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Data fusion of radar and image measurements for multi-object tracking via Kalman filtering

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ABSTRACT

Data fusion is an important issue for object tracking in autonomous systems such as robotics and surveillance. In this paper, we present a multiple-object tracking system whose design is based on multiple Kalman filters dealing with observations from two different kinds of physical sensors. Hardware integration which combines a cheap radar module and a CCD camera has been developed and data fusion method has been proposed to process measurements from those modules for multi-object tracking. Due to the limited resolution of bearing angle measurements of the cheap radar module, CCD measurements are used to compensate for the low angle resolution. Conversely, the radar module provides radial distance information which cannot be measured easily by the CCD camera. The proposed data fusion enables the tracker to efficiently utilize the radial measurements of objects from the cheap radar module and 2D location measurements of objects in image space of the CCD camera. To achieve the multi-object tracking we combine the proposed data fusion method with the integrated probability data association (IPDA) technique underlying the multiple-Kalman filter framework. The proposed complementary system based on the radar and CCD camera is experimentally evaluated through a multi-person tracking scenario. The experimental results demonstrate that the implemented system with fused observations considerably enhances tracking performance over a single sensor system.

1. Introduction

Since the seminal paper of Kalman in 1960 [16], the Kalman filter has been the workhorse of various disciplines due to its properties of optimality in linear Gaussian systems and easy implementation for the real-world estimation problem. The literature shows that further research has been conducted to relax strict assumptions of the Kalman filter (e.g., prior knowledge of the system, Gaussian noises) that inhibit its applicability to real-world applications. Variants of the Kalman filter were rigorously investigated to overcome the practical issues; however, there are still several remaining issues for efficient implementation and development. In early days, Kalman filtering was usually applied to the aerospace science [25], navigation systems [29,33,36] and the mechanical system control [14]. Recent advances in theory and hardware extend its applicability to more diverse areas such as the process control in chemical engineering [15], bio-medical application [4,20], mobile robotics [6,7,17,18], image processing [10] and computer vision [9,12].

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Among them, we focus on the very intuitive application of Kalman filtering, e.g., the object tracking, which has been implemented in many application areas. In this work, regarding two specific physical sensors we limit our discussion of related works to vehicle applications [19] and surveillance [34].

Conventional object tracking in the aerospace science utilizes the large-size radar system that returns point-wise measurements. However, recent electronics technology makes the radar systems small and cheap, enabling them to be used in commercial vehicle navigation systems [19,30]. In those systems, the radar measures relatively short range that can be utilized for pedestrians and adjacent vehicles detection to avoid collision. One shortcoming of this radar system is the low resolution in bearing angle information due to the wide beam width. In [30], authors proposed a combined system of a millimeter-wave radar and a CCD camera with a calibration method via homography. However, since their system simply combines detection data obtained from two sensors using the calibrated homography without considering noise model at all, it cannot track objects successfully when noises exist. In addition, spurious measurements from false targets are not considered so that many false tracks can be generated from background reflections.

There have been several studies about the tracking based on the single camera in surveillance which uses the special configuration of the camera to explain the relationship between the object size and its radial distance [34]. The multiple-camera system is also developed with overlapping or non-overlapping views [21] to reconstruct the 3D trajectories of objects. One of main tasks of the multiple-camera based tracking in surveillance system is the calibration of cameras to reconstruct 3D position of the object from 2D image planes [3]. Recent works tried to calculate the normal and inclination vectors to reconstruct 3D position of pedestrians from calibrated multiple cameras; however, the critical restriction of these system is that it can be used only for the fixed location set-up. Therefore, the multiple-camera system is seldom utilized for unconstrained applications (i.e., autonomous systems).

The main purpose of our research in this paper is to design a robust and cost-effective multi-object tracking system for autonomous agents which can be deployed in unconstrained environments. To this end, by adopting the sensor geometry [30] to combine a visual sensor with radar, we propose to employ Kalman filtering and data fusion technique underlying a Gaussian mixture form. As mentioned earlier, main differences between [30] and our work is that detection procedure of [30] is not able to circumvent sensor noises and false positive detections, whereas the proposed multi-object tracking system has such functionality that it can successfully track multi-object without failure.

Since a linear Gaussian state-space model (2) is considered in this paper, the Kalman filter is naturally used to guarantee the best linear minimum mean square error performance [1,16]; resulting in reduction of sensor noises. Additionally, we utilize data fusion technique which is embedded in the Kalman filtering framework to reduce the uncertainty originated from different sensor models and different types of sensor noises that are not taken into account in [30]. In tracking problems with multisensory observations, data fusion is important because different types of uncertainties are originated from individual sensors so that they affect the tracking performance differently. Here, we mean data fusion as the mathematical methodology to combine data collected from different sources with uncertainty models in order to provide more reliable information, which will be discussed in detail in Section 3.2. In addition, false positive detections (e.g., non-target originated measurements) are avoided substantially by incorporating the IPDA technique [23].

In the theoretical aspect, we extend the mixture of Kalman filter algorithm to use multisensory measurements for multi-object tracking that is implemented in the developed hardware module. A new tracker is called mixture of fusion Kalman filter because it fuses two independent observations from two physical sensors (i.e., radar, optical sensor) to construct the complementary system and tracks multiple-object under the Gaussian mixture structure.

The remainder of this paper is organized as follows. In Section 2, the Bayesian filtering problem is introduced and Kalman filtering equations are given for its solution. For the developed measurement system, radar and CCD sensors are also explained in Section 2. In Section 3, the proposed algorithm implemented in the system is subsequently explained in detail with the homography learning, data fusion technique, and multi-object tracking. Then, the proposed system is evaluated in real-world implementation of multi-person tracking in Section 4. Finally, conclusions are made in Section 5.

2. Kalman filter and developed measurement system

2.1. Dynamic system and Kalman filter

The fundamental formulation of the Kalman filter would be understood as a Bayesian filtering framework. Here, we introduce the basic Bayesian filtering framework and define the problem to be solved. Let $x_t \in \Re^{n_x}$ denote the state of object (e.g., position and velocity) at time t and the given sensor collects the observation $y_t \in \Re^{n_y}$ of the state x_t. In sequential Bayesian filtering, we want to construct $p(x_t|y_t)$, the probability density function (pdf) of x_t given y_t using two key equations.

$$\begin{aligned}&\text{Prediction}: \; p(x_{t+1}|y_{1:t}) = \int p(x_{t+1}|x_t)p(x_t|y_{1:t})dx_t \\ &\text{Update}: \; p(x_{t+1}|y_{1:t+1}) = \frac{p(y_{t+1}|x_{t+1})p(x_{t+1}|y_{1:t})}{\int p(y_{t+1}|x_{t+1})p(x_{t+1}|y_{1:t})dx_{t+1}}\end{aligned} \tag{1}$$

In practice, however, it is impossible to analytically obtain the complete pdf because of intractable integrals and arbitrary pdf forms. In 1960, Kalman proposed the optimal estimator using the minimum mean square error criterion under the linear