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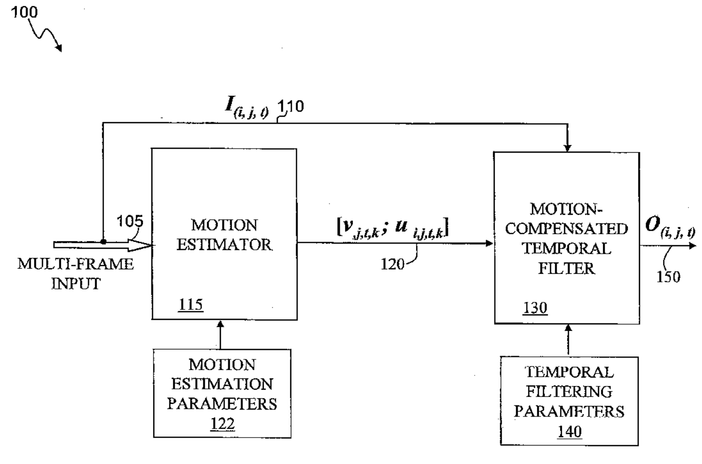
(54) **Title**: MOTION-COMPENSATED TEMPORAL FILTERING BASED ON VARIABLE FILTER PARAMETERS

FIG. 1



(57) **Abstract**: Systems and devices for, and methods of, motion-compensated temporal filtering based on variable filter parameters. A method embodiment includes (a) determining, by a processor having memory, a pixel-related residue image based on a set of differences between a current pixel intensity of a current frame and a corresponding pixel intensity of a previous frame, wherein the corresponding pixel intensity is augmented by a motion-compensated vector of the previous frame; (b) determining an intensity weight based on the determined pixel-related residue image and a temporal filtering parameter; and (c) filtering the pixel intensity of the current frame based on the determined intensity weight and the motion compensated vector of the previous frame.

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DESCRIPTION

TITLE OF INVENTION: MOTION-COMPENSATED TEMPORAL FILTERING BASED ON VARIABLE FILTER PARAMETERS

TECHNICAL FIELD

Embodiments pertain to systems and devices for, and methods of, motion-compensated temporal filtering based on variable filter parameters.

BACKGROUND ART

In video coding data, compression may be achieved by removing temporal and/or spatial redundancies. Video coding may use prediction and/or block-based motion compensation to reconstruct an approximation of the video data with minimal bits. Prediction-based compensation may use data in the current frame or in one or more previous and/or neighboring frames.

SUMMARY OF INVENTION

Embodiments include systems and devices for, and methods of, motion-compensated temporal filtering based on variable filter parameters. For example, a method embodiment includes (a) determining, by a processor having memory, a pixel-related residue image based on a set of differences between a current pixel intensity of a current frame and a corresponding pixel intensity of a previous frame, wherein the corresponding pixel intensity is augmented by a motion-compensated vector of the previous frame; (b) determining an intensity weight based on the determined pixel-related residue image and a temporal filtering parameter; and (c) filtering the pixel intensity of the current frame based on the determined intensity weight and the motion compensated vector of the previous frame.

Another exemplary method embodiment of a motion-compensated temporal filtering may include the steps of: (a) determining, by a processor having memory, a pixel-related residue image based on a set of differences between a current pixel intensity of a current frame and a corresponding pixel intensity of a previous frame, wherein the corresponding pixel intensity is augmented by a motion-compensated vector of the previous frame; (b) determining a set of intensity weights based on the determined pixel-related residue image and a temporal filtering parameter; (c) determining a set of spatial weights based on a set of neighboring pixels; and (d) filtering the pixel intensity of the current frame based on the set of determined intensity weight, the set of determined spatial weight, and the motion compensated vector of the previous frame.

Some embodiments pertain to devices for motion-compensated temporal filtering, for example, the device embodiment may comprise: a processor and addressable memory, wherein the processor is configured to: (a) determine a pixel-related residue image based on a set of differences between a current pixel intensity of a current frame and a corresponding pixel intensity of a previous frame, the corresponding pixel intensity augmented by a motion-compensated vector of the previous frame; and (b) determine an intensity weight based on the determined pixel-related residue image and a temporal filtering parameter; and (c) filter the pixel intensity of the current frame based on the determined intensity weight and the motion compensated vector of the previous frame.

Some embodiments may include a computer-readable non-transitory medium having computer-executable instructions stored thereon which, when executed by a computer, configure the computer to: (a) determine a pixel-related residue image based on a set of differences between a current pixel intensity of a current frame and a corresponding pixel intensity of a previous frame, the corresponding pixel intensity augmented by a motion-compensated vector of the previous frame; (b) determine an intensity weight based on the determined pixel-related residue image and a temporal filtering parameter; and (c) filter the pixel intensity of the current frame based on the determined intensity weight and the motion compensated vector of the previous frame.

The foregoing and other objectives, features, and advantages of the invention will be more readily understood upon consideration of the following detailed description of the invention, taken in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

Embodiments are illustrated by way of example, and not limitation, in the figures of the accompanying drawings, and in which:

FIG. 1 is a functional block diagram depicting an embodiment of a temporal filtering system;

FIG. 2 depicts a functional block diagram of an exemplary motion-compensated temporal filtering system;

FIG. 3 depicts an example of a histogrammed, square-rooted, residue image;

FIG. 4 depicts a table of parameter values for exemplary prediction schemes;

FIG. 5 is a functional block diagram depicting an embodiment of a motion-compensated multi-candidate temporal filtering system; and

FIG. 6 is a functional block diagram depicting an embodiment of a temporal, locally adaptive, filtering system.

DESCRIPTION OF EMBODIMENTS

Disclosed herein are embodiments that include systems and devices for, and methods of, motion-compensated temporal filtering based on variable filter parameters.

Also disclosed herein are embodiments that may include a computer-readable non-transitory medium having computer-executable instructions stored thereon.

Optionally, the temporal filtering parameter may be based on the determined set of residue images. Further, the temporal filtering parameter may be based on a histogrammed set of square-rooted determined pixel-related residue images. The histogrammed set of square-rooted determined pixel-related residue images may also be based on a mode of the histogrammed set of square-rooted determined pixel-related residue images. In some embodiments the histogrammed set of square-rooted determined pixel-related residue images may be further based on a portion, e.g., a one-sided tail portion, of the histogrammed set of square-rooted determined pixel-related residue images.

Embodiments include motion-compensated temporal filtering where the filtering parameter is a spatial statistical representation of at least one of: intensity and the motion vector. Optionally, the filtering parameter may be based on a variance of image intensity within a region about the current pixel. In another embodiment the filtering parameter may be based on a variance of at least one directional component of a motion vector within a region associated with the current pixel. Optionally, the filtering parameter may be based on a variance of the current pixel intensity of the current frame and a variance of the motion vector within a region associated with the current pixel.

Optionally, the set of spatial weights may be further based on a spatial candidate set comprising a plurality of motion compensated vectors of the previous frame. The spatial candidate set may be further based on a set of neighboring pixels where the weight is attenuated distal from the pixel around which the intensity vector is being determined.

In some embodiments, the processor may be further configured to determine a set of spatial weights based on a set of neighboring pixels.

Disclosed are systems and devices for, and methods of, temporal filtering of pixels, or subpixels, of frames based on frame-to-frame pixel residues. FIG. 1 is an exemplary functional block diagram depicting an embodiment of a temporal filtering system 100. Embodiments of the temporal filtering system 100 may be executed in real time or near real time. One or more frames 105 may be received, read, or accessed, that may carry pixels in a current frame. A motion estimator 115 may be based on a set of one or more estimated motion vectors of one or more previous frames and a set of motion estimation parameters 122. A set of one or more motion vectors 120 may comprise the motion vectors between one or more previous frames and a current frame. The set of one or more motion vectors may be generated and passed to a motion-compensated temporal filter (MCTF) 130. A pixel may be denoted in the current frame to be $I(i, j,t)$ 110 and previous frame to be $I(i, j, t-1)$. The MCTF 130 is depicted as determining a filtered intensity vector 150, $O(i,j,t)$, based on a set of temporal filtering parameters 140, the set of one or more motion vectors 120, $v_{i,j,t,k}$, $u_{i,j,t,k}$, and the current frame pixel 110, $I(i,j,t)$.

