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Detection and tracking of ships in open sea with rapidly moving buoy-mounted camera system

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ABSTRACT

Visual surveillance in the maritime domain has been explored for more than a decade. Although it has produced a number of working systems and resulted in a mature technology, surveillance has been restricted to the port facilities or areas close to the coast line assuming a fixed-camera scenario. This paper presents a novel algorithm for open-sea visual maritime surveillance. We explore a challenging situation with a forward-looking camera mounted on a buoy or other floating platform. The proposed algorithm detects, localizes, and tracks ships in the field of view of the camera. Specifically, developed algorithm is uniquely designed to handle rapidly moving camera. Its performance is robust in the presence of a random relatively-large camera motion. In the context of ship detection we developed a new horizon detection scheme for a complex maritime domain. The performance of our algorithm and its comprising elements is evaluated. Ship detection precision of 88% is achieved on a large dataset collected from a prototype system.

1. Introduction

Surveillance systems play an important role in management and monitoring of littoral and maritime areas by providing tools for situation awareness, threat assessment, and decision making. Various sources of surveillance, monitoring, maritime safety information are available. These include the Automatic Identification System (AIS), Vessel Monitoring Systems (VMS), air- and space-borne SAR systems, ship- and land-based radars, air- and space-borne optical sensors, harbor-based visual surveillance. During the last decade technology has been moving towards integration of several information sources, of which one essential component is vision. Fusion of vision with other information sources allows more accurate and descriptive monitoring of coastal areas, maritime borders, and offshore assets. Examples of this trend include systems that integrate AIS/VMS with SAR-imagery (Lemoine et al., 2005; Saur et al., 2011), radar- and visual-based surveillance for ports (Seibert et al., 2006; Rodriguez Sullivan and Shah, 2008), land-radars with visual information from air-borne platforms, and ship-based systems that integrate visual and other sensor's information (Wei et al., 2009; Liu et al., 2008).

A new concept (Fefilatyev et al., 2009; Kruger and Orlov, 2010) helps to integrate information from radars/AIS with vision sensors placed on autonomous buoys. Such an autonomous unmanned buoy-system is an attractive choice for integrated surveillance for reasons of cost, persistent ocean presence, form-factor, and flexibility. A network of vision sensors with on-board processing and bi-directional communication can provide a real-time intelligence for critical maritime areas. It can detect, classify, identify and track small vessels at sea often associated with issues of illegal immigration, smuggling, and poaching. Examples of use of vision information from such source include verification of vessel's class, intent, and behavior, as well as description of state and status of the vessels. A passive vision sensor is also more desirable in military applications because it does not reveal the location of the surveillance system.

The aim of this paper is to present a novel algorithm for on-board processing of image- and video-data obtained by a buoy-based maritime surveillance system equipped with a low-sitting forward-looking camera. The system operates autonomously and intelligently in a maritime area away from the visible coast-line. This involves detection, localization, and tracking of ships or other marine vehicles of interest in imagery taken by its color camera that is mounted on a buoy and is a subject to rapid random motion associated with the buoy's flotation. The output of the algorithm are images of the found unique target candidates. The algorithm, described in the paper, addresses the most common problems in buoy-based visual surveillance: horizon detection in complex maritime scenes; frame stabilization in video with large

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inter-frame motion; segmentation of low-contrast targets in imagery corrupted by compression artifacts; inter-frame tracking. The algorithm is formulated for real-time execution on a limited-memory commercial of-the-shelf computing platform and is suited for low-powered autonomous systems deployed for long periods of time. The performance of proposed algorithm is evaluated on a large set of annotated image data obtained from a prototype. The results are shown for the most important characteristics: detection, localization, and tracking accuracy.

The rest of the paper is structured as follows. Section 2 relates our work to the existing work on visual maritime surveillance. Section 3 presents the algorithms for horizon detection, frame stabilization, segmentation, detection, and tracking of ships. The description of metrics used to evaluate the performance of the proposed approach is given in Section 4. Section 5 reports experimental evaluations on data obtained from a prototype system. Conclusions are drawn in the last section.

Initial work on this problem was presented in earlier publications (Fefilatyev et al., 2009, 2010).

2. Related work

We review the developments in the area with respect to several aspects. First, in Section 2.1 we review the general topic of visual maritime surveillance with stationary cameras, mostly related to port security. Second, in Section 2.2 we review surveillance from non-stationary platforms: air- and sea-borne. Third, because of the importance of horizon detection in our algorithm, in Section 2.3, we briefly review the existing approaches to horizon line detection.

