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Pedestrian recognition and tracking using 3D LiDAR for autonomous vehicle☆

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HIGHLIGHTS

- Curb information is used to divide pedestrian candidates into two classes, i.e., on-road and out of road.
- Tracking aided recognition strategy is used to improve the true positive rate, for example, for those on-road candidates, who have been recognized as pedestrians in former frame are classified to be pedestrians directly.
- This may increase the true positive rate for candidates who become too close or too far from moving autonomous vehicle in the following frames, where only a few laser beams are irradiated on pedestrians.
- Hash table is used for searching and comparison in the segmentation procedure to increase the efficiency of the proposed algorithm.
- The pedestrian recognition and tracking system is integrated with the autonomous vehicle platform which provides timely prediction of pedestrian motions.

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ABSTRACT

This paper studies the pedestrian recognition and tracking problem for autonomous vehicles using a 3D LiDAR, a classifier trained by SVM (Support Vector Machine) is used to recognize pedestrians, the recognition performance is further improved with the aid of tracking results. By comparing positions and velocity directions of pedestrians with curb information, alarms will be generated if pedestrians are detected to be on road or close to curbs. The proposed approach has been verified on an autonomous vehicle platform.

1. Introduction

Research on autonomous vehicles such as driverless cars has received great attention in the past ten years, pedestrian recognition and tracking, as one of the most important issues for autonomous vehicles, also grows exponentially with the development of self-driving techniques. For cases where autonomous vehicles operate in close proximity with pedestrians, recognition and tracking of moving pedestrians are two basic tasks of autonomous vehicle's collision avoidance system. In addition, the timely prediction of most likely near future positions of pedestrians being tracked is essential for the real-time path planning of autonomous vehicles.

In the literature, cameras are commonly used low cost sensors for pedestrian recognition, e.g., by analyzing each image, contour cues are used to detect pedestrians in [1], while in [2], by investigating the characteristic appearance patterns of pedestrians in crowded street, a joint detector is proposed to improve the detection result for pedestrians with partial occlusions. Since humans are highly articulated, it is common to use part-based representations and multi-layer strategy for pedestrian recognition, in [3], pedestrians are modeled as flexible assemblies of parts, a coarse-to-fine cascade approach is used for part detection, and a part assembly strategy is proposed to recognize pedestrians. In [4], a bottom-up parsing of partial body masks strategy is proposed, at each level of the parsing process, partial body masks are evaluated via shape matching with exemplars. In [5], multiscale deformable part models are mixed and a margin sensitive approach for data-mining hard negative examples is combined with latent SVM to detect highly variable objects including pedestrians. In [6], leg

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segments are considered to be 'arc-like' shapes, a circle detection technique called inscribed angle variance (IAV) is presented.

LiDARs are another kind of commonly used sensors for pedestrian recognition, compared with cameras, LiDARs can provide accurate range information and larger field of view. In [7], 3D point clouds are seen as a collection of several 2D point clouds at different heights, detectors trained by AdaBoost are used to detect pedestrians. In [8], 3D point clouds in the target are divided into parts, i.e., trunk and legs, to achieve robust *in situ* pedestrian recognition. In [9], both geometric and motion features are used to represent pedestrians, which deal with static and moving pedestrians, respectively. In [10], two new features are introduced to improve the classification performance, one is the slice feature, which represents the profile of a human body by widths at different height levels, the other is the distribution of reflection intensities of point clouds. In [11], AdaBoost is used to learn a robust leg detector from a set of statistic features, such as number of points. The same classification strategy is used in [12], where the possible distance between legs is taken into account, and a probabilistic body part-based detection framework is presented. In [13], an algorithm to combine 3D and 2D LiDARs is proposed, where 3D data is used to construct a ground elevation map while 2D data is used to detect pedestrians at a certain height above the ground. In [14], data collected by a Lidar and a monocular camera is combined, and an active pedestrian detection system is designed, through using sliding window detectors, image-based detection module is used to validate the presence of pedestrians in the regions of interest generated by Lidar module.

