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Stereo obstacle detection for unmanned surface vehicles by IMU-assisted semantic segmentation

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HIGHLIGHTS

- A new obstacle detection algorithm for unmanned surface vehicles (USVs) is presented.
- A state-of-the-art graphical model for semantic segmentation is extended with inertial measurement unit (IMU).
- A stereo verification algorithm that consolidates tentative detections is proposed.
- A new, fully annotated, challenging multi-modal dataset is presented.
- Significant outperformance of current state-of-the-art semantic segmentation method.

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ABSTRACT

A new obstacle detection algorithm for unmanned surface vehicles (USVs) is presented. A state-of-the-art graphical model for semantic segmentation is extended to incorporate boat pitch and roll measurements from the on-board inertial measurement unit (IMU), and a stereo verification algorithm that consolidates tentative detections obtained from the segmentation is proposed. The IMU readings are used to estimate the location of horizon line in the image, which automatically adjusts the priors in the probabilistic semantic segmentation model. We derive the equations for projecting the horizon into images, propose an efficient optimization algorithm for the extended graphical model, and offer a practical IMU–camera–USV calibration procedure. Using an USV equipped with multiple synchronized sensors, we captured a new challenging multi-modal dataset, and annotated its images with water edge and obstacles. Experimental results show that the proposed algorithm significantly outperforms the state of the art, with nearly 30% improvement in water-edge detection accuracy, an over 21% reduction of false positive rate, an almost 60% reduction of false negative rate, and an over 65% increase of true positive rate, while its Matlab implementation runs in real-time.

1. Introduction

The past decade of research in marine and field robotics has led to establishment of a new class of small-sized unmanned surface vehicles (USVs). Such boats are typically less than 2 m long, and can be guided either manually or programmed to follow a predetermined path. Their main advantage over the larger counterparts is portability and the ability to navigate relatively shallow waters and narrow marinas. This broadens the potential areas of applications, which range from coastal water and environmental surveillance to inspection of man-made structures above and below water.

On the other hand, the small form factor of such USVs limits the available sensor payload, which is further restricted by the power consumption limitations. Therefore, cameras are gaining prominence as light-weight, low-power, and information-rich sensors, which represent a viable alternative or addition to other sensor modalities [1,2]. In contrast to LIDAR, the camera systems do not contain moving parts, which makes them robust to mechanical stress. Compared to RADAR and LIDAR, the camera systems are completely passive and are therefore inherently safe in any environment, without the potential risk of interfering with other critical systems, such as radio communication or GPS [3]. Furthermore, the commercially available high-performance LIDAR systems are typically unsuitable for small-sized USVs, as their weight and size may compromise the boat stability [4]. Similarly, the usefulness of affordable and commonly used laser sensors is limited even on

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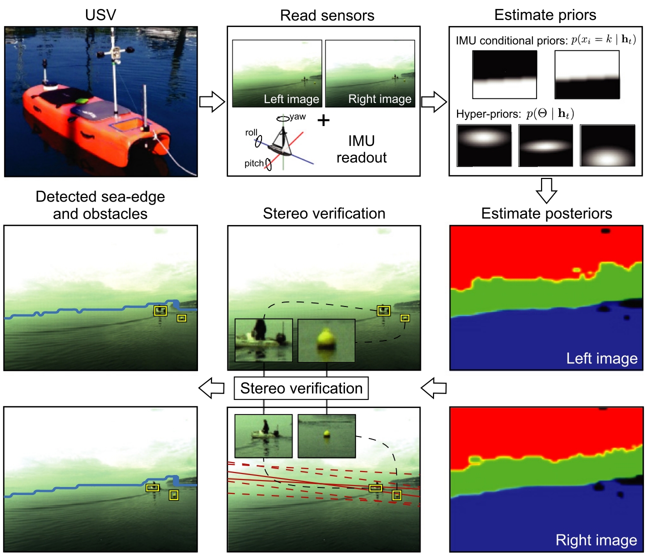

Fig. 1. Outline of our IMU-assisted semantic segmentation method using stereo verification (ISSM$_S$) for obstacle detection. The IMU measurements constrain the semantic segmentation, and provide sea-edge estimate and obstacle candidates in each camera. Afterwards, the stereo verification step is applied to reduce the false negative and false positive detections.

larger vessels, due to significant variations in lighting and constant rocking of the boat [5,6].