FIG. 2 depicts a functional block diagram of an exemplary motion-compensated temporal filter 130 having, as input, temporal filtering parameters 140. In this depicted embodiment, the current pixel 210, e.g., $I(i,j,t)$, and motion vectors 220, u, v, may be stored in memory 212, for example, a delay buffer. Once stored in memory 212, the current pixel 210, $I(i,j,t)$, may then have available from the previous frame both $I(i,j,t-1)$ 215 and u_{t-1}, v_{t-1} 225. A pixel-related residue image 231, $D_{i,j,t-1}$, may then be determined (block 230) based on a pixel of the current frame 210, $I(i,j,t)$, the spatially related pixel of the previous frame 215, $I(i,j,t-1)$, and the motion vectors 225, u_{t-1}, v_{t-1}, from the previous frame to current frame. An intensity weight 251, $w_{i,j,t-1}$, may be determined (block 250) based on the pixel-related image residue, $D_{i,j}$, 231, and a temporal filtering parameter 241, σ_t. In some embodiments, the temporal filtering parameter 241, σ_t, may be generated (block 240) based on offline training, or optionally the temporal filtering parameter 241, σ_t, may be generated and/or revised based on a set previously determined image residues. In some embodiments, a filtered pixel-related intensity vector 281, $O(i,j,t)$, may be determined (block 280) based on the intensity weight 251, *w*, the intensity vector of the previous frame 215, $I(i,j,t-1)$, and the associated motion vectors 225, u_{t-1}, v_{t-1}, from the previous frame, t-1, to the current frame, t.

In some embodiments, the temporal filtering parameter 241, σ_t, may be revised or updated concurrently with image processing and pixel filtering where, for example, the image residue 231, D, may be passed to an optional histogrammer 260, i.e., defined frequency bins may be populated via tracking the count of the frames and apportioning according to the resulting square-root of each image residue 231, D, in the count according to a particular bin range. An estimate of the standard deviation of the square-root of the residue 262, $\hat{\sigma}_n$, may then be determined based on the mode of the histogrammed data. In one embodiment, an estimate of a motion compensation error 264, $\hat{\sigma}_{me}$, may be determined based on an upper tail percentage of the histogrammed data. The estimate of a motion compensation error 264, $\hat{\sigma}_{me}$, may be combined with $\hat{\sigma}_n$ 262, e.g., in a second order polynomial function, to determine the temporal filter parameter, σ_t.

The motion-compensated temporal filter may first perform motion compensation of the pixel of the current frame based on the estimated motion vectors from the previous frame. Then the output of MCTF may be a weighted combination of the motion-compensated previous frame pixel and the spatially related pixel of the current frame. Motion vectors between a previous frame and current frame, *u, v,* may be expressed relative to a pixel, *I*, of the previous frame t-1, i.e., relative to $I(i,j,t-1)$, as $v_{i,j,t-1}$ and $u_{i,j,t-1}$. The averaging window for determining the image pixel residue may be expressed as *d*, where *d* represents half of the averaging window length in either direction. The temporal filtering parameter σ_t is the filtering parameter applied to temporally smooth the output pixels. The output of MCTF, i.e., $O(i,j,t)$, may be determined according to the following:

$$O(i,j,t) = \frac{w_{i,j,t-1} I(i + v_{i,j,t-1}, j + u_{i,j,t-1}, t-1) + I(i,j,t)}{1 + w_{i,j,t}}; \qquad [1]$$

where the weight, $w_{i,j,t-1}$, may be determined according to the following:

$$w_{i,j,t-1} = \exp\{-D_{i,j,t-1}/(2\sigma_t^2)\};\qquad [2]$$

and, where the image pixel residue D for a range of $\pm d$ pixels in both spatial directions about the reference pixel $I(i,j,t)$, applying the motion vectors, u, v, from $I(i,j,t)$ to $I(i,j,t-1)$, may be determined according to the following:

$$D_{i,j,t-1} = \frac{1}{(2d+1)^2}\sum_{m=i-d}^{i+d}\sum_{n=j-d}^{j+d}(I(m,n,t) - I(m+v_{i,j,t-1}, n+u_{i,j,t-1}, t-1))^2 \qquad [3]$$

For a particular D, increasing σ_t provides more de-noising power, while concurrently tending toward over-smoothing, and potentially producing image artifacts. Embodiments determine values of σ_t that provide de-noising effects while not over-smoothing and/or generating artifacts.

The filtering parameter, σ_t, may be treated as spatially invariant, i.e., uniform for an entire frame, but may change over frames, i.e., temporally variant. The global properties of input frames and their sequences, such as their noise statistics, may affect the σ_t. An effective σ_t value may be defined as the one maximizing the peak signal-to-noise ratio between the filtered image and a ground truth. Alternatively, a metric such as the Structure Similarity Index (SSIM) may be applied to assess effective values of σ_t. In one embodiment, determining values of σ_t may be done a priori via trials that may be carried on sequences that have various texture complexity and motion complexity.

Although an averaged numerically optimal $\sigma_t s$ may be closely related to noise level, a factor that may model the deviation from the average for each frame may be lacking. For frames with $\sigma_t s$ above the average, the motion compensation errors may be, in general, small. Images having $\sigma_t s$ that are below the average in each level may correspond to large motion compensation errors in the compensated previous frames. Therefore, an additional feature related to the motion compensation error may be used for predicting the numerically optimal σ_t.

FIG. 3 provides an example of a histogram of a square-rooted residue image with the same noise level which corresponds to a large motion error. Thus, the percentage of the tail 320 as an indicator of the motion compensation error may be considered in constructing σ_t. The tail 320 may be defined as the portion larger than three times the mode 310. Prediction of the σ_t may depend on the noise level and the motion compensation error. The noise level may be estimated using the mode of the histogram of the square-rooted residue image, denoted by $\hat{\sigma}_n$, and the motion compensation error may be estimated using the tail percentage of the same histogram, denoted by σ_{me}. Derivations below at equation 31 suggest the form as the functional form for prediction, but in practice, the mode and tail percentage may not correspond exactly to the σ_n and σ_{me}. So, a second-order polynomial function of σ_n may be applied for the prediction of σ_t. Optionally, a second-order polynomial function of σ_n and σ_{me} may also be applied for the prediction of σ_t. The following are exemplary functional forms for σ_t prediction:

$$\sigma_t = a_2\hat{\sigma}_n^2 + a_1\hat{\sigma}_n + a_0;\ \text{and} \qquad [4]$$

$$\sigma_t = a_2\hat{\sigma}_n^2 + a_1\hat{\sigma}_n + b_2\hat{\sigma}_{me}^2 + b_1\hat{\sigma}_{me} + c. \qquad [5]$$

The determining of the parameters a_2, a_1, a_0, for the first polynomial-based predictor, and/or a_2, a_1, a_0, b_2, b_1, and c for the second polynomial-based predictor, may be accomplished via a training process. The polynomial parameters defining fitted curves of two exemplary prediction methods are listed as training output in Table 1 of Fig. 4. A testing of the effectiveness of the resulting predictive polynomials may be conducted. The polynomial parameters, the noise statistics, and the motion error statistics—computed from the output—may be used to calculate the $\hat{\sigma}_t$ and then the $\hat{\sigma}_t$ may be used to compute the output of temporal filtering.

Embodiments may include one or more processing modules where they comprise a processor, such as a central processing unit (CPU), and a memory store, such as addressable memory.

Multi-Candidate Temporal Filtering

In some embodiments, the motion estimation may give incorrect correspondence between the current pixel and the pixel in the previous frame, and it may be possible that the correct corresponding pixel may be within the neighborhood of the incorrect pixel. Therefore, taking multiple candidates into account, multiple candidates may help recover the correct temporal correspondence. Some embodiments may consider only one pixel in the previous frame for filtering each pixel in the current frame. In another embodiment, the temporal filtering may be extended to consider multiple pixels in the previous frame for filtering one pixel in the current frame. These pixels may be referred to as candidates. Multiple candidates may have more de-noising power and may aid in correcting for the motion error.