On the other hand, reliable tracking and prediction of pedestrian motions can make an autonomous vehicle aware of potential collision with pedestrians in its vicinity [15]. Kalman filters with nearest neighbor data association [16] and Monte Carlo Particle filters [17] are two commonly used approaches to estimate motions of pedestrians, and in [18], feature matching, ICP (Iterative Closest Point), Kalman filtering, and dynamic mapping are combined together to estimate motions. This paper deals with the pedestrian recognition and tracking problem for an autonomous vehicle which is moving on road. The contribution of this paper includes the following aspects. (1) Curb information is used to divide pedestrian candidates into two classes, i.e., on-road and out of road. Tracking aided recognition strategy is used to improve the true positive rate, for example, for those on-road candidates, who have been recognized as pedestrians in former frame are classified to be pedestrians directly. This may increase the true positive rate for candidates who become too close or too far from moving autonomous vehicle in the following frames, where only a few laser beams are irradiated on pedestrians. (2) Hash table is used for searching and comparison in the segmentation procedure to increase the efficiency of the proposed algorithm. (3) The pedestrian recognition and tracking system is integrated with the autonomous vehicle platform which provides timely prediction of pedestrian motions. The rest of this paper is organized as follows. Section 2 introduces the system architecture. Section 3 presents the pedestrian recognition method including how to choose the training examples. Section 4 discusses the pedestrian tracking approach, based on which alarms are also generated when collision dangers are predicted. Experiments are presented in Section 5, while conclusions are given in Section 6.

2. System overview

2.1. System introduction

The main sensor used in this paper is Velodyne 64 LiDAR (Light Detection And Ranging) which is mounted on the top of an autonomous vehicle as shown in Fig. 1. Besides Velodyne 64,

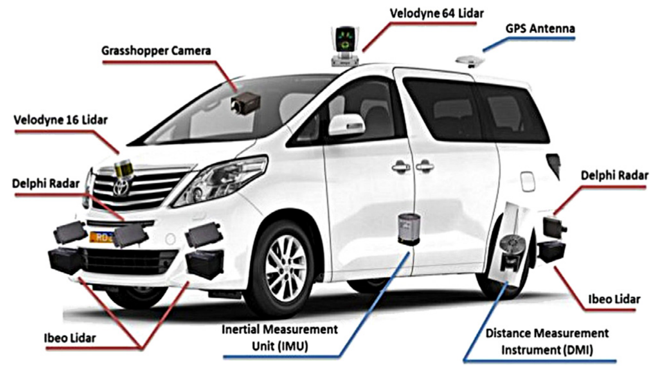

Fig. 1. Autonomous vehicle platform of Institute for Infocomm Research.

GPS (Global Positioning System), IMU (Inertial Measurement Unit) and DMI (Distance Measurement Unit) are fused to localize the autonomous vehicle in real time. Since we mainly focus on pedestrian recognition and tracking problem in this paper, it is assumed that the autonomous vehicle is localized with enough accuracy. In addition, a Velodyne 16 Lidar is used to detect and fit curbs, which is mounted in the front of the vehicle. The other sensors mounted on the autonomous vehicle are used for other purposes which are ignored.

The Velodyne 64 incorporates 64 laser diodes and spins at up to 15 Hz, generates dense range data covering a 360-deg horizontal field of view and a 26.8-deg vertical field of view. A 3D point cloud is acquired from Velodyne: around 100,000 points per frame at frequency of 10 Hz, each point includes range, intensity and *xyz* coordinates. Similar to Velodyne 64, Velodyne 16 incorporates 16 laser diodes whose size is much smaller than Velodyne 64 and can be mounted more flexibly. In this paper, we use the raw data collected by Velodyne 64 and Velodyne 16 to recognize pedestrian and detect curbs, respectively. All the *xyz* coordinates of point clouds collected by both Velodyne 64 and Velodyne 16 are converted into the same global coordinate frame.

In the following sections, we will describe pedestrian recognition and tracking using the data collected by Velodyne 64 in details. 3D point clouds are firstly projected onto 2D plane and are gridded, then a nearest-distance algorithm is proposed for clustering, Kalman filter is used to track objects whose sizes are under a limit after clustering. At the same time, a trained classifier is used to recognize whether the tracked objects are pedestrians or not. In addition, pedestrian recognition performance is further improved by tracking results.

3. Pedestrian recognition

3.1. Initial processing

For further clustering and recognition, 3D point clouds acquired from Velodyne 64 are firstly processed to filter noises and uninterested areas, e.g., points whose heights are larger than some limit are removed. All the 3D points are projected onto 2D occupancy grid, Fig. 2 shows a schematic diagram of a 5 × 5 occupancy grid map, where grid cells (2,3), (3,2), (3,3) and (5,5) are occupied, and grid cells (2,3), (3,2) and (3,3) are called connected cells. The cell size of each occupancy grid is set to be 0.1 m × 0.1 m, a threshold η_1 is chosen to limit the height difference in each grid which is set to be 0.4 m in this paper, by comparing the average height in each grid with η_1, grids corresponding to ground and low objects such as curbs are filtered. Since ground and low objects are removed from occupancy grid, the occupancy grid can be represented by a sparse matrix where non-zero elements are randomly distributed.

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