2.1. Visual surveillance in maritime domain with stationary cameras

The harbor, port, and coast surveillance have been extensively studied for more than a decade (Voles et al., 1999; Socek et al., 2005; Seibert et al., 2006; Feineigle et al., 2007; Rodriguez Sullivan and Shah, 2008; Chen, 2008; Sanderson et al., 2008; Bloisi et al., 2009). In general, all the existing systems for port surveillance assume that the camera is in a fixed position, and the water surface is fixed in terms of a camera view. With this set of assumptions, algorithms for background subtraction or background suppression are mostly used. Many of the mentioned papers describe already existing systems (Seibert et al., 2006; Rodriguez Sullivan and Shah, 2008; Bloisi et al., 2009; Cao et al., 2010), signifying matureness of the topic and spread of the commercial applications. Reported functionality of such systems include vessel detection, discrimination between vessel classes, comparison of the detections with the notifications of arrival received by the port, and geo-registration of ships that navigate in port waters. Those methods rely on stationary camera, the assumption that is not valid in our settings.

2.2. Visual surveillance in maritime domain from non-stationary platforms

Many applications for visual maritime surveillance from non-stationary platforms stem from Automated Target Detection (ATR) systems (Li et al., 2004; Valin et al., 2006; Tao et al., 2007; Li and Wang, 2008; Araghi et al., 2009; Shaik and Iftekharuddin, 2009). ATR systems are designed to be air- or sea-borne. They rely on forward-looking infrared (FLIR) cameras as a primary source of the imagery because the infrared sensors are less-sensitive to variations in illumination and appearance changes, which is common in maritime scenes. A notable disadvantage of FLIR-based systems is the low resolution of images and significant power consumption which makes these systems less capable for autonomous operation. The most significant applications not related to ATR or harbor surveillance are classification of ships (Enríquez de Luna et al., 2005; Gupta et al., 2009), image stabilization (Morris et al., 2007; Cao and Zhang, 2007), ship motion estimation (Benetazzo, 2011), and, relevant to our work, detection and tracking in non-stationary maritime environment (Liu et al., 2008; Kruger and Orlov, 2010; Teutsch and Kruger, 2010; Wei et al., 2009).

The systems described by Liu et al. (2008), Kruger and Orlov (2010), and Teutsch and Kruger (2010) differ from ours in terms of data source. Liu et al. (2008) rely on color visual data from omni-directional camera. Although their approach addresses many segmentation problems and provides a 360° surveillance with a single camera, the authors admit a limited the effective range because of very wide-angle of observation. Increase in the range requires substantial increase in the pixel resolution of the camera and height of the mast where the omni-directional camera is installed. Kruger and Orlov (2010) and Teutsch and Kruger (2010) rely on a narrow-angle buoy-based FLIR camera and share some ideas with our earlier work (Fefilatyev and Goldgof, 2008; Fefilatyev et al., 2009). However, they focus on detection and tracking in data from FLIR cameras which requires different approach to segmentation.

The system described by Wei et al. (2009) has similar assumptions to the ones used in this work. However, their surveillance system is designed for ships, and performance of the described detection and tracking algorithm may be limited in the case of buoy-based mechanically not stabilized camera that experiences high-magnitude rapid motion in pitch, yaw, and bank dimensions. The specific background-subtraction algorithm they proposed relies on the horizon line that is always present in an image, is sensitive to fast illumination changes caused by the dynamics of maritime scenes, and, thus, does not show robustness on the data obtained from a buoy-based camera. Wei et al. (2009) also assume a high-sitting camera with objects of interest located below the horizon line. Our paper aims to cover the issue of a very dynamic scenes with targets on-or-above the horizon line, and provides performance evaluation of the proposed approach.

2.3. Approaches to horizon detection

The two main application domains for horizon estimation are vanishing line estimation and unmanned aerial vehicle (UAV) navigation.

The vanishing line approaches (Lv et al., 2006; Cao et al., 2010; Guo and Chellappa, 2006; Criminisi and Zisserman, 2000; Sheikh et al., 2006) are aimed to locate a vanishing line of the horizon which may or may not be the actual visible horizon. All the methods from this category of approaches are related to a fixed camera and, thus, are not applicable in our case. The only method that could be used in a non-stationary environment is the approach described by Criminisi and Zisserman (2000), which utilizes the assumption of homogeneity of surface's texture. However, such geometry-based solution does not provide sufficient precision for stochastic textures.

In the case of UAV navigation, the horizon line is used as an alternative to inertial sensors (Ettinger et al., 2003; McGee et al., 2005; Bao et al., 2005; Zhang et al., 2010; Dusha et al., 2007). There are several approaches in this category to find the horizon line: by using analysis of projection profiles of the edge map of an image (Bao et al., 2005; Zhang et al., 2010), using Hough transform (Wei et al., 2009) and optical flow (Dusha et al., 2007). Those algorithms are inappropriate for our case because of either high computational demands, or assumption on always present horizon. The horizon detection algorithm described by McGee et al. (2005) is fast and addresses both situations: when the horizon line is visible and when it is absent. The approach classifies the pixels into sky/ground regions and finds the boundary between