FIR Filters for Visual Object Tracking

Yung Hak Mo, Chang Joo Lee, Choon Ki Ahn, and Myo Taeg Lim

***Abstract*—** In this paper, we propose a novel finite impulse response (FIR) filter for visual object tracking. The proposed FIR filter shows robustness against modeling uncertainty, while the performance of the Kalman filter is very poor in this case. Via experiment, we demonstrate the usefulness of the proposed FIR filter for visual object tracking.

***Keywords*—** Finite impulse response (FIR) filter, Kalman filter, vision-based control, visual object tracking.

I. Introduction

DURING the past decade, vision based systems have been used in various fields such as intelligence vehicle, robotics system, unmanned aircraft, and factory automation [1-3]. Especially, visual object tracking is an important research topic in the field of visual applications and it can be considered as a state estimation problem [4-5]. If the dynamic characteristic of the object state satisfies the Gaussian probability distribution and linear conditions, Kalman filter can obtain the optimal solution for the visual object tracking problem [2-3, 6-8]. However, Kaman filter provides poor performance and even divergence phenomena when the modeling has uncertainty. In order to overcome the divergence problems of the Kalman filter, various researches have been done in the literature. Jazwinski and Scheweppe introduced the limited memory filters that are obtained with finite measurements by the maximum likelihood [9-10]. Bruckstein suggested a sliding window filter for both continuous and discrete time state-space models with the minimum variance criterion [11]. However, these filters have common limitations that have not been strictly analyzed. Besides, the optimal FIR filter for time-invariant and time-varying state-space models was derived by Kwon with minimum variance criterion [12-13]. FIR filters guarantee the robustness to numerical error and modeling uncertainty. Since FIR filters use finite measurements, they prevents the state estimation from divergence [12-18]. This property of FIR filters was applied to several problems such as output feedback controls [19-20]. Thus, we propose a novel visual object tracking method based on FIR filters. Using the proposed method, we can guarantee the great performance compared to the Kalman filter based method.

This paper is organized as follows. In section II, FIR filter for visual tracking is introduced. In section III, experiment results are provided. Finally, the conclusion of this paper is provided in section IV.

II. FIR Filters for Visual Tracking

Consider the following visual tracking model :

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$$s_{k+1} = As_k + w_k, \tag{1}$$
$$z_k = Cz_k + v_k, \tag{2}$$

Where

$$s_k = \begin{bmatrix} x \\ \dot{x} \\ y \\ \dot{y} \end{bmatrix}, \quad z_k = \begin{bmatrix} x \\ y \end{bmatrix}, \tag{3}$$

$$A = \begin{bmatrix} 1 & dt+\delta & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & dt+\delta \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad C = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}, \tag{4}$$

Where $s_k \in \mathbb{R}^n$ and $y_k \in \mathbb{R}^q$ are the state and measurement respectively. At the initial time, the state is a random variable with mean $\bar{s}_{k0}$ and covariance P_{k0}. The process noise and measurement noise are zero-mean white Gaussian and mutually uncorrelated. The variance of each noises is denoted by *q* and *r*, and covariance of each noises is denoted by Q and R.

Then, the FIR filter is given by when *(A,C)* is observable and *N*>*n* where *N* is horizon size of FIR filter[21].

$$\hat{s}_k = (\bar{C}_N^T \Pi_N^{-1} \bar{C}_N)^{-1} \bar{C}_N^T \Pi_N^{-1} Z_{k-1}, \tag{5}$$

Where

$$Z_{k-1} \triangleq [z_{k-N}^T \; z_{k-N+1}^T \; \cdots \; z_{k-1}^T], \tag{6}$$
$$\bar{C}_N \triangleq \tilde{C}_N A^{-N}, \tag{7}$$
$$\bar{G}_N \triangleq \tilde{G}_N - \tilde{C}_N A^{-N} M_N, \tag{8}$$
$$\Pi_N \triangleq \bar{G}_N [diag(Q \cdots Q)] \bar{G}_N^T + [diag(R \cdots R)], \tag{9}$$
$$Q = \begin{bmatrix} q & 0 & 0 & 0 \\ 0 & q & 0 & 0 \\ 0 & 0 & q & 0 \\ 0 & 0 & 0 & q \end{bmatrix}, R = \begin{bmatrix} r & 0 \\ 0 & r \end{bmatrix}. \tag{10}$$

and $\tilde{C}_N$, $\tilde{G}_N$, and M_N are defined by

$$\tilde{C}_N = \begin{bmatrix} C \\ CA \\ \vdots \\ CA^{N-1} \end{bmatrix} \in \mathbb{R}^{Nq \times n}, \tag{11}$$

$$\tilde{G}_N = \begin{bmatrix} 0 & 0 & \cdots & 0 & 0 \\ C & 0 & \cdots & 0 & 0 \\ CA & C & \cdots & 0 & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ CA^{N-2} & CA^{N-3} & \cdots & C & 0 \end{bmatrix} \in \mathbb{R}^{Nq \times Np}, \tag{12}$$

$$M_N \triangleq [A^{N-1} \; A^{N-2} \; \cdots \; I \; 0] \in \mathbb{R}^{n \times Np}. \tag{13}$$

