Image Sequence Stabilization Scheme Using FIR Filtering

Pyung-Soo Kim

Abstract: This paper proposes a new image sequence stabilization (ISS) scheme based on filtering of absolute frame positions. The proposed ISS scheme removes undesired motion effects in real-time, while preserving desired gross camera displacements. The well-known finite impulse response (FIR) filter is adopted for filtering. The proposed ISS scheme provides a filtered position and velocity with fine inherent properties. It is demonstrated that the filtered position is not affected by the constant velocity. It is also shown that the filtered velocity is separated from the position. Via numerical simulations, the performance of the proposed scheme is shown to be superior to the existing Kalman filtering scheme.

Keywords: FIR filtering, image sequence stabilization (ISS), Kalman filtering.

1. INTRODUCTION

Recently, video communication and processing have been playing a significant role in mobile platforms such as mobile phones, handheld PCs, digital consumer camcorders, and so on. Thus, cameras have become an inherent part in acquiring video images. However, image sequences acquired by a camera mounted on a mobile platform are usually affected by undesired motions causing unwanted positional fluctuations of the image.

To remove undesired motion effects and to produce compensated image sequences that expose requisite gross camera displacements only, various image sequence stabilization (ISS) schemes have been developed and widely used, such as the motion vector integration (MVI) in [1] and the discrete-time Fourier transform (DFT) filtering in [2]. However, in the MVI scheme, the filtered position trajectory is delayed owing to filter characteristics imposing larger frame shift than actually required for stabilization, in which stabilization performance is degraded. The DFT filtering scheme is not suited for real-time application since off-line processing is required. Therefore, recently, the ISS scheme using the Kalman filtering has been made by posing the optimal filtering problem due to the compact representation and the most efficient manner [3, 4].

However, the Kalman filter has an infinite impulse response (IIR) structure that utilizes all past information accomplished by equaling weighting and also has a recursive formulation. Thus, the Kalman filter tends to accumulate the filtering error with the progression of time. In addition, the Kalman filter has been known to be sensitive and demonstrate divergence phenomenon for temporary modeling uncertainties and round-off errors [5-9].

Therefore, in the current paper, an alternative ISS scheme is proposed. The proposed ISS scheme gives the filtered absolute frame position in real-time, removing undesired motion effects, while preserving desired gross camera displacements. For the filtering, the proposed ISS scheme adopts the well known finite impulse response (FIR) filter that utilizes only finite information on the most recent window [7-9]. The proposed ISS scheme provides the filtered velocity as well as the filtered position. These filtered positions and velocities have good inherent properties such as unbiasedness, efficiency, time-invariance, deadbeat, and robustness due to the FIR structure. It is revealed that the filtered position is not affected by the constant velocity. It is also shown that the filtered velocity is separated from the position. These remarkable properties cannot be obtained from the Kalman filtering based scheme in [3, 4]. Via numerical simulations, the performance of the proposed ISS scheme using the FIR filtering is shown to be superior to the existing Kalman filtering scheme.

The paper is organized as follows. In Section 2, an alternative ISS scheme is proposed. In Section 3, inherent properties of the proposed scheme can be seen. In Section 4, numerical simulations are performed. Finally, concluding remarks are made in Section 5.

2. ISS SCHEME USING FIR FITERING

As shown in [3, 4], the fourth order state space

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model for the image sequence stabilizer is constructed as:

$$x(i+1) = Ax(i) + Gw(i), \\ z(i) = Cx(i) + v(i), \tag{1}$$

where

$$x(i) = \begin{bmatrix} x_p(i) \\ x_v(i) \end{bmatrix}, \; w(i) = \begin{bmatrix} w_p(i) \\ w_v(i) \end{bmatrix},$$
$$A = \begin{bmatrix} I & I \\ 0 & I \end{bmatrix}, \; G = \begin{bmatrix} I & 0 \\ 0 & I \end{bmatrix}, \; C = [I \;\; 0].$$

The state $x_p(i) = [x_{p1} \;\; x_{p2}]^T$ represents horizontal and vertical *absolute frame position* and the state $x_v(i) = [x_{v1} \;\; x_{v2}]^T$ represents the corresponding *velocity* in the frame i acquired by a camera mounted on a mobile platform. The process noise $w(i)$ and observation noise $v(i)$ are a zero-mean white noise with covariances Q and R, respectively. Note that noise covariances Q and R can be determined via experiments or left as design parameters.