Therefore, in some embodiments, the temporal filtering may consider multiple pixels in a previous frame for filtering the current pixel in the current frame. This may be in addition to considering only one pixel in the previous frame for filtering each pixel in the current frame. In a multi-pixel embodiment, the filtered intensity vector may be based additionally on a weighting, e.g., a spatial Gaussian distribution, to further determine the frame weighting. If applied, the spatial Gaussian may be positioned to attenuate the value of the weighting factor as the distance increases from the current pixel of the current frame.

FIG. 5 depicts a functional block diagram of an exemplary motion-compensated multi-candidate temporal filter 300 having input of temporal filtering parameters. The temporal filtering may consider multiple pixels in a previous frame for filtering the current pixel in the current frame. FIG. 5 depicts a pixel, e.g., $I(i,j,t)$ 210 and a set of candidate pixels depicted by motion vectors 220, that may be stored in memory 212 e.g., a buffer. Once stored in memory 212, the current pixel $I(i,j,t)$ may then have available the previous frame, $I(i,j,t-1)$ and the set of u_{t-1}, v_{t-1} 225 as a candidate set. A residue image, D 231 may then be calculated (block 230) based on the current frame, $I(i,j,t)$ 210, the previous frame, $I(i,j,t-1)$ 215, and the motion vectors, u_{t-1}, v_{t-1} 225, between the previous frame and current frame. An intensity weight, w 251, may be calculated (block 250) based on the residue image 231 and a temporal filtering parameter, σ_t, 241. In some embodiments, a filtered intensity vector, $O(i,j,t)$ 281, may be determined (block 280) based on the intensity weight, w 251, the intensity vector of the previous frame, $I(i,j,t-1)$

215, the set of motion vectors, u_{t-1}, v_{t-1} 225—between the previous frame and current frame—and a spatial Gaussian kernel $\gamma(m,n)$.

An exemplary multi-candidate filtering scheme may be expressed where the output of the filter may be given by:

$$O(i,j,t) = \frac{\sum_{m,n \in N(i+v_{i,j,t-1}, u_{i,j,t-1})} \gamma(m,n)\, w_{m,n,t-1} I(m,n,t-1) + I(i,j,t)}{1 + \sum_{m,n \in N(i+v_{i,j,t-1}, u_{i,j,t-1})} \gamma(m,n)\, w_{m,n,t-1}} \quad [6]$$

where the weight $w_{m,n,t-1}$ may be defined by

$w_{m,n,t-1} = \exp\{-D_{m,n,t-1}/(2\sigma_t^2)\}$; the residue may be defined by: [7]

$$D_{m,n,t-1} = \frac{1}{(2d+1)^2} \sum_{m'=m-d}^{m+d} \sum_{n'=n-d}^{n+d} (I(m',n',t) - I(m'+v_{i,j,t-1}, t-1, n'+u_{i,j,t-1}, t-1))^2 \; ; \quad [8]$$

—where

$$N(i+v_{i,j,t-1}, j+u_{i,j,t-1}) \quad [9]$$

denotes the neighbor of point

$$(i+v_{i,j,t-1}, j+u_{i,j,t-1}) . \quad [10]$$

In addition, $\gamma(m,n)$ may be based on a spatial Gaussian kernel, i.e.,

$$\gamma(m,n) = \exp\{-(m-(i+v_{i,j,t-1}))^2 + (n-(j+u_{i,j,t-1}))^2)/(2\sigma_s^2)\} \quad [11]$$

where σ_s is the standard deviation parameter for the kernel. For single candidate, the optimal σ_t may have been searched. For the multi-candidate, the jointly optimal σ_t and σ_s may have been searched.

Locally Adaptive Filtering

Filtering parameters for the motion-compensated temporal filtering may be locally adaptive. That is, one may predict the $\hat{\sigma}_t$ for each pixel in the image depending on local features of the input frame. FIG. 6 is an exemplary function block diagram depicting an embodiment of a temporal, locally adaptive, filtering system 600. In this depicted embodiment, the current pixel 610, e.g., $I(i,j,t)$, and motion vectors 620, u, v, may be stored in memory 612, e.g., a buffer. Once stored in memory 612, the current pixel 610, *I(i,j,t)*, may then have available from the previous frame both *I(i,j,t-1)* 615 and u_{t-1}, v_{t-1} 625. A pixel-related residue image 631, $D_{i,,j,t-1}$, may then be determined (block 630) based on a pixel of the current frame 610, *I(i,j,t)*, the spatially related pixel of the previous frame 615, *I(i,j,t-1)*, and the motion vectors 625, u_{t-1}, v_{t-1}, from the previous frame to current frame. An intensity weight 651, $w_{i,j,t-1}$, may be determined (block 650) based on the pixel-related image residue, $D_{i,j}$, 631, and a temporal filtering parameter 641, σ_t. Each pixel in the image may have a different predicted σ_t depending on local features of the input frame. In some embodiments, a filtered pixel-related intensity vector 681, *O(i,j,t)*, may be determined (block 680) based on the intensity weight 651, *w*, the intensity vector of the previous frame 615, *I(i,j,t-1)*, and the associated motion vectors 625, u_{t-1}, v_{t-1}, from the previous frame, t-1, to the current frame, t.

For example, the local features may comprise a local variance of the image intensity, $Var_I(i,j,t)$ and a local variance of each of the motion vectors, $Var_u(i,j,t)$ and $Var_v(i,j,t)$. The local variance of the image intensity, $Var_I(i,j,t)$, may be determined 660 based on subtracting the squared sum across the 2-D local window of the intensity vector of the current frame, *I(m,n,t)*, divided by the square of unity plus the local window size, from the sum of the square of the intensity vector of the current frame, *I(m,n,t)*, divided by the square of unity plus the local window size.

Also for example, the local variances of the motion vector for each component direction, $Var_u(i,j,t)$ and $Var_v(i,j,t)$, may be determined 660 by subtracting the square of the sum of the motion vector of the current frame, divided by the sum of unity plus the local window size, from the sum of the square of the motion vector divided by the square of unity plus the local window size. A total motion vector variance, $Var_{MV}(i,j,t)$ may then be determined by adding each direction vector, i.e., $Var_u(i,j,t) + Var_v(i,j,t)$.

The filtering parameter $\hat{\sigma}_t$ may therefore be predicted according to local features. For example, the local variance of the image intensity, $Var_I(i,j,t)$, may be determined 660 according to the following:

$$Var_I(i,j,t) = \frac{1}{(2d+1)^2}\sum_{m=i-d}^{i+d}\sum_{n=j-d}^{j+d} I(m,n,t)^2 - [\frac{1}{(2d+1)^2}\sum_{m=i-d}^{i+d}\sum_{n=j-d}^{j+d} I(m,n,t)]^2 . \quad [12]$$

Also for example, the local variance of the motion vector. The variance of each direction, u, v, of the motion vector, MV, may be determined 670 by:

$$Var_u(i,j,t) = \frac{1}{(2d+1)^2}\sum_{m=i-d}^{i+d}\sum_{n=j-d}^{j+d} u(m,n,t)^2 - [\frac{1}{(2d+1)^2}\sum_{m=i-d}^{l=d}\sum_{n=j-d}^{j+d} u(m,n,t)]^2 ;$$

[13]

and

$$Var_v(i,j,t) = \frac{1}{(2d+1)^2}\sum_{m=i-d}^{i+d}\sum_{n=j-d}^{j+d} v(m,n,t)^2 - [\frac{1}{(2d+1)^2}\sum_{m=i-d}^{i+d}\sum_{n=j-d}^{j+d} v(m,n,t)]^2 \quad [14]$$

The total variance, Var_{MV}, may be given by

$$Var_{MV}(i,j,t) = Var_u(i,j,t) + Var_v(i,j,t). \quad [15]$$

A test set for the predicting of the filtering parameter $\hat{\sigma}_t$ according to local features may be a synthetic dataset with, for example, additive Gaussian noise, std. dev.=10, and a compression rate=20Mbps.

