Kalman Filter-Based Suspicious Object Tracking for Border Security and Surveillance System using Fixed Automotive Radar

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***Abstract*—As research related to autonomous driving has been actively conducted recently, object tracking technology using autonomous driving sensors such as LiDAR and radar has also been extensively developed. Accordingly, attempts are being made to apply autonomous sensors not only to autonomous vehicles but also to various fields such as security and surveillance. However, since a security and surveillance system should be able to detect and track objects even in extreme environments such as snow, rain, and fog in day or night conditions, radar systems that meet the relevant requirements are essential. In South Korea, the distance of the MDL (Military Demarcation Line) is 250 km, and it requires a considerable investment to install more than 1,000 radars and PCs with built-in GPUs in all sections of a border security and surveillance system . Therefore, in this study, a Kalman filter-based object tracking system is explored rather than applying deep learning, which requires a GPU. Additionally, most of the objects within the MDL are highly likely to be suspicious objects, so a radar sensor is most suitable because it provides coordinates, distance, and speed of movement without needlessly determining whether an object is an enemy or not. For accurate object detection and tracking performance, the motion models of the Kalman filter CAM (constant acceleration model) and CTRAM (constant turn rate and acceleration model) are compared to identify a suitable model for each movement state of objects.**

***Index Terms*—Radar tracking, Kalman filter, Security and surveillance, Scientific security system, Defense Innovation**

I. Introduction

Radar systems provide essential sensors for autonomous driving research because they are minimally influenced by environmental noise, such as snow, rain and fog, compared to cameras and LiDAR. Another advantage is that the velocity and position of an object can be accurately measured based on the Doppler effect. For these reasons, radar is used not only in vehicles but also in various fields, such as aviation and ground surveillance, particularly in the defense field.

However, recent attempts have been made to apply automotive radar to security and surveillance systems. This is possible due to the development of object detection and tracking technology in autonomous driving research, and autonomous driving sensors can now be applied in border security and surveillance systems. In particular, the long-range radar systems used in vehicles have a detection distance of 250 m, which is the similar to the effective range of rifles; therefore, they are suitable for surveillance purposes in the defense field, and despite the narrow FOV (Field of View) of radar, the advantage of being able to monitor a wide range of areas through rapid rotation is important.

Some previous studies used radar detection data to track objects. Here, object tracking technology refers to an algorithm that uses estimated dynamics to predict the new position of an object in the next frame and update it based on measurements. Research on tracking objects using only radar sensors has been mainly conducted in the field of aviation. A study on the application of EKF and UKF to radar systems for targeting aircraft was conducted by U.K. Singh et al. [1]. However, in the study, the tracking performance of EKF and UKF was compared only through simulation. In addition, various studies have been conducted to improve the tracking performance of radar systems for detecting aircraft [2] [3] [4] [5].

Systems for detecting and tracking objects for surveillance purposes have been mainly developed based on cameras. Object tracking using a camera is a process in which a surveillance system finds an object in every frame of a video

This research was financially supported by a National Research Foundation of Korea (NRF) grant funded by the Korean government (MSIT) (No. NRF-2020R1G1A1008489).

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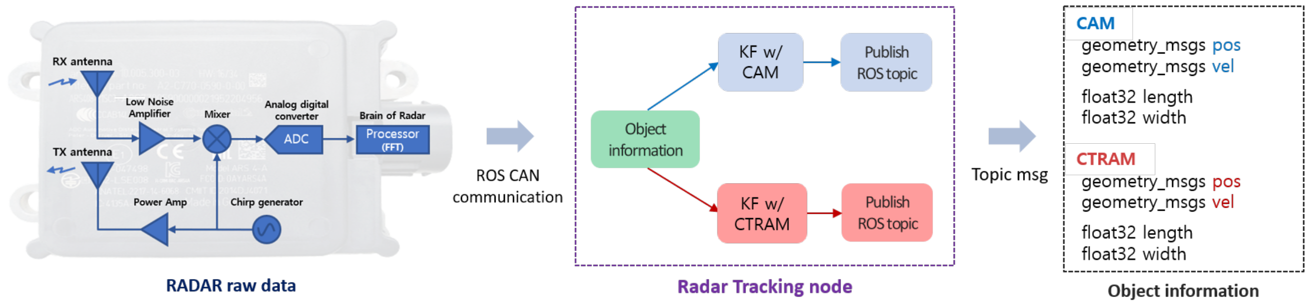

