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Kalman filter-based tracking of moving objects using linear ultrasonic sensor array for road vehicles

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ABSTRACT

Detection and tracking of objects in the side-near-field has attracted much attention for the development of advanced driver assistance systems. This paper presents a cost-effective approach to track moving objects around vehicles using linearly arrayed ultrasonic sensors. To understand the detection characteristics of a single sensor, an empirical detection model was developed considering the shapes and surface materials of various detected objects. Eight sensors were arrayed linearly to expand the detection range for further application in traffic environment recognition. Two types of tracking algorithms, including an Extended Kalman filter (EKF) and an Unscented Kalman filter (UKF), for the sensor array were designed for dynamic object tracking. The ultrasonic sensor array was designed to have two types of fire sequences: mutual firing or serial firing. The effectiveness of the designed algorithms were verified in two typical driving scenarios: passing intersections with traffic sign poles or street lights, and overtaking another vehicle. Experimental results showed that both EKF and UKF had more precise tracking position and smaller RMSE (root mean square error) than a traditional triangular positioning method. The effectiveness also encourages the application of cost-effective ultrasonic sensors in the near-field environment perception in autonomous driving systems.

1. Introduction

With rapid development of advanced driver assistance systems (ADAS) and intelligent vehicles, various types of sensors (e.g., radars with79 GHz or 24 GHz, lidar, camera, ultrasonic sensor, etc.) have been utilized to percept the surrounding traffic environment of road vehicles [1,2]. Among these sensors, ultrasonic ones have the advantages of low cost, wide detection angle, small blind zone in the near-field and relatively good robustness to variant environmental conditions (e.g., lighting, fog, etc.) [3–6]. Additionally, the detection range of ultrasonic sensors can be significantly expanded from near-field (< 2 m) to middle-distance (5 m or even longer) by reducing signal attenuation and increasing the sensitivity of signal processing circuit [7] .

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Ultrasonic sensors apply the principle of 'time of flight' (TOF) to measure distance, which computes the travel time of ultrasonic echo reflected from the target [8]. Therefore, the performance of ultrasonic sensors highly depends on the reflective characteristics (e.g., shape, surface material) of the target surface. In urban traffic environments, traffic participants and road facilities are with various shapes and surface materials. For example, the shapes of vehicles and pedestrians are largely different from each other. The surface material of vehicles is metal, while that for pedestrians is usually cloth. Besides, variation of ultrasound speed due to fluctuations of temperature, humidity and wind may also have noticeable effects on the measurement accuracy [9], which complicates the analysis of ultrasonic signals.

Thus, an accurate and reliable model of ultrasonic sensors is of critical importance to the design of detection and tracking algorithms. In the literature, the models can be divided into two types based on their modeling principles: physical models and empirical models. The physical models are derived from the fundamentals of sensor working process, which simulate the errors based on the mechanisms of generation. For example, Kuc and Siegel designed a three-level model including geometric distance calculation, attenuation from reflection and transmission, and object recognition based on threshold methods [10]. A physical model has strong ability to predict sensing process; however, it is difficult to be adopted in traffic environment due to the hardness of ultrasound propagation simulation in unstable atmosphere and attenuation simulation from complex surfaces. The empirical model, by considering the ultrasonic sensor as a black box, interprets sensor measurements as outcomes of the underlying random process [11]. Building an empirical model usually requires various environments and large amounts of experiments, which discourages its applicability in the traffic environments [12]. Some empirical models only focus on the observable performance metrics, for example, detection range and measurement error, which are more environmentally flexible and can be generated through a few experiments. For example, Ishihara et al. built a deterministic sensor model with ranging accuracy influenced by object orientations, and discovered that object orientation could affect the ranging accuracy up to 3% [13]. Majchrzak et al. developed a deterministic sensor model based on experimental results with measurement error related to target distance [14]. These models consider a few factors like target distance and orientation. In this study, we build a new deterministic model that incorporates additional factors such as target shape and target surface material to extend its suitability in traffic environment.

Using ultrasonic sensor models with good accuracy and reliability, arrayed sensors could be employed to localize and track objects. Existing methods on object localization and tracking can be classified into two categories: deterministic methods and probabilistic methods. Deterministic methods usually utilize the spherical positioning technique for object localization, which computes the intersection area of circles centered at each sensor with radius equal to the measured distance [15]. The triangle method is a representative using the framework of deterministic methods, cooperating measures from two sensors for two dimensional positioning. These methods are relatively simple to implement but do not take the uncertainty of sensor into consideration. Probabilistic methods, on the other hand, represent information in a probabilistic way [16]. Common approaches include nonparametric filters and parametric filters. Nonparametric filters such as histogram filter and particle filter decompose the state space probability distribution into a histogram and a series of particles respectively. Köhler et al. set up a linear sensor array with three sensors mounted on both sides of a vehicle and utilized the particle filter to track objects [17]. Joint particle weighting was decided by an inverse sensor model and a reliability model. Yang developed an improved partible filter using a four fixed features based system model to limit the density of the landmarks and as well as the computing complexity [18]. Above that, a map adjustment technique was used to increase the accuracy and efficiency of the tracking algorithm. Other examples can be found in Adiprawita et al. [19], Zhang and Zapata [20] and Muller [21]. Such nonparametric filters as particle filters have good tracking performance on nonlinear sensing dynamics, yet it incurs high computation burden when large number of particles are needed to ensure tracking precision. The case is even severe in arrayed sensors when multiple sensor measurements are utilized at each step. In contrast, the parametric filter based tracking approaches, including Kalman filter, Extended Kalman filter and Unscented Kalman filter, use time-varying parameters to represent probability distribution and are well suited for continuous tracking with low computational complexity in dynamic environment. D'Alfonso et al. set up a sectorial sensor array with five ultrasonic sensors and utilized EKF and UKF which contains a switching sensor activation policy for indoor position and orientation estimating [22]. A substantial equivalence of the two filters was showed by real data based tracking results. Ko and Choi developed an UKF for indoor object localization, which used a pre-filtering method to overcome the bad effect from unexpected external noise [23]. Kim SJ and Kim BK used isotropic ultrasonic Tx and Rx array for the tracked object and the tracking platform separately [24]. An EKF is developed to compensate the ultrasonic distances from the odometric information traveled by the platform. Beyond that, Extended Kalman filter and Unscented Kalman filter are also capable in sensing systems with nonlinear dynamics and are therefore be adopted in this work for object tracking in traffic environment.

This paper aims to: 1) develop an accurate and reliable ultrasonic sensor model for traffic environment recognition considering the shapes and surface materials of traffic participants and road facilities; and 2) design object tracking algorithms using linearly arrayed ultrasonic sensors and compare their tracking performances to the triangle positioning method. The main contribution of this paper lies in the successful attempts to track surrounding objects dynamically in traffic environments using improved Kalman filtering algorithms based on cost-effective ultrasonic sensor array. This work also encourages the application of cost-effective ultrasonic sensors in the near-field environment perception in fuel consumption strategies [25] and autonomous driving systems.