III. Experiment Results

In order to verify the performance, we conduct a tracking experiment. In the experiment, we adopt linear dynamic model which is frequently used to track a visual object as shown in equation (3) and (4) [22]. In equation (4), δ is the modeling uncertainty parameter that may be caused by sampling time errors. We conduct experiments with various δ by Visual C++ applications as shown in Fig. 1. In Fig. 1, the blue circle is the real position, the red circle is the position using Kalman filter, and the green circle is the tracking position using FIR filter.

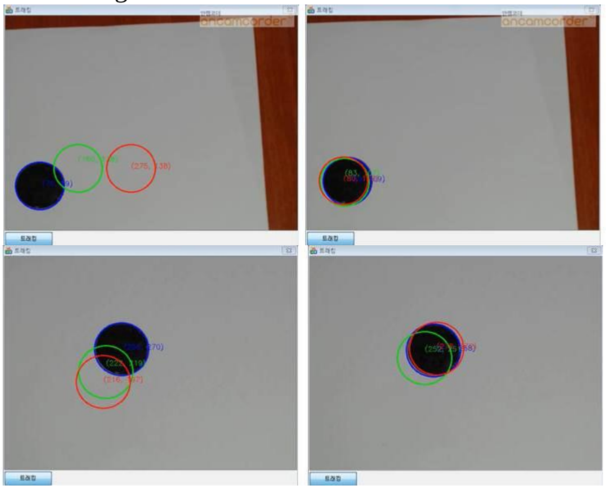
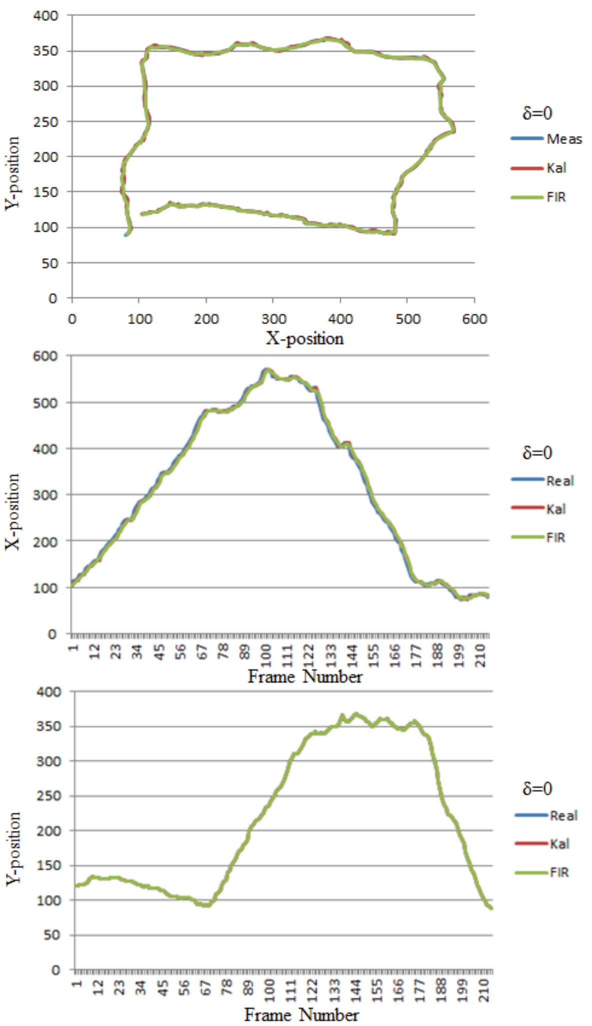


Fig. 1 Visual tracking application developed by Visual C++.