Additional features that may be considered for predicting the filtering parameter $\hat{\sigma}_t$ —according to local features—include, for example, normalized cross-correlation and mean-square difference. Additionally, in one embodiment, the use of other features for classification, such as gradient features which corresponds to edges, histogram features such as histogram similarity measurements—e.g., Bhattacharyya distance or Mahalanobis distance—or other spatial noise statistics may be used.

Mathematical Derivations Supporting the Filtering Parameter

A prediction process depends on the existence and uniqueness of the optimal σ_t. The numerically optimal σ_t may relate to the noise level and motion compensation error. The numerical optimal σ_t for motion-compensated temporal filtering may be based on minimizing the mean-square error. For example, a point x_0 in a scene at time t, i.e., the current frame, may be considered. The observed image pixel may be y_0 where $y_0 = x_0 + n_0$. Similarly, the corresponding point may be assumed x_1 in time $t-1$ and the observed pixel may be $y_1 = x_1 + n_1$. n_0 and n_1 may be additive Gaussian noise with zero mean and having a standard deviation, σ_n. A motion transformation M between x_1 and x_0, i.e., $x_1 = M(x_0)$ may be considered. The motion transformation may be invertible. An estimate of the motion transformation $\hat{M}$ in the motion estimation stage may be obtained, then the inverse of the estimated motion may be applied to the $t-1$ frame, i.e.,

$$\hat{M}^{-1}(y_1) = \hat{M}^{-1}(x_1 + n_1) = \hat{M}^{-1}(M(x_0) + n_1). \qquad [16]$$

A filtering process may be express as: $\hat{x}_0 = \frac{y_0 + w\hat{M}^{-1}(y_1)}{1+w}$; where w may be the weighting value. If the motion estimation is correct, i.e., $\hat{M} = M$, the above equation becomes $\hat{M}^{-1}(y_1) = x_0 + \hat{M}^{-1}(n_1)$. Since the motion transformation does not change the statistics of the noise, we denote $\hat{M}^{-1}(n_1) \triangleq n_0'$, which is independent and identically distributed (i.i.d) with respect to n_0. So, for the situation of correctly estimated motion, the optimal weight, w, when defined as the weight that results in the largest de-noising power, is unity. Accordingly, the de-noised result will have noise variance of $\sigma_n^2/2$.

The motion estimation is not always correct, and when the motion transformation is not correct, one may assume the difference between the true value and the compensated value to be Δx, i.e., $\hat{M}^{-1}M(x_0) - x_0 = \Delta x$. Accordingly:

$$\hat{M}^{-1}(y_1) = x_0 + \Delta x + n_0' \qquad [17]$$

The correct motion estimation is a special case when $\Delta x = 0$. However, for the incorrect motion estimation, the filtered result is thus

$$\hat{x}_0 = \frac{x_0 + n_0 + w(x_0 + \Delta x + n_0')}{1+w} \qquad [18]$$

$$= x_0 + \frac{n_0 + wn_0'}{1+w} + \frac{w\Delta x}{1+w} \qquad [18.1]$$

One may define the filtering error for pixel x_0 as the expected mean-square error over the probability distribution of the Gaussian noise, i.e.,

$$error(x_0) \equiv E_n[(\hat{x}_0 + x_0)^2] \quad [19]$$

$$= E_n[(\frac{n_0 + wn_0'}{1+w} + \frac{w\Delta x}{1+w})^2] \quad [19.1]$$

$$= E_n[(\frac{n_0 + wn_0'}{1+w})^2] + (\frac{w\Delta x}{1+w})^2 + 2\frac{w\Delta x}{1+w}E_n[\frac{n_0 + wn_0'}{1+w}]. \quad [19.2]$$

With n_0 and n_0' being independent and identically distributed (i.i.d) with zero mean and standard deviation σ_n^2, the above expected mean-square error equation can be simplified as:

$$E_n[(\hat{x}_0 - x_0)^2] = \frac{1}{(1+w)^2} E_n[n_0^2 + w^2 n_0'^2 + 2wn_0 n_0'] + (\frac{w\Delta x}{1+w})^2 \quad [20]$$

$$= \frac{1+w^2}{(1+w)^2}\sigma_n^2 + \frac{w^2\Delta x^2}{(1+w)^2} \quad [20.1]$$

A partial derivative with respect to w, yields the following:

$$\frac{\partial En}{\partial w} = \frac{2w(1+w) - 2(1+w^2)}{(1+w)^3}\sigma_n^2 + \frac{2w(1+w) - 2w^2}{(1+w)^3}\Delta x^2. \quad [22]$$

If the error is minimized for weight, then the partial derivative with respect to weight is zero, i.e., $\frac{\partial E_n}{\partial w} = 0$, which in turn yields

$$[w(1+w) - (1+w^2)]\sigma_n^2 = [w(1+w) - w^2]\Delta x^2, \quad [23]$$

from which we derive the optimal weight, ***w****, is given by

$$w^* = \frac{\sigma_n^2}{\sigma_n^2 + \Delta x^2}, \quad [24]$$

which is equivalent to

$$\frac{1}{w^*} = 1 + \frac{\Delta x^2}{\sigma_n^2}. \quad [25]$$

When motion estimation is correct, $\Delta x = 0$, then $w=1$. Another case that $\Delta x = 0$, meaning that the pixel locates in a uniform area and the wrong motion compensation does not cause a difference, the weight is still unity. When σ_n increases, w increases, resulting more de-noising power. Accordingly, the upper bound of the weight is unity.

Local averaging may be an approximation to taking the expectation, and so the weight, w, may be expressed as:

$w = \exp\{-d/(2\sigma_t^2)\}$ where d, which is an expectation and not the one-half the window distance applied in a previous section, may be expressed as:

$$d = E_n[(\hat{M}^{-1}(y_1) - (y_0)^2] = E_n[(\Delta x + n_o' - n_0)^2] = \Delta x^2 + 2\sigma_n^2. \qquad [26]$$

The above equation for d has an underlying assumption that Δx varies little within a small local region. Therefore, the inverse of the weighting factor may be expressed as

$$\frac{1}{w} = \exp\{(\Delta x^2 + 2\sigma_n^2)/(2\sigma_t^2)\} \qquad [27]$$

Based on the Taylor Series of $e^x = 1 + x + x^2/2 \ldots$, one may approximate the above inverted weighting factor equation by a first order, e.g.,

$$\frac{1}{w} \cong 1 + \frac{\Delta x^2 + 2\sigma_n^2}{2\sigma_t^2} \qquad [28]$$

Therefore the numerically optimal σ_t should approximately satisfy the following:

$$\frac{\Delta x^2 + 2\sigma_n^2}{2\sigma_t^2} = \frac{\Delta x^2}{2\sigma_n^2}, \qquad [29]$$

and the above relationship can be solved as

$$2\sigma_t^2 = \frac{1}{2} 2\sigma_n^2 (\frac{2\sigma_n^2}{\Delta x^2} + 1) \qquad [30]$$

$$= \frac{1}{2} \frac{d\sigma_n^2}{d - 2\sigma_n^2} \qquad [30.1]$$

The above equation shows the numerically optimal σ_t relates to the noise level. That is, the larger the value of σ_n, then the larger the value of σ_t. The above equation also relates to Δx, or d, which can be spatially variant. If $\Delta x >> \sigma_n$, the numerically optimal

σ_t may be given by $\sigma_t = \frac{\sigma_n}{\sqrt{2}}$. This case of $\Delta x >> \sigma_n$, the value σ_t increases linearly with the value of σ_n.