Fig. 1: ROS-based object tracking system configuration

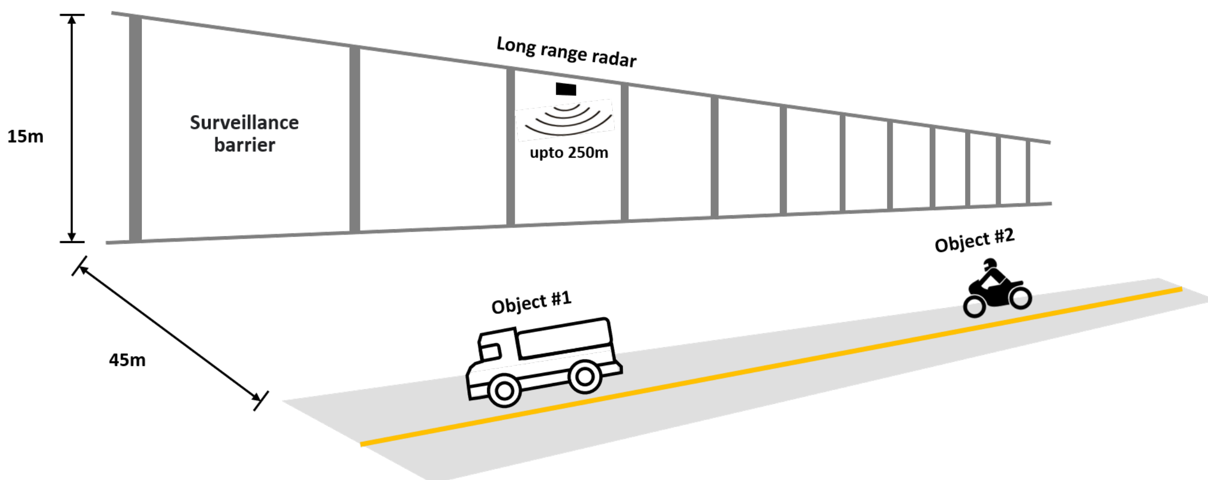

Fig. 2: Acquisition of object tracking data from an experimental environment similar to the real Freedom House area

and tracks the object over time. The most representative method in camera-based object tracking is the optical flow approach. Sepehr Aslani et al. detected and tracked moving objects through the intensity changes in each frame of video [6]. In addition, various studies have used cameras to track objects for the purpose of security and surveillance [7] [8] [9] [10], but it is still difficult to apply this approach at some important security facilities due to the characteristics of the cameras, which are not robust to environmental changes [11].

Therefore, this study focuses on improving object tracking performance with a radar sensor that is robust to environmental changes and can detect objects over long distances. A comparison of Kalman filter-based object detection systems using two motion models (CAM and CTRAM) is performed, and the most suitable model for a security and surveillance system is identified.

II. Experimental Setup

A. Environment configuration

The radar tracking code was written in C++ and configured in an ROS (robot operating system) environment. As shown in Fig. 1, the raw data sensed by the radar are transmitted to the radar tracking node through ROS CAN communication, and then the tracking node generates object information through this raw data and publishes it as an ROS topic. The published topic message includes position, velocity, length, and width of object information. Data collection was performed using a Continental ARS 408-21, which is a 77 GHz long-range radar system capable of sensing up to 250 m. Additionally, we used an Nvidia Jetson Xavier to obtain data.

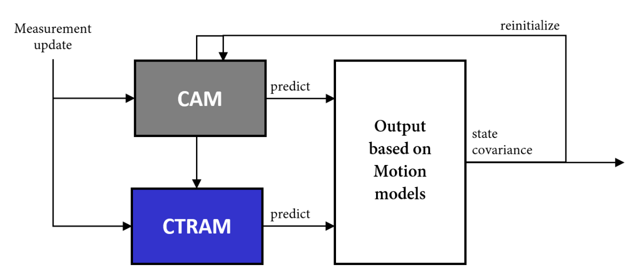

Fig. 3: System structure for performance comparison of CAM & CTRAM.

TABLE I: Standard deviation of radar measurement noise for CAM and CTRAM. The units of parameters are m, m/s, m/s^2, rad, and rad/s.

