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컨텐트 적응적 비정형 메쉬를 이용한 전방향 움직임보상

(Forward Motion Compensation with Content-Adaptive Irregular Meshes)

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요 약

기존의 블록기반 움직임 예측방법은 특히 저전송률 비디오 압축에 사용 될 경우 움직임 필드에서의 블록화 현상이나 불안정한 움직임 예측과 같은 문제를 수반한다. 본 논문은 이러한 단점을 극복하기 위해 H.263의 기존 블록기반 DCT부호화 구조를 최대한 유지하면서 비정형 삼각형 메쉬에 기반한 새로운 움직임 보상 방법을 수용할 수 있는 하나의 방법을 제안한다. 제안방법은 복원된 이전 프레임 영상을 최소의 제어점들을 이용해 표현하기 위해, 주어진 영상의 컨텐트에 적응적으로 삼각형 비정형 메쉬를 설정한다. 그리고 Affine 변환에 기반한 매칭을 이용해, 설정된 각 제어점의 움직임벡터를 구한 후, 이를 이용해 각 메쉬를 Affine변환하여 예측된 현재 프레임을 얻는 전방향 움직임 보상을 제안한다. 이 방법은 컨텐트에 적응적으로 설정된 메쉬 정보를 보내지 않아도 되는 장점이 있다. 실제 비디오 데이터를 이용해 실험한 결과 제안방법이 객관적 및 주관적 화질 평가에서 기존의 블록기반 H.263 방법보다 개선되었음을 알 수 있다.

Abstract

The conventional block-based motion prediction suffers, especially in low bit-rate video application, from shortcomings such as blocking artifacts of motion field and unstable motion estimation. To overcome the deficiency, this paper proposes one method of adopting a new motion compensation scheme based on the irregular triangular mesh structure while keeping the current block-based DCT coding structure of H.263 as much as possible. To represent the reconstructed previous frame using minimal number of control points, the proposed method designs content-adaptive irregular triangular meshes, and then, estimate the motion vector of each control point using the affine transformation-based matching. The predicted current frame is obtained by applying the affine transformation to each triangular mesh. Experiment with the several real video sequences shows improvement both in objective and subjective picture quality over the conventional block-based H.263 method.

I. INTRODUCTION

Image sequence coding consists of two major processes: texture and motion field coding. The quality of reconstructed image not only depends on the texture coding but also strongly on the quality of encoded motion field. It is well known that the motion estimating and encoding framework adopted by most of the current block-based coding methods is by no means sufficient, and the quality of coded motion information becomes critical in low bit rate applications. For more natural and smoother rendition of motion, it is important to encode dense motion

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field.

There are two issues in motion estimating and its encoding; the first one is how to estimate the motion field. The method currently used in MPEG-1, 2 and *H.263 assumes the simplest model of linear motion,* thus excluding more general motions such as rotation, shearing, and zooming, etc. Even though the true motion is different from the model of simple translation, the quality of reconstructed image can be acceptable if the motion-compensated error signal is faithfully coded. In the low-bit rate coding, however, the motion estimation must be carried out very carefully so that the residual prediction error should become trivial simply because not much bit can be spared to encode it. In this regard, the performance of a specific motion model can be compared in terms of its PSNR measure of the motion-compensated residual signal. A proper model of motion and its estimation is a very important task in low bit rate coding.

The second issue is how to encode the motion field. The current block-based approach samples the motion field at a regular block basis blindly of the image content. In many cases, more than one object with different motion can fall on the same unit of motion estimation. Therefore, it is totally irrespective of the local characteristics of the motion field. As a consequence, the block-based method encodes an ambiguous motion vector that may not be equal to any of the true motion vectors of objects found in the unit. It inevitably causes unnaturalness of reconstructed picture unless sufficient bits are consumed for coding of the residual prediction error. In addition, the nature of relatively coarse sampling of block-based approach causes blocking artifacts to the motion field which undoubtedly introduces significant degradation of image quality. One may foresee that reduced block size of motion compensation can avoid this kind of problem, however, it brings in stability problem to the estimated motion field.