To define a uniform σ_t for an entire frame, one may consider Δx to be a random variable having a zero mean and a variance of σ^2_{me}. One may use the expected value of Δx^2 to approximate the σ_t, i.e.,

$$\sigma_t^2 = \frac{1}{2}\sigma_n^2\left(\frac{2\sigma_n^2}{E(\Delta x^2)}+1\right) = \frac{1}{2}\sigma_n^2\left(\frac{2\sigma_n^2}{\sigma_{me}^2}+1\right). \quad [31]$$

Definitions and notations are similar to the previous section. One may assume Δx to be a random variable of zero mean and variance of σ^2_{me}. The filter weighting may be defined as in equation no. 7 (above), i.e.,

$$w = \exp\{-(\Delta x^2 + 2\sigma_n^2)/(2\sigma_t^2)\}. \quad [32]$$

One may define the normalized weight to be $\rho = \frac{1}{1+w}$. Therefore the filter output is may be expressed as:

$$\hat{x}_0 = \rho y_0 + (1-\rho)\hat{M}^{-1}(y_1). \quad [33]$$

One may define the error as expected mean-square-error over both the distribution of additive noise and distribution of motion error,

i.e., $E_{n,\Delta x}[(\hat{x}_0 - x_0)^2] = E_{n,\Delta x}[(\rho n_0 + (1-\rho)n_0' + (1-\rho)\Delta x)^2]$. [34]

Taking expectation on the noise first, one may arrive at the expectation, or objective function, expressed as:

$$E_{n,\Delta x}[(\hat{x}_0 - x_0)^2] = E_{\Delta x}[((1-\rho)^2+\rho^2)\sigma_n^2 + (1-\rho)^2\Delta x^2] \quad [35]$$

$$= E_{\Delta x}[2\rho^2 - 2\rho]\sigma_n^2 + E_{\Delta x}[(1-\rho)^2\Delta x^2] + \sigma_n^2. \quad [35.1]$$

A partial derivative of the above objective function with respect to σ_t, where the order of expectation and derivative are exchanged, one has the following:

$$\frac{\partial E_{n,\Delta x}}{\partial \sigma_t} = E_{\Delta x}[4\rho\frac{\partial \rho}{\partial \sigma_t} - 2\frac{\partial \rho}{\partial \sigma_t}]\sigma_n^2 + E_{\Delta x}[2(1-\rho)\frac{\partial \rho}{\partial \sigma_t}\Delta x^2]. \quad [36]$$

The following approximations on ρ:

$$\rho = \frac{1}{1+w} = 1 - w + w^2 - w^3 \ldots \quad [37]$$

$$\cong 1 - w = 1 - \exp\{-(\Delta x^2 + 2\sigma_n^2)/(2\sigma_t^2)\} \quad [37.1]$$

$$\cong 1 - (1 - (\Delta x^2 + 2\sigma_n^2)/(2\sigma_t^2)) \quad [37.2]$$

$$= \frac{\Delta x^2 + 2\sigma_n^2}{2\sigma_t^2} \quad [37.3]$$

The two approximations are all based on Taylor series. Therefore,

$$\frac{\partial \rho}{\partial \sigma_t} = -\frac{\Delta x^2 + 2\sigma_n^2}{\sigma_t^3} \quad [38]$$

Substituting the expression for $\frac{\partial \rho}{\partial \sigma_t}$ into the expression for $\frac{\partial E_{n,\Delta x}}{\partial \sigma_t}$ yields the following:

$$\frac{\partial E_{n,\Delta x}}{\partial \sigma_t} = E_{\Delta x}[-4\frac{\Delta x^2 + 2\sigma_n^2}{2\sigma_t^2}\frac{\Delta x^2 + 2\sigma_n^2}{\sigma_t^3} + 2\frac{\Delta x^2 + 2\sigma_n^2}{\sigma_t^3}]\sigma_n^2 \quad [39]$$

$$+E_{\Delta x}[-2(1 - \frac{\Delta x^2 + 2\sigma_n^2}{2\sigma_t^2})\frac{\Delta x^2 + 2\sigma_n^2}{\sigma_t^3}\Delta x^2].$$

The above expression can be simplified as:

$$\frac{\partial E_{n,\Delta x}}{\partial \sigma_t} = \frac{2}{\sigma_t^5}[(-E(\Delta x^4) - (E(\Delta x^2)\sigma_n^2 + 2\sigma_n^4)\sigma_t^2 - 4\sigma_n^6 + 3E(\Delta x^4)\sigma_n^2 + E(\Delta x^6)] \quad [40]$$

Let $\frac{\partial E_{n,}\Delta x}{\partial \sigma_t} = 0$, optimal σ_t^2 may be solved for as follows:

$$(\sigma_t^2)^* = \frac{4\sigma_n^6 - 3E(\Delta x^4)\sigma_n^2 - E(\Delta x^6)}{2\sigma_n^4 - E(\Delta x^2)\sigma_n^2 + E(\Delta x^4)} \quad [41]$$

So, the optimal variance, $(\sigma_t)^*$ and the associated square root, σ_t, relate to both the noise variance and second, fourth and sixth moment of motion error.

It is contemplated that various combinations and/or sub-combinations of the specific features and aspects of the above embodiments may be made and still fall within the scope of the invention. Accordingly, it should be understood that various features and aspects of the disclosed embodiments may be combined with or substituted for one another in order to form varying modes of the disclosed invention. Further, it is intended that the scope of the claimed invention (below), disclosed herein by way of examples, should not be limited by the particular disclosed embodiments described above.

CLAIMS

What is claimed is:

1. A method of motion-compensated temporal filtering comprising:

determining, by a processor having memory, a pixel-related residue image based on a set of differences between a current pixel intensity of a current frame and a corresponding pixel intensity of a previous frame, wherein the corresponding pixel intensity is augmented by a motion-compensated vector of the previous frame;

determining an intensity weight based on the determined pixel-related residue image and a filtering parameter; and

filtering the pixel intensity of the current frame based on the determined intensity weight and the motion compensated vector of the previous frame.

2. The method of claim 1 wherein the filtering parameter is a temporal filtering parameter based on the determined set of residue images.

3. The method of claim 2 wherein the temporal filtering parameter is further based on a histogrammed set of square-rooted determined pixel-related residue images.

4. The method of claim 3 wherein the histogrammed set of square-rooted determined pixel-related residue images is based on a mode of the histogrammed set of square-rooted determined pixel-related residue images.

5. The method of claim 4 wherein the histogrammed set of square-rooted determined pixel-related residue images is further based on a portion of the histogrammed set of square-rooted determined pixel-related residue images.

6. The method of claim 5 wherein the portion of the histogrammed set of square-rooted determined pixel-related residue images is a one-sided tail portion.

7. The method of claim 1 wherein the filtering parameter is a spatial statistical representation of at least one of: intensity and the motion vector.

8. The method of claim 7 wherein the filtering parameter is based on a variance of image intensity within a region associated with the current pixel.

9. The method of claim 8 wherein the filtering parameter is based on a variance of at least one directional component of a motion vector within a region associated with the current pixel.

10. The method of claim 9 wherein the filtering parameter is based on a variance of the current pixel intensity of the current frame and a variance of the motion vector within a region associated with the current pixel.

11. A method of motion-compensated temporal filtering comprising:

determining, by a processor having memory, a pixel-related residue image based on a set of differences between a current pixel intensity of a current frame and a corresponding pixel intensity of a previous frame, wherein the corresponding pixel intensity is augmented by a motion-compensated vector of the previous frame;

determining a set of intensity weights based on the determined pixel-related residue image and a temporal filtering parameter;

determining a set of spatial weights based on a set of neighboring pixels; and

filtering the pixel intensity of the current frame based on the set of determined intensity weight, the set of determined spatial weight, and the motion compensated vector of the previous frame.

12. The method of claim 11 wherein the set of spatial weights is further based on a spatial candidate set comprising a plurality of motion compensated vectors of the previous frame.

13. The method of claim 11 wherein the spatial candidate set is further based on a set of neighboring pixels wherein the weight is attenuated distal from the pixel around which the intensity vector is being determined.

14. A device comprising:

a processor, configured to:

determine a pixel-related residue image based on a set of differences between a current pixel intensity of a current frame and a corresponding pixel intensity of a previous frame, the corresponding pixel intensity augmented by a motion-compensated vector of the previous frame;

determine an intensity weight based on the determined pixel-related residue image and a filtering parameter; and

filter the pixel intensity of the current frame based on the determined intensity weight and the motion compensated vector of the previous frame.

15. The device of claim 14 wherein the processor is further configured to determine a set of spatial weights based on a set of neighboring pixels, and is further configured to filter the pixel intensity of the current frame based on the determined intensity weight, the set of determined spatial weights, and the motion compensated vector of the previous frame.