Parameters	CAM				CTRAM				
	px, py	vel	yaw	$yaw\,rate$	px, py	vel	acc	yaw	$yaw\,rate$
Value	0.1	0.1	0.1	0.5	0.1	0.1	0.01	0.1	0.5

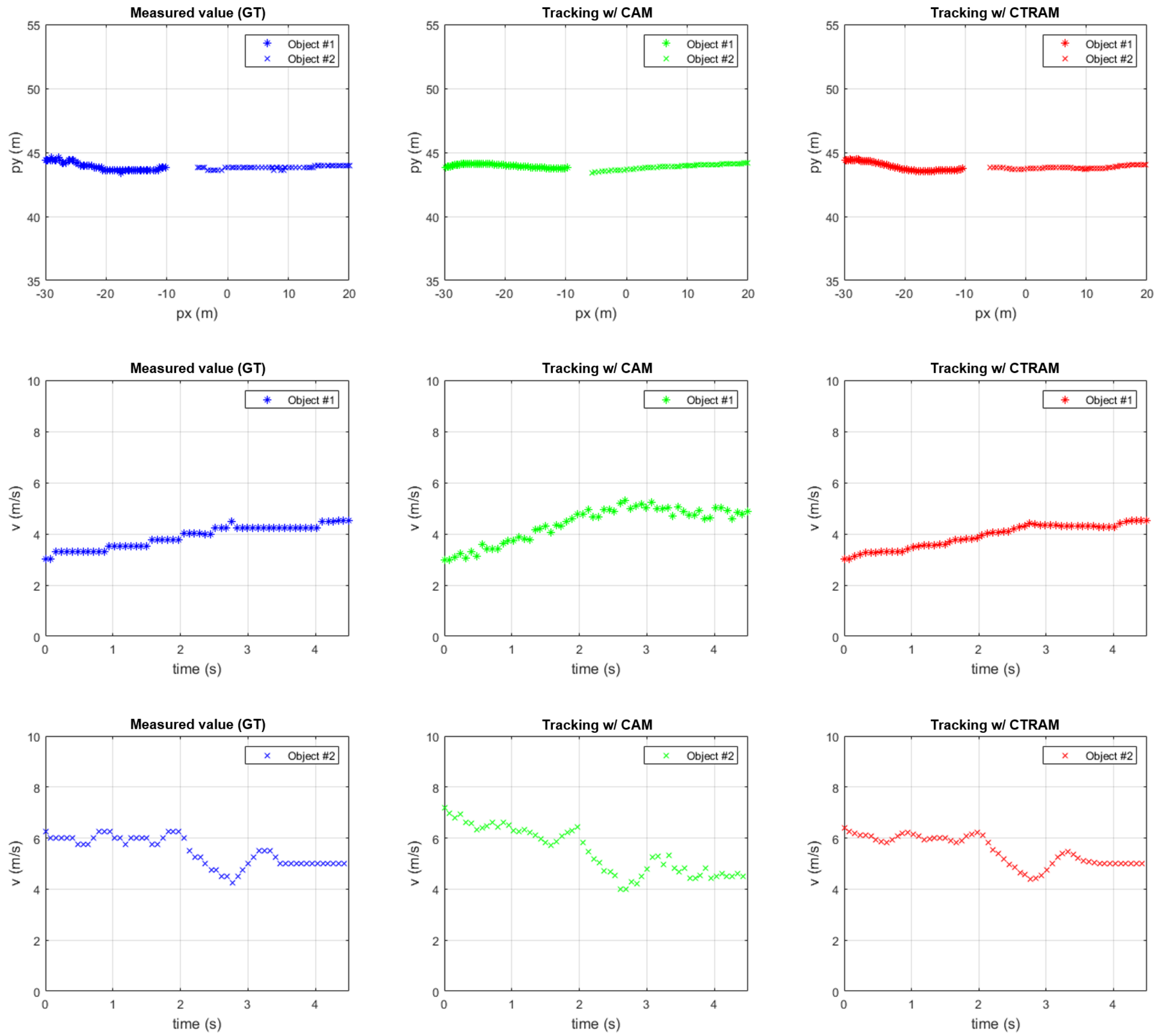

Fig. 4: Comparison of tracking performance with CAM and CTRAM (position and velocity)

$$
\begin{aligned}
p(x) &= p(x) + \frac{1}{yawd^2}\{(v \cdot yawd + a \cdot yawd \cdot dt) \cdot \sin(yaw + yawd \cdot dt) \\
&\quad + a \cdot \cos(yaw + yawd \cdot dt) - v \cdot yawd \cdot \sin(yaw) - a \cdot \cos(yaw)\} \\
p(y) &= p(y) + \frac{1}{yawd^2}\{(-v \cdot yawd - a \cdot yawd \cdot dt) \cdot \cos(yaw + yawd \cdot dt) \\
&\quad + a \cdot \sin(yaw + yawd \cdot dt) + v \cdot yawd \cdot \sin(yaw) - a \cdot \sin(yaw)\} \\
yaw &= yaw + yawd \cdot dt \\
v &= v + a \cdot dt \\
yawd &= yawd \\
a &= a
\end{aligned}
\tag{1}
$$

As shown in Fig. 2, the radar system was installed on a 15-meter-high barrier to acquire a dataset for testing security and surveillance systems. Then, data were acquired for multiple vehicles on the road 45 m away from the installation point. The difference from previous studies is that the radar sensor in this study is installed at a height of 15m rather than on the ground, and accordingly, objects are sensed diagonally instead of from the front or side.