To overcome the deficiencies, several coding methods employing more general 3D motion models [2-5] are recently proposed. One of them is the image warping (or, spatial transformation) [1][3] which predicts image by spatially transforming selected meshes located at the reference frame. According to the number of parameters to estimate, several motion models are conceivable. If motion compensation is carried out on a triangular mesh, the affine transformation is used, and for each mesh, 6 parameters are estimated [3]. In case the motion estimation is carried out on a quadrilateral element, then, the bilinear transformation is used with 8 parameters. Note that the amount of motion information encoded is related to the number of control points (vertexes) defining the meshes. Therefore, one important issue in the 3D motion estimations is the optimal design of meshes, that is, how to minimize the number of control points without sacrificing fidelity of the encoded motion field. It is worthwhile to note that all the problems mentioned above are inter-related, and in this regard, consideration of a new motion model calls for the total system-wide optimization in the joint rate-distortion framework especially in low-bit rate coding: if the deficiency in coding aspect of derived motion field surpasses the gain obtained by the new motion model, the system-wide optimization will definitely choose the other approach.

This paper proposes one solution to solve the two issues explained above using motion compensation with content-based meshes. Content-based adaptive representation of an image using meshes is reported quite useful in terms of representation efficiency of the image [1]. This paper is one way of extending the result to coding problem of motion picture. A faithful representation of an image using adaptive meshes implies that boundaries of meshes are likely to coincide well with objects. Therefore, the motion compensation using so derived mesh structure is one straightforward extension of the current block-based coding structure of H.263 to the object-based motion compensation with minimal modification. One strong motivation for this is that the performance of motion compensation is utmost important in low bit rate coding. In this respect, more sophisticated methods of motion compensation justify their practical usefulness even with implication of slight complexity increase. The computational complexity is by no means a trivial issue, however, the continued advent of new computing techniques and their low-cost implementation hint that this is at least not an absolutely imperative requirement.

The intent of this paper is to propose a method of adopting a new motion compensation scheme based on the irregular triangular mesh structure while keeping the current block-based DCT coding structure of H.263 as much as possible. In addition, we like to answer following two questions: one is how much important it is to have an optimum content-based mesh structure in mesh-based motion prediction. The other is, compared to the conventional block-based low-bit rate coding method such as H.263, how much performance improvement one can achieve with the mesh-based motion prediction method. To answer these in both a subjective and an objective manner, we experiment the proposed motion prediction method with several real video sequences in QCIF format to observe that the content-based mesh design is indeed important in order to have successful motion prediction using meshes.

II. BACKGROUND

Traditionally, the mesh-based approach has been popular in the modeling problem of 3D surface in computer graphics [6][7]. Due to its easy adaptability to the content-based processing of images, many techniques based on the mesh modeling of images are being developed for encoding both the natural and synthetic video. The conventional block-based coding such as MPEG-1, 2 defines a basic unit of motion estimation, namely the macroblock, irrespectively of image content. However, the meshes can be defined adaptively to the image content, thus well delineating the object boundaries. The inefficiency of simple overlay of regular meshes on the image [5] in representing the image content properly motivated several researches on optimal mesh design. The hierarchical mesh design [2][4] was developed to efficiently cope with the image objects. More recent approach is the content-based mesh design [8][9] that adaptively modifies meshes to reflect details of image contents by minimizing a cost function. In this paper, we exploit the irregular mesh representation scheme [1] for the motion compensation purpose.