16. The device of claim 14 wherein the filtering parameter is a temporal filtering parameter and the processor is further configured to determine the temporal filtering parameter based on the determined set of residue images.

17. The device of claim 16 wherein the temporal filtering parameter is further based on a histogrammed set of square-rooted determined pixel-related residue images.

18. The device of claim 17 wherein the histogrammed set of square-rooted determined pixel-related residue images is based on a mode of the histogrammed set of square-rooted determined pixel-related residue images.

19. The device of claim 18 wherein the histogrammed set of square-rooted determined pixel-related residue images is further based on a portion of the histogrammed set of square-rooted determined pixel-related residue images.

20. The device of claim 14 wherein the processor is further configured to determine the filtering parameter based on a spatial statistical representation of at least one of: intensity and the motion vector.

21. The device of claim 20 wherein the filtering parameter is based on a variance of image intensity within a region associated with the current pixel.

22. The device of claim 21 wherein the filtering parameter is based on a variance of at least one directional component of a motion vector within a region associated with the current pixel.

23. The device of claim 22 wherein the filtering parameter is based on a variance of the current pixel intensity of the current frame and a variance of the motion vector within a region associated with the current pixel.

24. A computer-readable non-transitory medium having computer-executable instructions stored thereon which, when executed by a computer, configure the computer to:

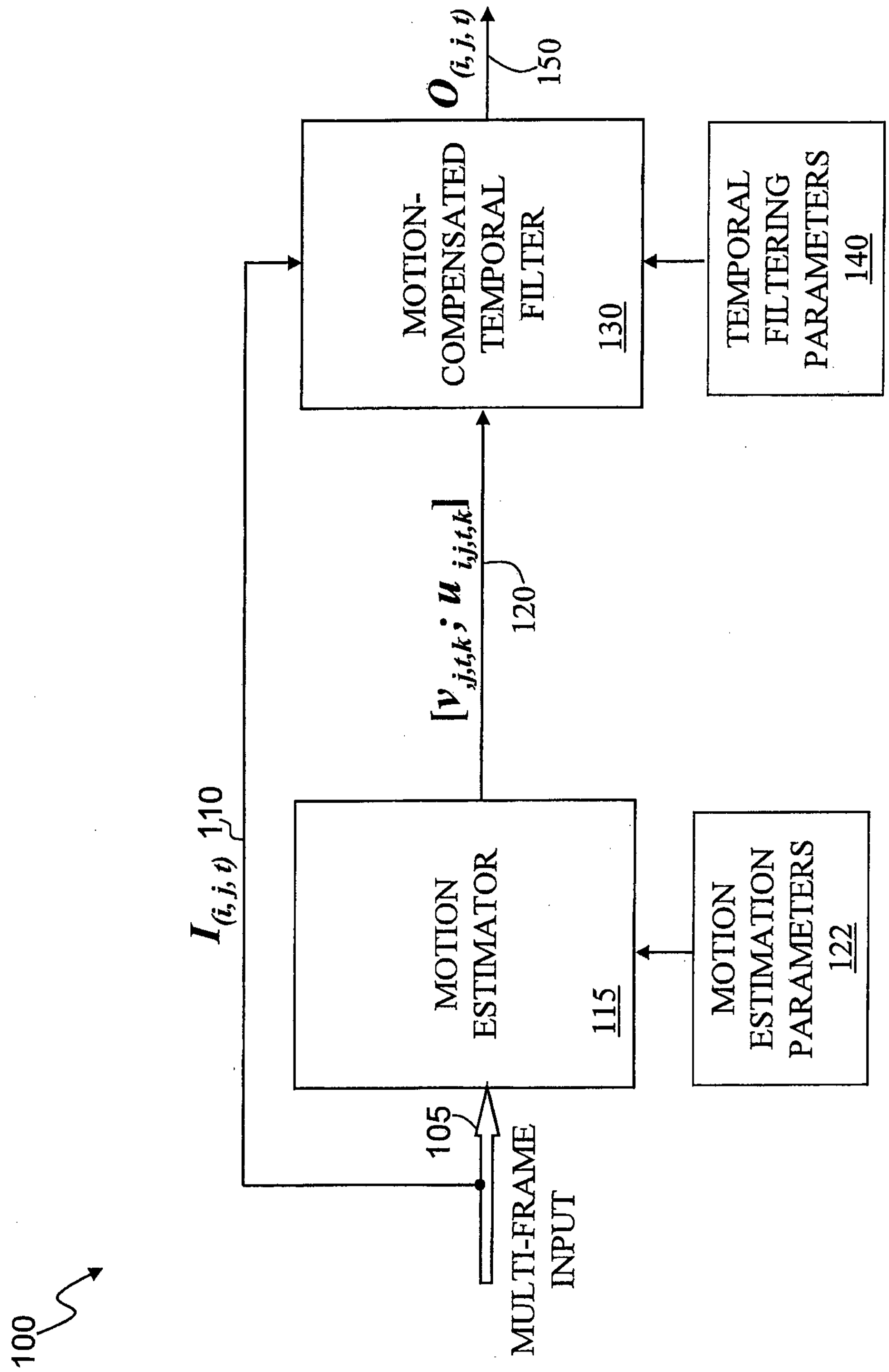
determine a pixel-related residue image based on a set of differences between a current pixel intensity of a current frame and a corresponding pixel intensity of a previous frame, the corresponding pixel intensity augmented by a motion-compensated vector of the previous frame;

determine an intensity weight based on the determined pixel-related residue image and a filtering parameter; and

filter the pixel intensity of the current frame based on the determined intensity weight and the motion compensated vector of the previous frame.

25. The computer-readable non-transitory medium of claim 24 wherein the computer-executable instructions further configure the computer to determine the filtering parameter based on a spatial statistical representation of at least one of: intensity and the motion vector.

26. The computer-readable non-transitory medium of claim 24 wherein the computer-executable instructions further configure the computer to determine a set of spatial weights based on a set of neighboring pixels, and to further configure the computer to filter the pixel intensity of the current frame based on the determined intensity weight, the set of determined spatial weights, and the motion compensated vector of the previous frame.



100
MULTI-FRAME INPUT
105
MOTION ESTIMATOR
115
MOTION ESTIMATION PARAMETERS
122
$I_{(i,j,t)}$
110
$[v_{i,j,t,k}; u_{i,j,t,k}]$
120
MOTION-COMPENSATED TEMPORAL FILTER
130
TEMPORAL FILTERING PARAMETERS
140
$O_{(i,j,t)}$
150

