Kalman Filtering in Video Coding

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October 22, 2010

Outline

- Introduction : Video Coding
- Motion Estimation in Video Coding
- Kalman Filtering Based Motion Estimation
- Conclusions

Video Coding

- Raw video contains an immense amount of redundant data.

- Communication and storage capabilities are limited and expensive.
  - Example HDTV video signal:

    - 720x1280 pixels/frame, progressive scanning at 60 frames/s,

$$\left\{\frac{720x1280\ pixels}{frames}\right\}\left\{\frac{60\ frames}{sec}\right\}\left\{\frac{3\ color}{pixels}\right\}\left\{\frac{8\ bits}{color}\right\} = 1.3\ Gb/sec$$

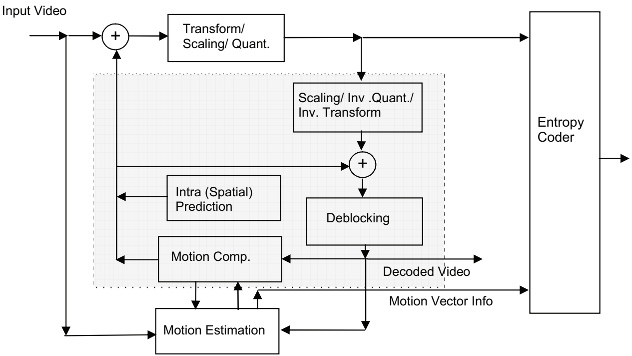
    - 20 Mb/sec HDTV channel bandwidth requires compression by a factor of 70.

- Compression is achieved by exploiting the redundancy inherent to video.
- Predict current frame based on previously coded frames.
- Technique: Motion-compensated (MC) Prediction

Video Coding

Motion-compensated Prediction

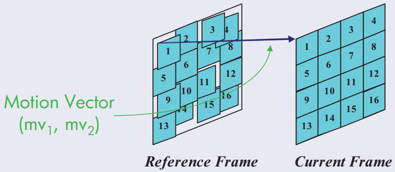
- It exploits similarity among video frames by using motion vectors.
- Motion vector estimation plays an important role in video coding systems with significant improvement in bit rate reduction.
- Example: Standard coding structure of H.264/AVC.



Motion Estimation

Block-Matching Algorithm

- Divided an image frame is into non-overlapping blocks.



- Motion vector of a block is estimated by searching for its best match in the previous frame.
- Matching criterion: Distortion between the current block and each searching block.
- Resulting motion vector and a prediction error are encoded and sent to decoder.

Motion Estimation

Previous frame

Frame with motion vectors

Current frame

Without motion compensation

After motion compensation

Motion Estimation

- Reduce coding rate for the prediction error(?)
- In low bit rate, motion vector bit rate is a significant part of all available budget(?)
- Optimally allocate a limited rate budget to the motion vector and prediction error(?)

Rate-Distortion (R-D) Motion Estimation

- By minimizing the following R-D cost function

$$J_{min}(v,\lambda) = \sum_{U^k} \min_{V \in U^k} \{\sum_{k=1}^{K} [D_k(\hat{v}_k)] + \lambda R_k(\hat{v}_k)\}$$

- Solution of the R-D cost function is locally optimal and globally sub-optimal.
- It gives highly correlated smooth motion vectors.

Approaches

I Kalman Filter as a Post Processing Scheme

- Extends integer-pixel accuracy of motion vectors to fractional-pixel accuracy.
- Enhancing the performance of motion-compensation without increasing bit rate.

II Kalman filter embedded R-D motion estimation

- Reduce distortion and thus lowering cost function.
- Improve distortion and bit rate simultaneously.

Approach I

Kalman Filter as a Post Processing Scheme

- Measured motion vectors are obtained from the any R-D motion estimation.
- Generate the predicted motion vectors by utilizing the inter-block correlation.
- Optimal estimate of motion vectors are obtain by Kalman filter.
- State-space representation for the motion vector $[v_{i,x}(m,n), v_{i,y}(m,n)]$ of the block (m,n) of the i-th frame,