B. Data acquisition

As shown in Figs. 2, the experimental site was constructed as similar as possible to the Freedom House area, where a North Korean soldier escaped in a vehicle in 2017. Then, object tracking data were obtained for vehicles rapidly approaching the MDL area along the road.

III. Object Tracking Using a Kalman Filter

A. Motion models

Two motion models (CAM and CTRAM) were applied with a Kalman Filter to compare the performance of the object

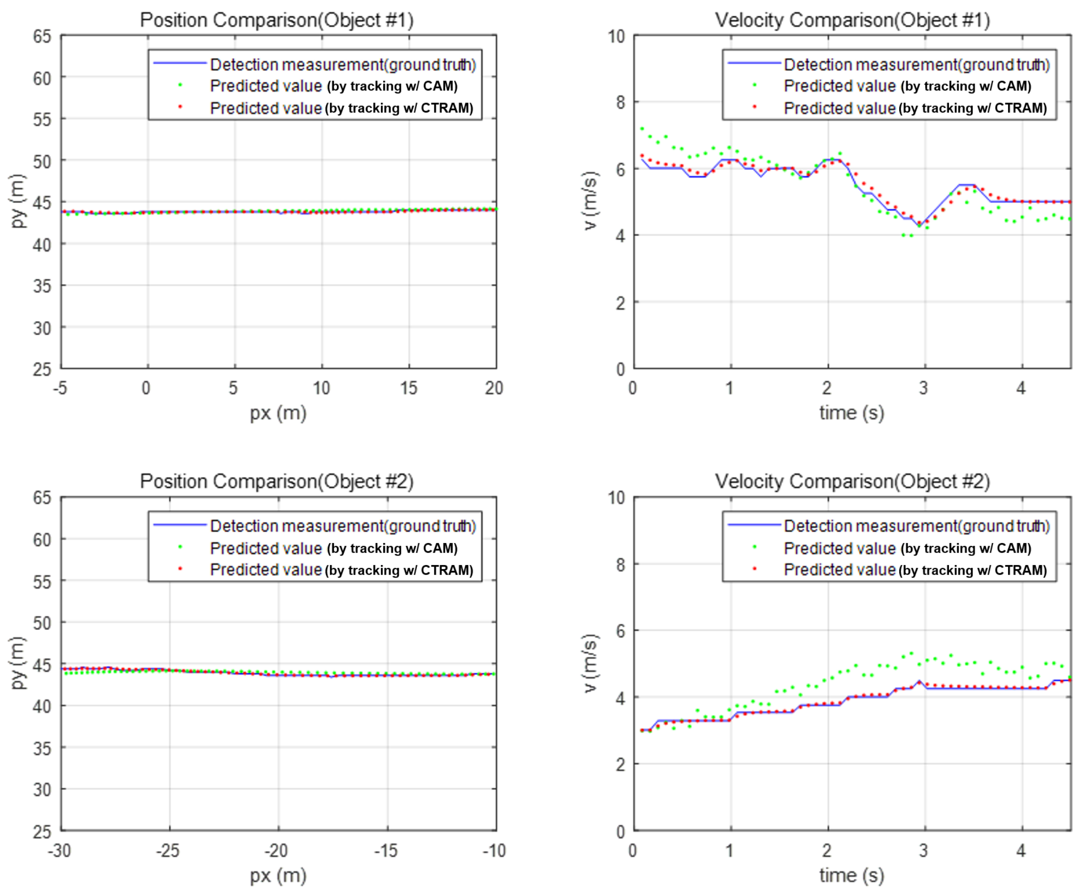

Fig. 5: Tracking performance evaluation for objects 1 and 2 (position and velocity)

tracking system with each model as shown Fig.3 and the equation for these two motion models are as (1). The black letters denote CAM, and the blue letters denote CTRAM. Here, the state vectors for CAM and CTRAM were px, py, vel, acc, yaw, and $yaw\,rate$, respectively and respectively, and the radar measurement noise parameters applied to each model are shown in Table 1.