FIG. 1

FIG. 2

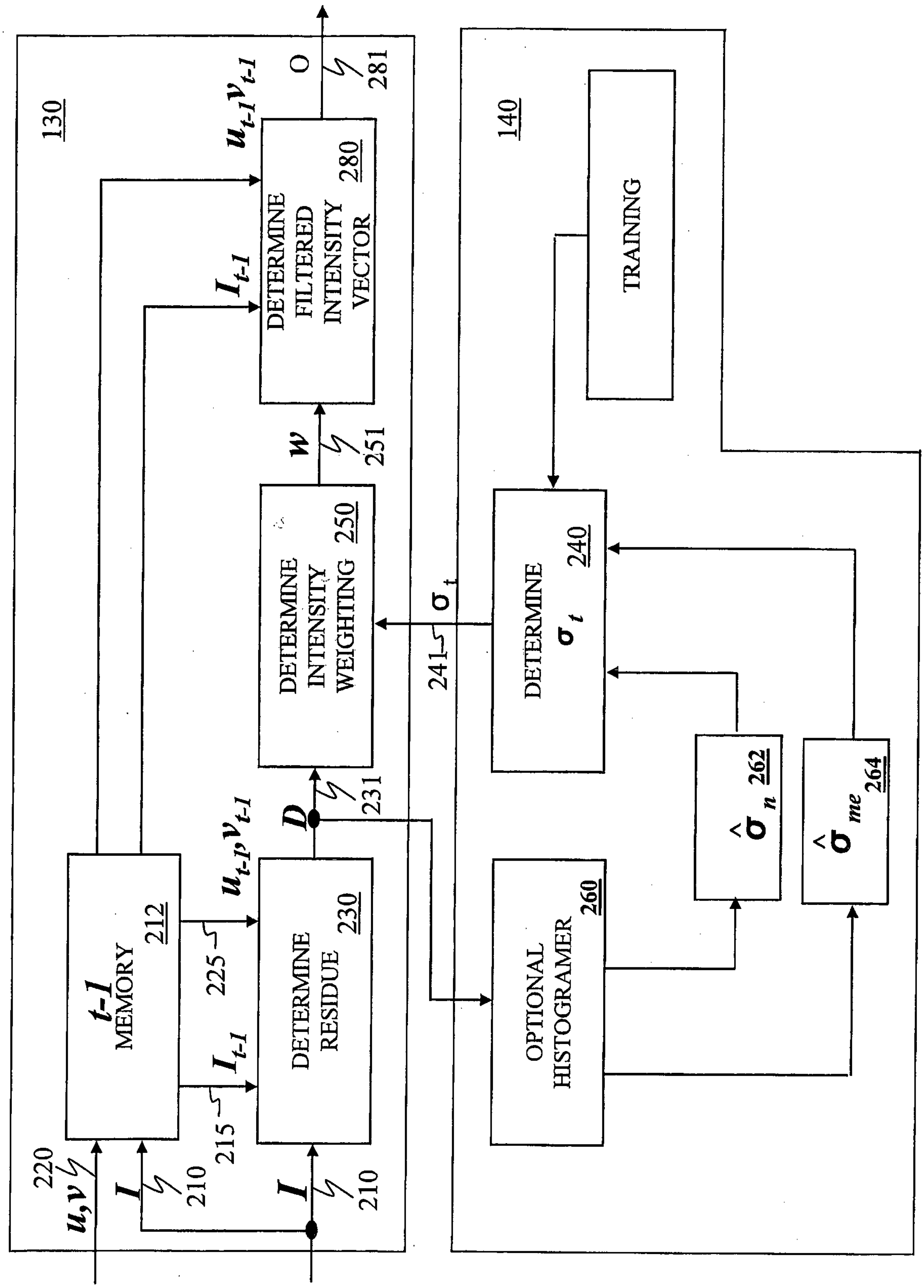

130
t-1
MEMORY
212
DETERMINE
RESIDUE
230
DETERMINE
INTENSITY
WEIGHTING
250
DETERMINE
FILTERED
INTENSITY
VECTOR
280
u,v
220
I
210
215
225
D
231
w
251
O
281
140
TRAINING
DETERMINE
240
241
OPTIONAL
HISTOGRAMER
260
262
264

FIG. 3

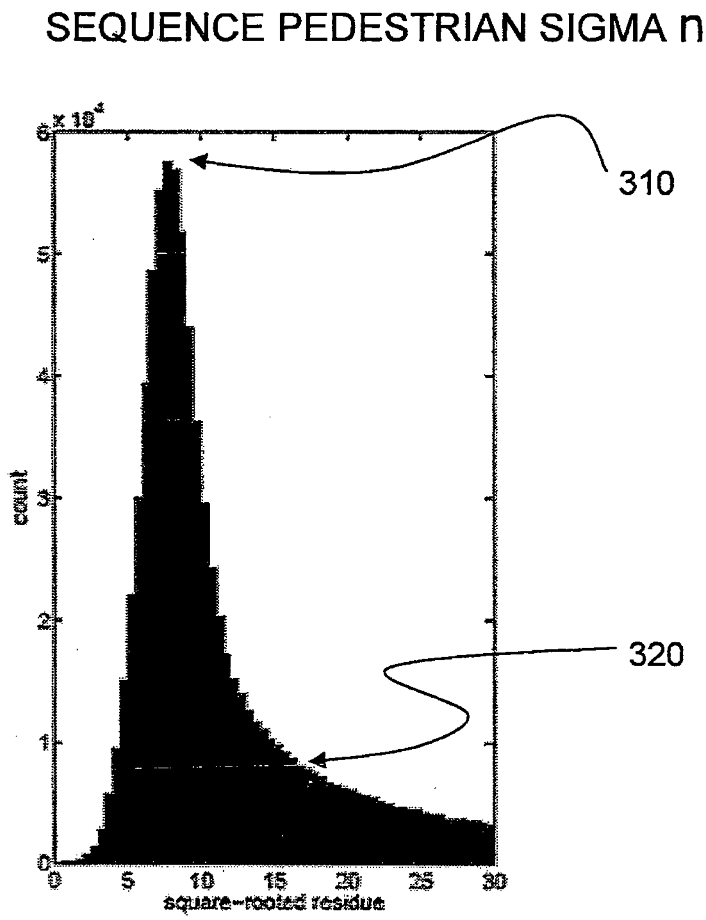

SEQUENCE PEDESTRIAN SIGMA n=10
x 10^4
6
5
4
3
2
1
0
count
0
5
10
15
20
25
30
square-rooted residue
310
320

FIG. 4

TABLE I

PARAMETER VALUES FOR THE THREE PREDICTION SCHEMES

	a_2	a_1	a_0	b_2	b_1	c
scheme (1)	0.1941	-0.0701	4.4724	-	-	-
scheme (2)	0.2439	-0.9529	-	25.4279	-23.3943	9.3214