The other issue in the 3D motion prediction is the prediction direction: backward [2] or forward estimation [3][4]. The forward estimation scheme establishes primary control points on a reconstructed previous frame, therefore, it requires the motion estimation to find the corresponding locations of the control points on the current frame. The backward estimation scheme, on the contrary, defines the control points on a current frame and searches their corresponding locations on the reconstructed previous frame. The content-adaptive mesh design can minimize, without degrading the quality of the encoded motion field, both the number of control points and the number of control points. Note that, to obtain the mesh structure, a decoder can execute on the reconstructed previous frame the same placement procedure of control points as the encoder

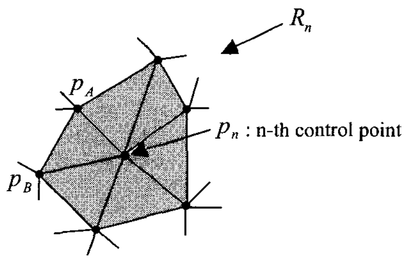


Fig. 1. Region of support (shaded area) of the n-th control point, P_n. It is denoted by R_n.

그림 1. n번째 제어점 P_n에 대한 지지영역(회색영역). R_n으로 표시

without requiring additional information from an encoder. Thus, the forward scheme is more suitable under the irregular mesh structure. For this reason, we choose the forward motion compensation scheme for the temporal prediction.

Here, we introduce some of the notations used in this paper. Suppose a pixel value at location $p=(x, y)$ is denoted by $f(p)$. We define a set of triangular meshes each of which is specified by a set of three control points. Let's assume that there are total N control points in a frame. The region formed by the triangular meshes sharing the n-th control point (denoted by p_n) is called as the region of support for the control point p_n, and it is denoted by R_n as in Fig.1.

Ⅲ. CONTENT-BASED MESH REPRESENTATION AND MOTION COMPENSATION

An encoding method based on the proposed motion prediction is shown in Fig.2. Its overall procedure consists of two steps. The first step is to design the content-adaptive meshes. After an optimum structure of irregular meshes is designed on the reconstructed previous frame, the corresponding new locations of the control points defining each mesh element are searched at half-pel accuracy on the current frame to encode. This is the second step. The motion vector of each control point is transmitted using the same scheme as in H.263. In matching and calculating the final predicted current frame, the motion vectors of pixels inside the mesh are calculated using the affine transformation equation.

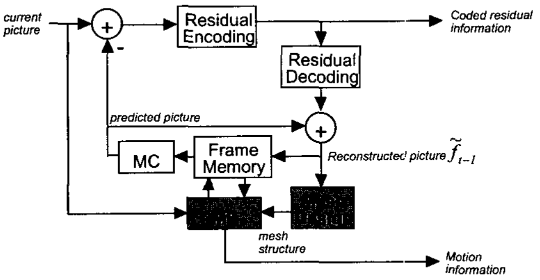


Fig. 2. Forward motion compensation based on content-adaptive mesh design.
그림 2. 컨텐트 적응적 메쉬설계에 기반한 전방향 움직임 보상

1. Content-Based Triangular Mesh Representation

Initially, a certain number of control points are placed uniformly on the image, and subsequently, selected control points are adaptively merged together according to the spatial features of the given frame. It is to generate a minimal number of meshes that can best represent given spatial characteristics of a frame [1]. Inattentive deletion of a control point effective in representing the image detail should be very detrimental to the quality of image representation. To quantify the degree of deterioration, we use ΔA_n, the effectiveness measure of the n-th control point in image representation as defined,

$$\Delta A_n \equiv A_n' - A_n \tag{1}$$

where and A_n' are the representation errors over the region of support R_n respectively before, and after removing the n-th control point p_n. The representation error over R_n before the deletion, which is denoted by A_n is calculated as,

$$A_n = \frac{1}{N_n}\sum_{p\in R_n}\left\{f(p)-\hat{f}_{rep}(p)\right\}^2 \quad n=1,\ldots,N \tag{2}$$

N_n is the number of pixels inside R_n, and $\hat{f}_{rep}(p)$ is the affine interpolation of pixel value at $p=(x, y)$ which is computed as,

$$\hat{f}_{rep}(p) = ax + by + c \tag{3}$$

The parameters (a, b, c) are associated with each mesh, and they are calculated by solving the three linear equations in eq.(4). That is, for the mesh defined by the control points, (p_A, p_B, p_n) in Fig.1, the parameters are obtained by matching the pixel values at the three control points with the values of