The main task of the proposed image sequence stabilization scheme is the filtering of absolute frame positions in real-time, removing undesired motion effects, while preserving desired gross camera displacements. For the filtering, the well known FIR filter in [7-9] is adopted. For the state-space model (1), the FIR filter $\hat{x}(i)$ processes lineally the only finite observations on the most recent window $[i-M, i]$ as the following simple form:

$$\hat{x}(i) = \begin{bmatrix} \hat{x}_p(i) \\ \hat{x}_v(i) \end{bmatrix} = HZ_M(i) = \begin{bmatrix} H_p \\ H_v \end{bmatrix} Z_M(i), \tag{2}$$

where the gain matrix H and the finite observations $Z_M(i)$ are represented by

$$H \equiv [h(M) \;\; h(M-1) \;\; \cdots \;\; h(0)]^T, \tag{3}$$

$$Z_M(i) \equiv [z^T(i-M) \;\; z^T(i-M+1) \;\; \cdots \;\; z^T(i)]^T. \tag{4}$$

Note that H_p and H_v are the first 2 rows and the second 2 rows of H, respectively. The algorithm for filter gain coefficients $h(\cdot)$ in (3) is obtained from [7-9] and shown in Appendix A. Note that $Z_M(i)$ in (4) can be represented in the following regression form:

$$Z_M(i) = L_M x_p(i-M) + N_M X_v(i) \\ + G_M W_p(i) + V(i), \tag{5}$$

where matrices L_M, N_M, G_M are defined in Appendix B and $X_v(i)$, $W_p(i)$, $V_v(i)$ have the same form as (4) $x_v(i)$, $w_p(i)$, $v(i)$, respectively.

3. MAIN RESULTS

Ultimately, the filtered absolute frame position $\hat{x}_p(i)$ is obtained from (2) as follows: As shown in [3, 4], the fourth order state space model for the image is

$$\hat{x}_p(i) = H_p Z_M(i). \tag{6}$$

The filtered position $\hat{x}_p(i)$ has good inherent properties of unbiasedness, efficiency, time-invariance and deadbeat since the FIR filter used provides these properties. The Kalman filter used in [3, 4] does not have these properties unless the mean and covariance of the initial state are completely known. Among them, the most remarkable is the deadbeat property which the filtered position $\hat{x}_p(i)$ tracks the actual position $x_p(i)$ exactly in the absence of noises. The deadbeat property gives the following matrix equality as shown in [7-9]:

$$H = \begin{bmatrix} C \\ CA \\ \vdots \\ CA^M \end{bmatrix} = A^M,$$

and then

$$\begin{bmatrix} H_p \\ H_v \end{bmatrix} [L_M \;\; \overline{N}_M] = \begin{bmatrix} I^M & MI \\ 0 & I \end{bmatrix},$$

where $\overline{N}_M = [I \;\; 2I \;\; \cdots \;\; (M+1)I]^T$. Therefore, the following matrix equalities are obtained:

$$H_p L_M = I, \;\; H_p \overline{N}_M = MI, \\ H_v L_M = 0, \;\; H_v \overline{N}_M = I, \tag{7}$$

which gives the following remarkable properties.

It will be shown in the following theorem that the filtered position $\hat{x}_p(i)$ in (6) is not affected by the velocity when the velocity is constant on the observation horizon $[i-M,i]$.

Theorem 1: When the velocity is constant on the observation window $[i-M,i]$, the filtered position $\hat{x}_p(i)$ in (6) is not affected by the velocity.