FIG. 5

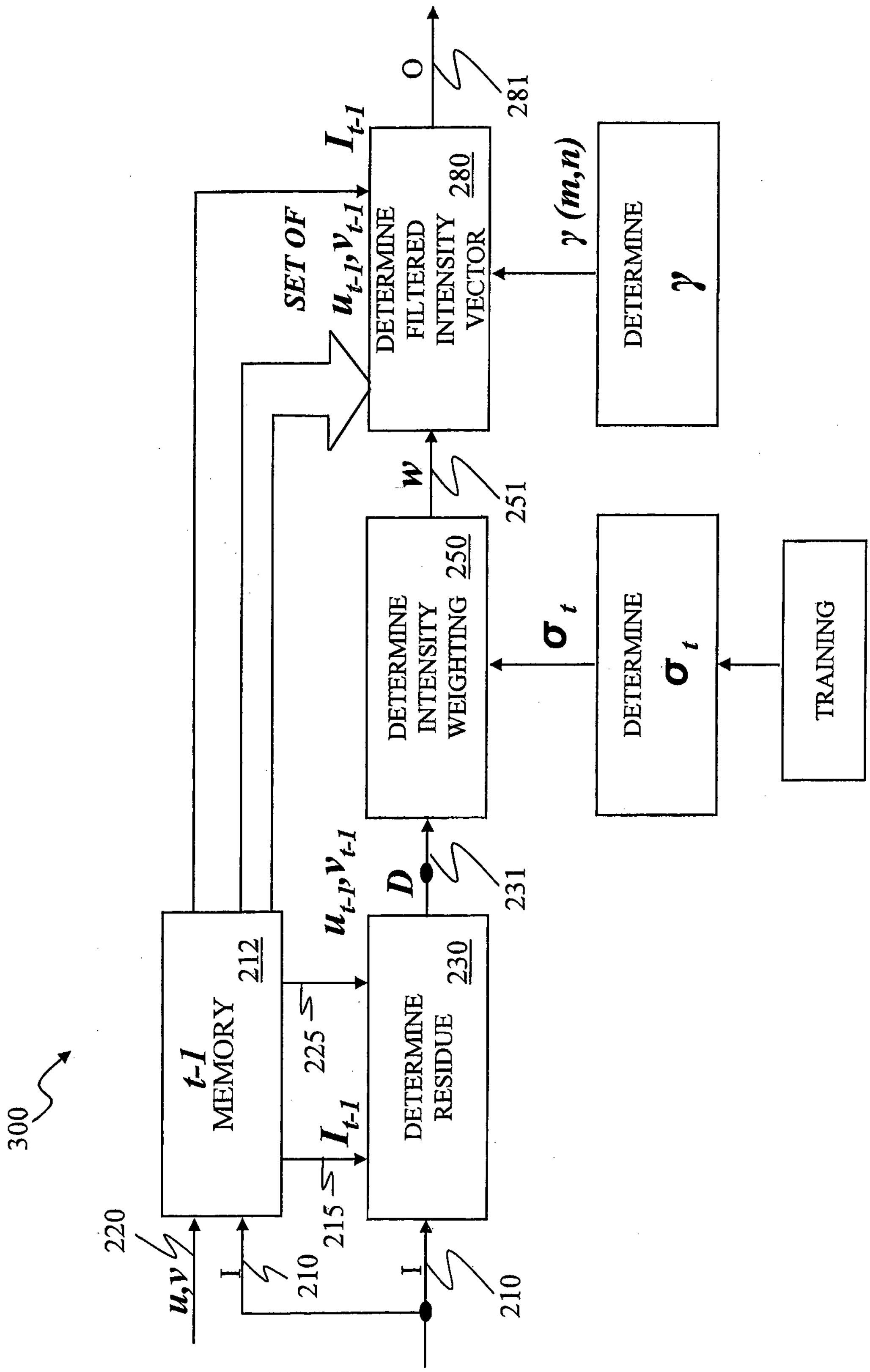
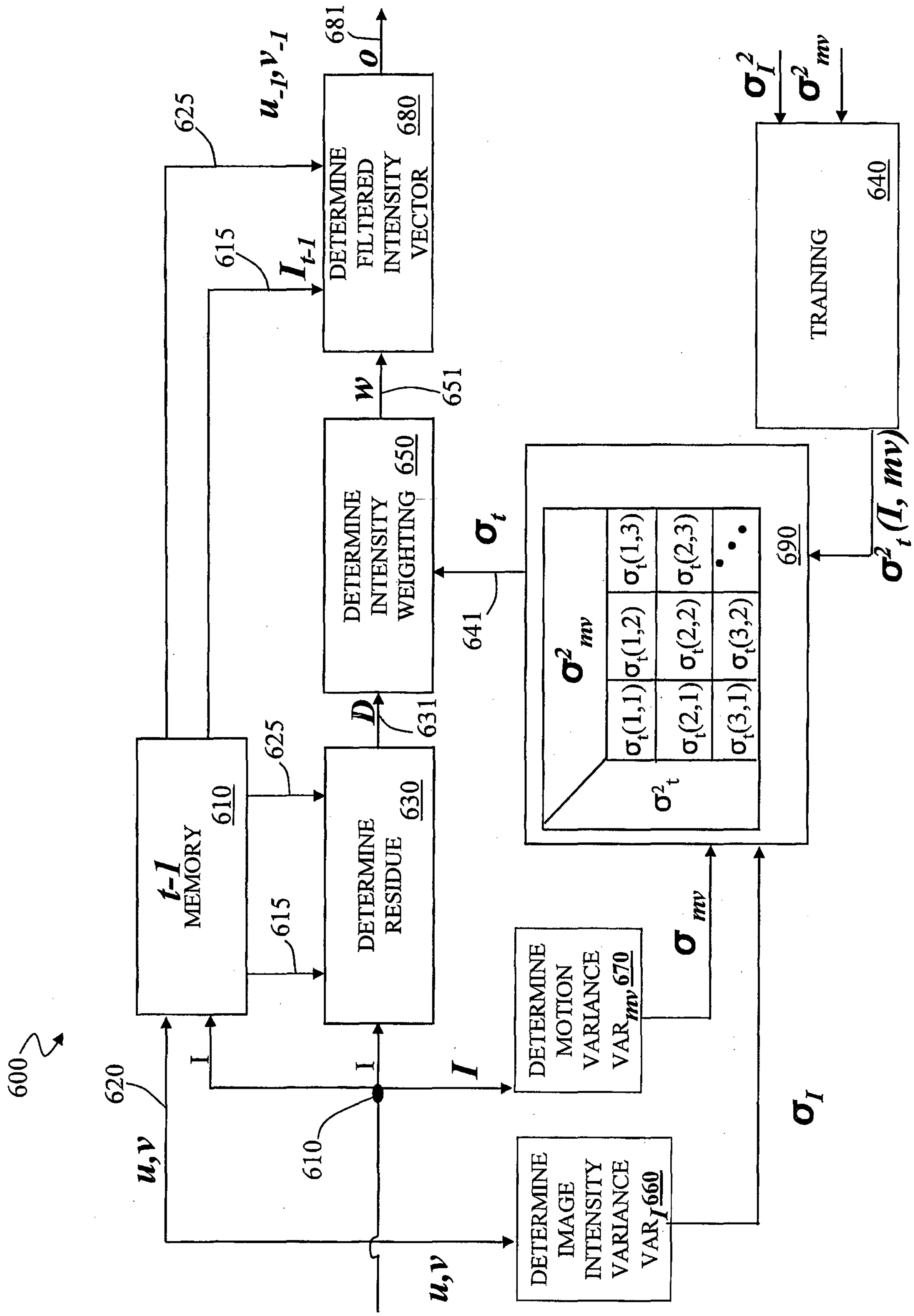

300
t-1
MEMORY
212
DETERMINE
RESIDUE
230
DETERMINE
INTENSITY
WEIGHTING
250
DETERMINE
FILTERED
INTENSITY
VECTOR
280
DETERMINE
γ
DETERMINE
σ t
TRAINING
u,v
I
I
220
210
210
215
225
I t-1
u t-1, v t-1
D
231
w
251
σ t
γ (m,n)
SET OF
u t-1, v t-1
I t-1
O
281

FIG. 6


600
t-1
MEMORY
610
DETERMINE
RESIDUE
630
DETERMINE
INTENSITY
WEIGHTING
650
DETERMINE
FILTERED
INTENSITY
VECTOR
680
TRAINING
640
DETERMINE
MOTION
VARIANCE
VAR$_{mv}$ 670
DETERMINE
IMAGE
INTENSITY
VARIANCE
VAR$_I$ 660
690
σ^2_{mv}
σ^2_t
$\sigma_t(1,1)$ $\sigma_t(1,2)$ $\sigma_t(1,3)$
$\sigma_t(2,1)$ $\sigma_t(2,2)$ $\sigma_t(2,3)$
$\sigma_t(3,1)$ $\sigma_t(3,2)$
u,v
620
610
I
615
625
D
631
w
651
σ_t
641
I_{t-1}
u_{-1},v_{-1}
o
681
σ_I^2
σ^2_{mv}
$\sigma^2_t(I, mv)$
σ_{mv}
σ_I

INTERNATIONAL SEARCH REPORT

International application No.
PCT/JP2011/063192

A. CLASSIFICATION OF SUBJECT MATTER

Int.Cl. H04N7/32(2006.01)i, H04N5/21(2006.01)i

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

Int.Cl. H04N7/24-7/68, H04N5/21

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Published examined utility model applications of Japan 1922-1996
Published unexamined utility model applications of Japan 1971-2011
Registered utility model specifications of Japan 1996-2011
Published registered utility model applications of Japan 1994-2011

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	JP 2007-221208 A (KABUSHIKI KAISHA TOSHIBA) 2007.08.30, [0042]-[0051] (Family: None)	1,14,24
A	JP 7-231450 A (AT & T CORP) 1995.08.29, whole document & US 5512956 A & EP 666695 A2	1-26
A	Ruiqin Xiong, Jizheng Xu, Feng Wu, Shipeng Li, "Adaptive MCTF based on Correlation Noise Model for SNR Scalable Video Coding", 2006 IEEE International Conference on Multimedia and Expo, 9 July 2006, p.1865-1868	1-26

☑ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

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"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
07.09.2011	20.09.2011

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INTERNATIONAL SEARCH REPORT

International application No.
PCT/JP2011/063192

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	JP 9-130648 A (KABUSHIKI KAISHA TOSHIBA) 1997.05.16, whole document (Family: None)	1-26
A	JP 2009-95004 A (MITSUBISHI ELECTRIC RESEARCH LABORATORIES INC) 2009.04.30, whole document & US 2008/0019605 A1	1-26
A	JP 2006-287848 A (NIPPON TELEGRAPH AND TELEPHONE CORPORATION) 2006.10.19, whole document (Family: None)	1-26