The performance of standard stereo-vision-based methods in USV applications is severely limited by rapidly-changing water surface, reflections, and the absence of texture in the absence of disturbances, such as waves. The obstacles often do not sufficiently protrude through the water surface to be reliably detected by stereo systems. Recently, Kristan et al. [7] proposed a graphical model for monocular obstacle detection via semantic segmentation (SSM) of the observed marine scene. The algorithm generates a water segmentation mask and treats all objects in the water as obstacles. Their approach runs in real-time and outperforms related approaches on the task of obstacle detection. However, it fails in the presence of significant rolling and pitching in rough seas, and is susceptible to false positives and degraded sea-edge estimation in the presence of visual ambiguities (e.g., when horizon is poorly distinguishable from the sky).

In this paper, we build upon [7], and propose a new segmentation-based obstacle detector for unmanned surface vehicles that incorporates the roll and pitch measurements from the on-board IMU and additionally verifies obtained detections using a stereo system (Fig. 1). We claim the following three major contributions. The first contribution is extension of the graphical model for semantic segmentation [7] with roll and pitch measurements from the IMU. This information is used to project the horizon onto the input image, and automatically adjust the priors and hyper-priors of the segmentation model. This enables reliable segmentation even during significant motion of the boat. We derive the required IMU-to-camera horizon projection equations, and propose a practical IMU-to-camera calibration procedure. Our second contribution is improvement of the segmentation-based obstacle detection via stereo verification. The approach applies epipolar constraints and template matching to reduce the amount of false positive and false negative detections. Our third contribution is a new challenging dataset for marine obstacle detection, which consists of multiple sequences with time-synchronized data streams from on-board stereo system, IMU and GPS, and is currently the largest of its kind. The extensive experimental analysis on this new dataset shows that the proposed approach significantly outperforms the state-of-the-art SSM [7], both in accuracy of sea-edge estimation and in the accuracy of obstacle detection.

The remainder of this paper is structured as follows. Section 2 provides a brief overview of the related work. Sections 3–5 present the proposed IMU-assisted segmentation model, stereo-based obstacle verification algorithm, and calibration procedure, respectively. Section 6 describes our new marine obstacle detection dataset, which is used in Section 7 for experimental evaluation of the proposed approach, while Section 8 wraps up the paper with concluding remarks.

2. Related work

Obstacle detection in unmanned surface vehicles is still a relatively young research area, especially compared to the already-established field of autonomous ground vehicles, where a considerable body of literature can be found on topic of obstacle detection and avoidance. Krotosky et al. [8], Zhang et al. [9], and Cao et al. [10] use a stereo camera system to compute disparity map and use it for obstacle detection. They apply different computer vision methods to filter the disparity map and remove noise in detected obstacles. Krotosky et al. [8] combine detections from disparity map with information from an infrared camera to further improve the detection of pedestrians. Shim et al. [11] use a combination of several sensors for obstacle detection. They use LIDAR to detect general obstacles on the road under the assumption of ground being a flat surface. In the next step, they use a monocular camera in combination with HOG [12] and SVM [13] algorithms to detect pedestrians and vehicles, while limiting the search area to bounding boxes of detections previously obtained from the LIDAR. Einhorn et al. [14] use frontally mounted monocular camera and Extended Kalman Filters to reconstruct the scene and consequently detect potential obstacles. They propose attention-driven method for image areas where the obstacle situation is unclear and a more detailed scene reconstruction is necessary. Ćesić et al. [15] fuse detections from stereo cameras and RADAR. Visually detected obstacle features are matched using stereo block matching and optical flow procedure. Filtered feature correspondences are projected to radar plane and passed to the multi-target tracking algorithm. Asvadi et al. [16] propose obstacle detection method using LIDAR fused with measurements from inertial navigation system (GPS/IMU). The method mainly improves detection of pedestrians and cyclists. Li et al. [17] presented a method for road detection with image segmentation based on dark channel prior [18] and horizon estimation.

The majority of approaches that were developed for autonomous ground vehicles rely on estimation of the ground plane, and cannot be readily applied to the aquatic environment of the USVs. A common practice for obstacle detection in marine environment is the use of RADAR, sonar, or LIDAR. Almeida et al. [19] proposed obstacle detection using on-board radar. They experienced difficulties in detecting small obstacles that were located in the near proximity (closer than 200 m) of the boat. The size and power consumption of radar units represent an additional challenge in application on small-sized USVs. Several approaches have therefore focused on obstacle detection using cameras.

Larson et al. [20] present advances in obstacle avoidance for USVs and point out the use of cameras. Their approach to obstacle detection with monocular camera relies on horizon estimation and image segmentation. On open sea, they use simple trigonometric calculations to estimate the horizon, while in marine environment and near shoreline, they use nautical charts, which provide them with analogous baseline distance to the shore. Guo et al. [21] use an omni-directional camera to detect obstacles in water, based on the difference between two consecutive frames and foreground extraction. However, this method does not consider the dynamic nature of clouds and sky, nor their effect on the visual properties