Ocean Engineering 130 (2017) 336–350

Contents lists available at ScienceDirect

Ocean Engineering

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

Autonomous detection, following and mapping of an underwater chain using sonar

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ARTICLE INFO

Keywords:
Mooring chain
Autonomous underwater vehicle
Sonar

ABSTRACT

Following an underwater chain using an autonomous vehicle can be a first step towards more efficient solutions for cleaning and inspecting mooring chains. We propose to use sonar as a primary perception sensor to enable the vehicle operation in limited visibility conditions and overcome the possible turbidity arising during marine growth removal. Despite its advantages, working with acoustic data raises additional challenges for the processing and control methodologies involved. We present two chain link detectors that make use of forward-looking sonar and multibeam data and we combine them with adequate planning and control strategies to achieve a robust framework to detect, follow and map an underwater chain. Experiments conducted in a water tank and in a real harbor environment demonstrate the capability of autonomously detecting and following a chain with sufficient accuracy to perform subsequent cleaning or inspection tasks. Besides this, we demonstrate the possibility of obtaining a preliminary map of the chain and its surroundings regardless of visibility conditions.

1. Introduction

Autonomy is a central aspect in the marine robotics community. The present work is framed in the context of the PANDORA European FP7 project (PANDORA, 2016), which aims to increase the range and complexity of underwater tasks that can be automated while reducing the need for operator supervision. To this end, one of the three core tasks of the PANDORA project is to work towards a cost and time efficient solution for the cleaning and inspection of mooring chains using an autonomous underwater vehicle (AUV).

Chain moorings on floating structures such as floating production, storage and offloading (FPSO) vessels are exposed to severe environmental and structural conditions. In order to avoid potential damage, chain status is monitored through periodic and exhaustive inspections. Traditional methods, which involve recovering the chain on deck or ashore, are being replaced by *in situ* in-water inspections using remotely-operated vehicles (ROVs) equipped with mechanical or optical callipers (Welaptega Marine Limited, 2016; Hall, 2005; Morandini and Legerstee,) or chain crawler vehicles (Reece Innovation, 2016). Recent tests have also shown preliminary results in performing a 3D laser scanner inspection from an AUV (Reeves et al., 2014). However, most available solutions require prior removal of the marine biofouling so that the chain can be properly examined. Cleaning solutions range from manual brushing with divers, which is potentially hazardous and has an inherent depth limit, to high-pressure water systems deployed with ROVs (Noble Denton Europe Limited, 2006). The time spent to clean depends strongly on the selected option, but in general is a tedious and slow task since optical visibility drops drastically as the removed marine growth floats in the water. Indeed, considering the cost of ROV vessels, chain cleaning can be a significant fraction of the cost of a chain inspection program (Noble Denton Europe Limited, 2006).

To avoid the presence of troublesome ROV cables and reduce the cost of the deploying vessel, the PANDORA project aims to demonstrate the feasibility of using an AUV equipped with a water jet to conduct chain cleaning and inspection tasks. Such a system could be useful as well in the cleaning and inspection of mooring buoy chains or in general to any large vessel anchor chain (see Fig. 1). Our proposal is to use an AUV with a high resolution imaging sonar (Aris explorer, 3000, 2016), which delivers acoustic images at near-video frame rate, in order to autonomously navigate along the chain and detect each of the links. In this way the cleaning process can be carried out regardless of the visibility conditions and the suspended marine fouling, thus speeding up the overall operation.

Moreover, by mosaicing the sonar images gathered along the chain trajectory, the same methodology provides the means to perform an initial visual inspection, from which it is possible to identify some major issues or locate problematic parts that need further cleaning or

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http://dx.doi.org/10.1016/j.oceaneng.2016.11.072
Received 17 May 2016; Received in revised form 22 October 2016; Accepted 30 November 2016

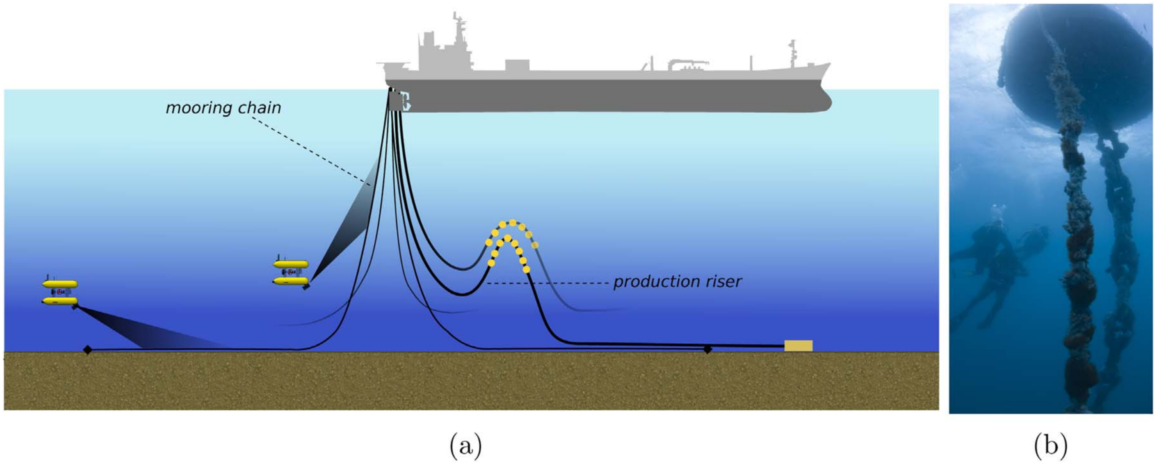

Fig. 1. Potential applications of the proposed system: (a) FPSO mooring lines, (b) buoy moorings and, in general, any scenario where underwater *in situ* chain cleaning and inspection is required.

inspection.