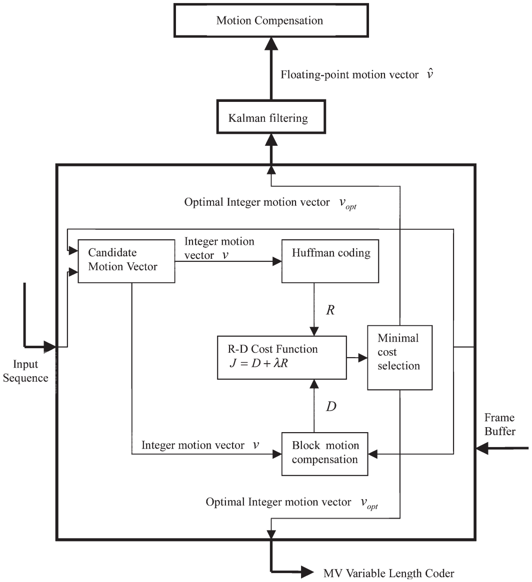
Prediction equation:

$$\begin{bmatrix} v_{i,x}(m,n) \\ v_{i,y}(m,n) \end{bmatrix} = \begin{bmatrix} a_1 & 0 \\ 0 & b_1 \end{bmatrix} \begin{bmatrix} v_{i,x}(m,n-1) \\ v_{i,y}(m,n-1) \end{bmatrix} + \begin{bmatrix} w_{i,x}(m,n) \\ w_{i,y}(m,n) \end{bmatrix}$$

Measurement equation:

$$\begin{bmatrix} z_x(m,n) \\ z_y(m,n) \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} v_{i,x}(m,n) \\ v_{i,y}(m,n) \end{bmatrix} + \begin{bmatrix} n_x(m,n) \\ n_y(m,n) \end{bmatrix}$$

Approach I


Motion Compensation
Floating-point motion vector $\hat{v}$
Kalman filtering
Optimal Integer motion vector v_{opt}
Candidate Motion Vector
Integer motion vector v
Huffman coding
R
R-D Cost Function
$J = D + \lambda R$
Minimal cost selection
D
Input Sequence
Frame Buffer
Integer motion vector v
Block motion compensation
Optimal Integer motion vector v_{opt}
MV Variable Length Coder

Approach II

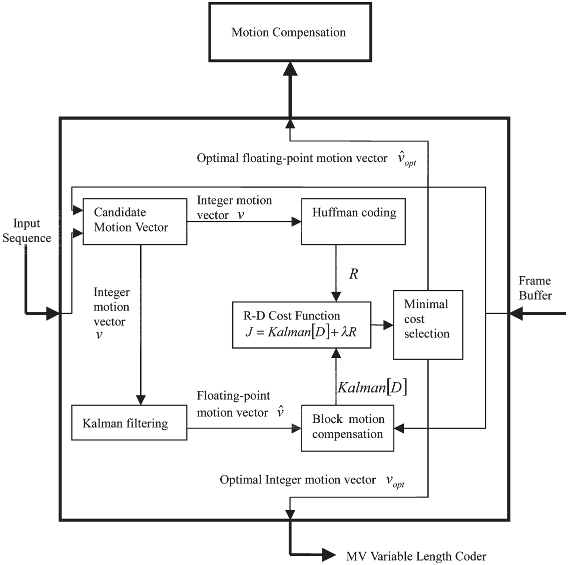
Kalman Filter Embedded Motion Estimation

- Obtain an optimal estimate of motion vector by using the Kalman filter
- Cost function of Kalman filter embedded R-D motion estimation.

$$J_{min}(v,\lambda) = \min_{V \in U^k}\{\mathit{Kalman}[D_k(\hat{v}_k)] + \lambda R_k(\hat{v}_k)\}$$

- $\mathit{Kalman}[D_k(\hat{v}_k)]$ is obtain by generating prediction error using fractional-point motion vector.
- Total cost function is reduced due to increase in compensation accuracy.

Approach II


Motion Compensation
Optimal floating-point motion vector $\hat{v}_{opt}$
Input Sequence
Candidate Motion Vector
Integer motion vector v
Huffman coding
R
Integer motion vector v
R-D Cost Function
$J = Kalman[D] + \lambda R$
Minimal cost selection
Frame Buffer
$Kalman[D]$
Floating-point motion vector $\hat{v}$
Kalman filtering
Block motion compensation
Optimal Integer motion vector v_{opt}
MV Variable Length Coder

Conclusion

- Provide fractional-pixel accuracy motion vector at low computation complexity.
- Achieves higher prediction quality without increasing the motion vectors bit rate.
- Improve the rate-distortion performance.