B. Performance

Tracking performance was analyzed for two objects acquired at the same time, and the CAM and CTRAM tracking results for the two approaching objects were compared. First, the position accuracy is shown in Fig. 4(a), and the positions of the two objects are displayed together in the figure. As shown in the position trajectory plot, the tracking result obtained with the Kalman filter shows displays reduced instantaneous position variation, and the trajectory is smoother compared to that of the measured values. However, the CAM results slightly differ from the measured values, unlike those of CTRAM.

This tendency is even more pronounced for velocity. As with position, the Kalman filter smoothed rapid increases or decreases in velocity compared to the measured values.

TABLE II: Root mean square error (RMSE) w.r.t. measured data (CAM and CTRAM) for objects 1 and 2

RMSE	object 1		object 2	
	CAM	CTRAM	CAM	CTRAM
Position	0.1660	0.0695	0.3009	0.0902
Velocity	0.7338	0.1264	0.8070	0.0584

Moreover, CTRAM displays superior performance compared to CAM, with a smooth trajectory very similar to that of the measured values, as shown in Fig. 4(b).

The error of CAM is likely due to the fact that the turn rate is not considered, and the magnitude of the error associated with this linear approximation will be quantitatively evaluated in the next section.

C. Evaluation

Object tracking performance should be evaluated by comparing the actual position of an object with the predicted position. However, it is difficult to obtain the ground truth values of objects for reference; therefore, a radar system was installed on the ground 10 m from the road to obtain ground

TABLE III: Processing time comparison (s)

	Average time	Std. dev. time
Tracking w/ CAM	0.00118015	0.00031656
Tracking w/ CTRAM	**0.00222676**	**0.00082623**

truth measurements. Then, these accurate object location data was used as the ground truth reference.

The tracking performance of CAM and CTRAM was evaluated by comparing the measured and predicted data for multiple objects moving on the road based on the characteristics of the radar sensor. Fig. 5 shows the measured data (blue line), the CAM tracking results (green line), and the CTRAM tracking data (red line) for the position and velocity of two objects (objects 1 and 2). The RMSE between the measured data and the CAM and CTRAM tracking results for the two objects is shown in Table II. It was confirmed that the RMSE of CTRAM is smaller than that of CAM for both the positions and velocities of all objects.

The speed performance was compared by calculating the processing times of CAM and CTRAM. The processing time was calculated as the total time from when the measured value was input into the Kalman filter until the predicted value was obtained. Because CAM is based on a relatively simple motion model without considering the turn rate, the processing time is very low compared to that of CTRAM, as expected; however, the actual processing time of CTRAM was still very short, and the latency was negligible. This finding suggests that both CAM and CTRAM are capable of real-time object tracking.

IV. Conclusion

This paper focuses on tracking multiple target objects by applying a radar sensor for security and surveillance, and the tracking performance of the proposed model is evaluated by comparing the prediction results to measured object data. The data used for the analysis in this paper included radar sensor data for two objects moving along a road measured from a height of 15 m. At the time of measurement, two objects were tracked at the same time with fixed radar. The experimental results showed that tracking with CTRAM was more robust to measurement errors than was tracking with CAM. Notably, CTRAM provides better tracking accuracy for moving objects because it considers not only acceleration but also a constant turn rate. However, this accuracy may vary depending on the movement characteristics of a given object (for example, whether the object moves completely straight). Thus, CAM or CTRAM could be optimal based on the movement state of an object (acceleration, turn rate, etc.). Combined filter-based models that apply various motion models depending on the movement of objects are often used, but they are complicated because they require motion models for all cases, and errors occur when the motion model changes (e.g., from CAM to CTRAM).

Accordingly, considering the requirements of boundary monitoring systems (object tracking using a fixed radar sensor, the curved shape of roads in the monitoring area, etc.), applying a motion model suitable for each region can yield good tracking performance. However, in most cases, there are many roads with slight curves, and using CTRAM, as confirmed in this study, would be most effective.

In this study, the possibility that automotive radar can be applied in boundary monitoring systems was confirmed. Currently, the South Korean military is trying to implement a science and technology force by promoting "Defense Innovation 4.0," and a high-efficiency and highly effective detection system can be developed through the implementation of a radar-based scientific security system using Kalman filters, as proposed in this study. In future research, we will develop optimal sensing hardware and tracking algorithms by applying 4D radar tracking systems for security and surveillance, such as military use.

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