Despite these advantages, the use of such a system produces several challenges that must be addressed. First, the automatic detection of the chain links in forward-looking sonar (FLS) images becomes a complex problem, due to the inherent sonar characteristics: noise, low resolution, moving shadows and intensity variations due to different vantage points. Besides, the control of the AUV must be adapted to take into account the imaging geometry of the FLS, which insonifies a fan-shaped 3D portion of the environment and maps it into a 2D representation. Moreover, the vehicle location at a given instant differs from the point that is being inspected, which is a few meters ahead depending on the sonar's range configuration. Therefore, to successfully follow the chain, the detection and control schemes must be tightly coupled so that the chain links do not drop off the sonar's narrow field of view and the vehicle keeps always track of the chain.

This paper proposes a framework to deal with such challenges, thus providing a solution for the autonomous detection, following and mapping of an underwater chain as a first step towards performing chain cleaning and inspection in a completely automated way.

Our mission scenario consists in an AUV that is deployed in the vicinity of a mooring chain. The presented methodology considers a chain lying approximately on a plane, either horizontal or vertical. Note though, that this approach could be extended to other configurations with the aid of a pan-and-tilt unit in order to set the imaging sonar to the appropriate grazing angle to image the scene. For instance, this would be convenient to address the transition portion of a mooring chain from horizontal to vertical. However, to start with, and given that most part of a mooring chain is either lying on the sea floor or suspended in the water column, the present work focuses in solving the problem in two independent scenarios: horizontal and vertical chain configurations. Even though we assume that the position of the chain in the environment is approximately known, it might not be always possible or practical to deploy the AUV in a location where the chain is readily visible by the sonar systems. Therefore, we must account for a detection phase, in which the vehicle automatically finds the chain in the environment, leading to the following maneuver through the different links, and finally the mapping, which is performed offline using the gathered data. In this paper we propose a framework to address all these phases focusing on the two mentioned scenarios (horizontal and vertical), and thus demonstrate the feasibility of autonomous operations in chain moorings. It is worth underlining here that the details of a possible cleaning system, by means of a water jet integrated on the AUV, fall beyond the scope of this paper.

This paper builds on previous work of the authors. A first offline version of the forward-looking sonar chain link detector was presented in Hurtós et al. (2013). A second version, already running online, was presented in Hurtos et al. (2014), together with a preliminary framework for chain following with the chain in horizontal configuration, which was demonstrated in a water tank. However, the framework presented in this paper has significant improvements, including a whole new trajectory planner module. Moreover, aside from the chain following in the horizontal scenario, we extend and complete the framework by including a new algorithm for dealing with the chain detection and following in the vertical configuration. Furthermore, experiments for both scenarios in a harbor environment have been conducted, reporting results from a more realistic setup.

The reminder of this document is organized as follows. Section 2 describes the proposed solution for detecting and following a chain in horizontal configuration. This includes the proposal of a detection algorithm developed to robustly detect chain links on sonar imagery, the generation of position waypoints from the link detections and the control system of the AUV. Section 3 describes the variations made to this approach in order to tackle the problem for the chain in vertical configuration, which includes the use of an auxiliary multibeam sensor to facilitate the detection and following in the water column. Experiments and results are reported in Section 4, showing the performance of the proposed framework in tests conducted both in a water tank and at sea. Furthermore, we prove the capability of the system to perform mapping with the gathered data by reporting some of the maps generated after the chain following procedures. Finally, Section 5 concludes the paper and points out future work.

2. Horizontal chain detection and following

Throughout this section we consider a mooring chain lying on the seabed. In this scenario, the vehicle navigates at a constant altitude from the seafloor and the FLS tilt angle is set at a small grazing angle ($\sim 15^\circ$ from the horizontal plane) in order to maximize the coverage of the imaged area (see Fig. 2).

Fig. 3 outlines the developed chain-following framework. As the vehicle navigates, the stream of sonar images is processed by a link

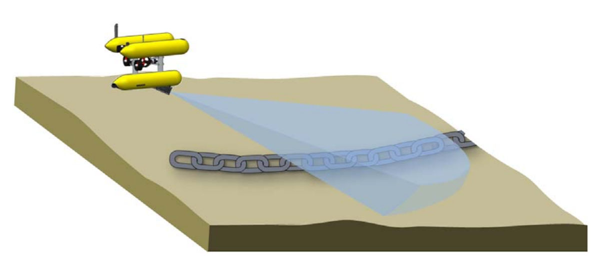

Fig. 2. Chain horizontal scenario.