Proof: When the velocity is constant as $\bar{x}_v$ on the observation window $[i-M,i]$, the finite observations $Z_M(i)$ in (5) can be represented in

$$\begin{aligned} &Z_M(i) \mid \{x_v(i)=\bar{x}_v \; for \, [i-M,i]\} \\ &= L_M x_p(i-M) + \bar{N}_M \bar{x}_v + G_M W_p(i) + V(i). \end{aligned} \tag{8}$$

Then, the filtered position $\hat{x}_p(i)$ is derived from (6)-(8) as

$$\begin{aligned} &\hat{x}_p(i) \\ &= H_p Z_M(i) \\ &= H_p[L_M x_p(i-M) + \bar{N}_M \bar{x}_v + G_M W_p(i) + V(i)] \\ &= H_p L_M x_p(i-M) + H_p \bar{N}_M \bar{x}_v \\ &\quad + H_p[G_M W_p(i) + V(i)] \\ &= x_p(i-M) + MI\bar{x}_v + H_p[G_M W_p(i) + V(i)]. \end{aligned} \tag{9}$$

From (1), the actual position $x_p(i)$ can be represented on $[i-M,i]$ as follows:

$$\begin{aligned} &x_p(i) \mid \{x_v(i)=\bar{x}_v \; for \, [i-M,i]\} \\ &\quad = x_p(i-M) + MI\bar{x}_v + \bar{G}_M W_p(i), \end{aligned} \tag{10}$$

where $\bar{G}_M = [I \;\; I \;\; \cdots \;\; I \;\; 0]$. Thus, using (9) and (10), the error of the filtered position $\hat{x}_p(i)$ is

$$\begin{aligned} &\hat{x}_p(i) - x_p(i) \\ &\quad = H_p[G_M W_p(i) + V(i)] - \bar{G}_M W_p(i), \end{aligned}$$

which does not include the velocity term. This completes the proof. □

The velocity itself can be treated as a variable which should be filtered. In this case, the filtered velocity is shown to be separated from the position term.

Theorem 2: The filtered velocity $\hat{x}_v(i)$ in (2) is separated from the position term.

Proof: The filtered velocity $\hat{x}_v(i)$ is derived from (2) and (7) as

$$\begin{aligned} &\hat{x}_v(i) \\ &= H_v Z_M(i) \\ &= H_v[L_M x_p(i-M) + N_M X_v(i) \\ &\qquad + G_M W_p(i) + V(i)] \\ &= H_v[N_M X_v(i) + G_M W_p(i) + V(i)], \end{aligned}$$

which does not include the position term. This completes the proof. □

The above remarkable properties of the proposed ISS scheme using the FIR filtering cannot be obtained from the existing Kalman filtering scheme in [3, 4]. In addition, as mentioned previously, the proposed scheme has the deadbeat property, which indicates the fast tracking ability of the proposed scheme. Furthermore, due to the FIR structure and the batch formulation, the proposed scheme might be robust to temporary modeling uncertainties and to round-off errors, while the Kalman filtering scheme might be sensitive to these situations.

The noise suppression of the proposed ISS scheme might be closely related to the window length M. However, although the proposed ISS scheme can have greater noise suppression as the window length M increases, too large M may yield the long convergence time of the filtered position and velocity, which degrades the filtering performance of the proposed scheme. This illustrates the proposed ISS scheme's compromise between the noise suppression and the tracking speed of the filtered position and velocity. Since M is an integer, fine adjustment of the properties with M is difficult. Moreover, it is not easy to determine the window length in systematic ways. In applications, one method to determine the window length is to take the appropriate value that can provide enough noise suppression.

4. NUMERICAL SIMULATIONS

The performance of the proposed ISS scheme using the FIR filtering is evaluated via a numerical simulation. It was already shown in [4] that the Kalman filtering scheme outperforms the MVI scheme of [1] for the 'bike' sequence acquired by a consumer camcorder mounted on the rear carrier of a moving motorcycle. Therefore, in this paper, the proposed FIR filtering scheme will be compared with the Kalman filtering scheme for the same 'bike' sequence of [4]. Noise covariances are also taken by $Q=0.1$ and $R=100$ as in [4]. The window length and the initial state are taken by $M=20$ and $x(0)=[0 \;\; 0 \;\; 0 \;\; 0]^T$, respectively. To make a