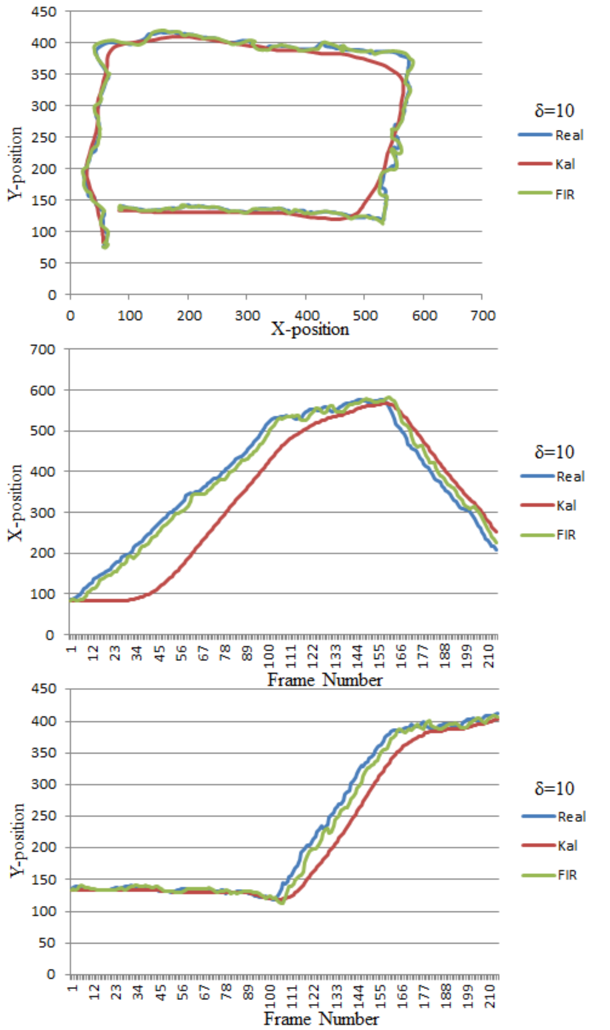


Fig. 2 Trajectory of moving object and tracking results on image plane.

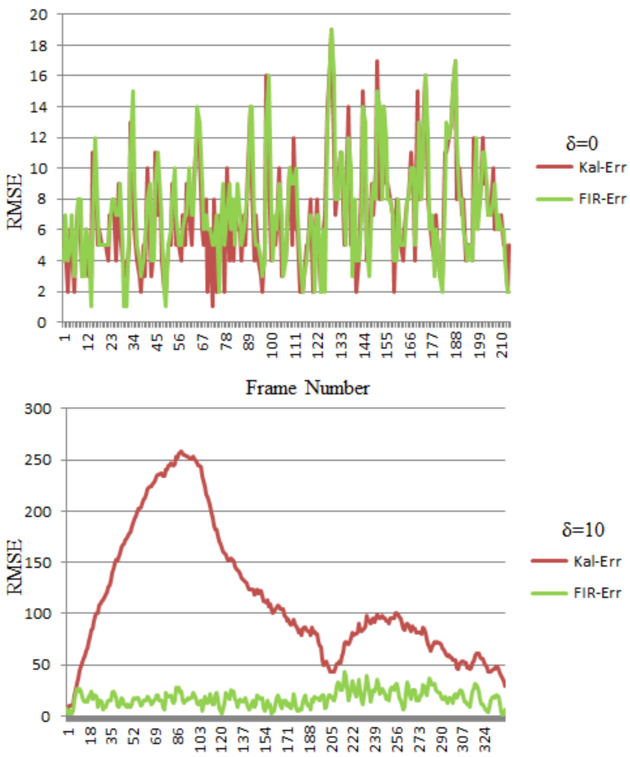


Fig. 3 RMSE of tracking results by frames.

Fig. 2 and Fig. 3 show the results of experiment. Fig. 2 shows trace and tracking result of the moving object on *x-y* image plane, and Fig. 3 shows the root mean square error (RMSE) between real position and predicted position by frame.

TABLE I
AVERAGE RMSE OF EACH EXPERIMENT

δ	0	10
Kalman Filter	6.88 Pixel	66.43 Pixel
FIR Filter	7.26 Pixel	21.57 Pixel

Table I shows average RMSEs of each experiment. When $\delta = 0$, the performance of FIR filter is similar to that of Kalman filter. However, FIR filter shows better tracking performance as δ increases. Thus, we can conclude that FIR filter is more robust to modeling uncertainty than Kalman filter.

IV. CONCLUSION

This paper proposes a visual tracking method based on FIR filter. The experiments show that FIR filter provides better visual tracking performance than Kalman filter when modeling uncertainty exists. Therefore, we can conclude that FIR filter is more robust to modeling uncertainty than Kalman filter. In addition, FIR filter provides similar performance with Kalman filter when there is no modeling uncertainty. Thus, FIR filter can be a good substitution for the Kalman filter in visual tracking applications.

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