & Meier, 1992), this approach remains the basis of current reef monitoring techniques. More sophisticated image processing techniques (e.g., Gintert et al., 2007) typically concentrate on 2-D image mosaics rather than investigating 3-D object recovery. Automatic 3-D reconstructions could be used to analyze the health of the reef by measuring changes to both the true size of the reef and the population density of the coral itself.

Given the importance of the underwater environment in terms of applications it is thus not surprising that there has been considerable interest in the development of autonomous and semiautonomous underwater systems. For example, Eustice, Singh, Leonard, Walter, and Ballard (2005) describe a tethered system that was used to map parts of the RMS Titanic, and Ribes and Borrelly (1997) describe a visually guided underwater pipe inspection robot.

In addition to addressing a wealth of application-specific needs, visual sensing is an enabling technology for autonomous underwater vehicles (AUVs). A critical requirement for many AUVs is the need to maintain an ongoing representation of its position with respect to some environmental representation (a map), and to construct the map while maintaining the vehicle’s position with respect to the map itself. There is a long history of research in the problem of simultaneous localization and mapping (SLAM) for robotic vehicles (e.g., Montemerlo, Thrun, Koller, & Wegbreit, 2003; Nettleton,
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