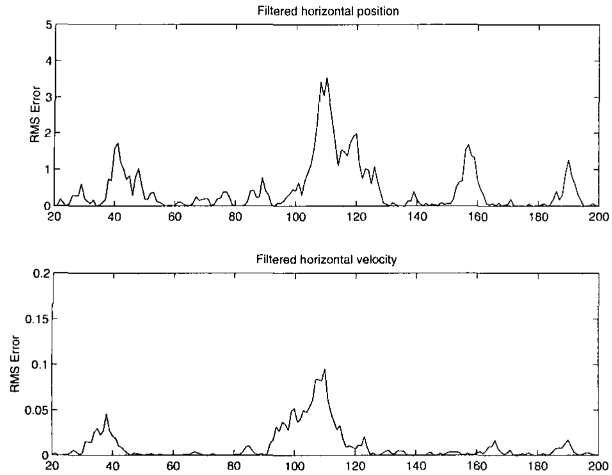

Fig. 1. Existing Kalman filtering scheme.

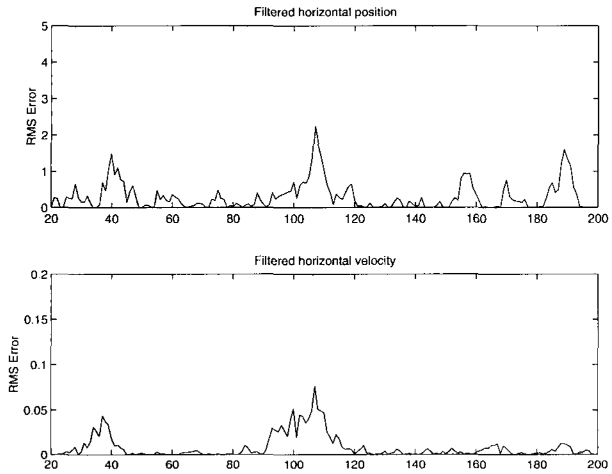

Fig. 2. Proposed FIR filtering scheme.

clearer comparison, thirty Monte Carlo runs are performed and each single run lasts for 200 samples. Figs. 1 and 2 illustrate root-mean-square (RMS) errors of the filtered position and velocity. For both filtered position and velocity, simulation results show that the performance of the proposed FIR filtering scheme is superior to the existing Kalman filtering scheme.

5. CONCLUDING REMARKS

This paper has proposed a new ISS scheme based on filtering of absolute frame positions. The proposed ISS scheme removes undesired motion effects in real-time, while preserving desired gross camera displacements. The well known FIR filter is adopted for the filtering. The proposed ISS scheme provides a filtered position and velocity with fine inherent properties. It is shown that the filtered position is not affected by the constant velocity. It is also demonstrated that the filtered velocity is separated from the position. Simulation results show that the performance of the proposed FIR filtering scheme is superior to the existing Kalman filtering scheme.

APPENDIX

A. Algorithm for filter gain coefficients

The algorithm for filter gain coefficients $h(\cdot)$ in (3) is obtained from the following algorithm:

$$h(j) = \Omega^{-1}(M)\Phi(j)C^T R^{-1}, \quad 0 \le j \le M,$$

where

$$\Phi(l+1) = \Phi(l)[I + A^{-T}\Omega(M-l-1)A^{-1}GQG^T]^{-1}A^{-T},$$
$$\Omega(l+1) = [I + A^{-T}\Omega(l)A^{-1}GQG^T]^{-1}A^{-T}\Omega(l)A^{-1} + C^T R^{-1}C,$$
$$\Phi(0) = I, \quad \Omega(0) = C^T R^{-1}C, \quad 0 \le l \le M-1.$$

B. Some matrices

$$L_M \equiv \begin{bmatrix} I \\ I \\ \vdots \\ I \end{bmatrix}, \quad N_M \equiv \begin{bmatrix} I & 0 & \cdots & 0 & 0 \\ I & I & \cdots & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ I & I & \cdots & I & I \end{bmatrix},$$
$$G_M \equiv \begin{bmatrix} 0 & 0 & \cdots & 0 & 0 \\ I & I & \cdots & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ I & I & \cdots & I & 0 \end{bmatrix}.$$

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