$\hat{f}_{rep}(p)$'s calculated at the three control points using eq. (3).

$$
\begin{aligned}
f(p_A) &= ax_A + by_A + c, \quad p_A = (x_A, y_A) \\
f(p_B) &= ax_B + by_B + c, \quad p_B = (x_B, y_B) \\
f(p_n) &= ax_n + by_n + c, \quad p_n = (x_n, y_n)
\end{aligned} \tag{4}
$$

When the n-th control point is removed, the meshes inside the region of support R_n no longer hold triangular mesh structure. We execute re-triangulation of the region in a way to make sure no overlap or crossing of meshes happens as detailed in [1]. Our rationale behind using interpolation of eq.(3) and evaluating the effectiveness measure of eq.(1) is as follows. If a mesh region is fairly homogeneous and does not contain edges, then the pixel values inside the mesh would be well approximated by the simple first-order affine model of eq.(3). Thus, the error $f(p) - \hat{f}_{rep}(p)$ would be very small, and so is the value of ΔA_n. By the way, when the control point is removed and the subsequent re-triangulation procedure sets up a new mesh covering two different regions inside the same mesh, then, the interpolation of eq.(3) would produce large values of error. Therefore, a large value of ΔA_n strongly advocates that the control point p_n is vital in preventing the inhomogeneous meshes from merging together, thus keeping the representation error low.

Equation (1) is iteratively evaluated for each control point and the lesser effective ones are removed one by one in the order of their ineffectiveness until the number of desired control points is reached. The iteration will favor more control points along object boundaries rather than in homogeneous regions. Once desired numbers of control points are all set up, then the motion compensation is performed individually on each mesh. Since we assume a forward prediction scheme, the aforementioned content-based mesh design is applied to the reconstructed previous frame so that the decoder can execute the same operation without any additional information on the mesh structure from the encoder.

2. Motion Compensation based on Mesh

Once the optimum mesh structure is obtained using the reconstructed previous frame, the motion vector of each control point is estimated in two steps as in Fig.3. The first step finds a coarse motion vector of each control point, and the next step refines these estimates. This two-step approach is by no means the optimum. Nevertheless, it is shown that this sub-optimal approach is a good and a practical compromise between the computational cost of estimating the motion vector and the accuracy of the estimated value [2]. The coarse estimation is obtained through the modified block *matching* [2] *of a square block centered* at each control point. The conventional block matching method serves well for this purpose.

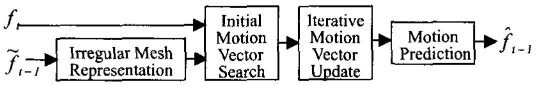


Fig. 3. Overall description of the proposed motion prediction scheme.
그림 3. 제안한 움직임 예측의 전체 개념도

Once a set of initial coarse motion vector estimates is in order for all the control points, then each estimate is iteratively updated one by one. Let $V(p)$ denote the motion vector associated with a pixel located at $p = (x, y)$, and suppose updating the motion vector of the control point p_n. The refinement procedure is to keep perturbing, within the given search range and without changing the motion vectors of neighboring control points, the motion vector of $V(p)$ around its initial coarse estimate until finding the optimum value of motion vector $V(p_n)$ which minimizes the following measure of matching error in eq.(5).

$$
E_n = \sum_{p \in R_n} \left| f_t(p) - \hat{f}_{t-1}(p + V(p)) \right| \tag{5}
$$

To evaluate eq.(5), one needs the motion vector at an arbitrary position $p=(x,y)$ inside R_n. The motion vector $V(p)$ is interpolated using the first order polynomial approximation as,

$$V(p) \equiv (V_X(p), V_Y(p)) \tag{6}$$

$$\text{where } V_X(p) = d_X x + e_X y + c_X$$

$$\text{and } V_Y(p) = d_Y x + e_Y y + c_Y$$

As before, the parameters (d_X, e_X, c_X) and (d_Y, e_Y, c_Y) are obtained by matching $V_X(p)$, $V_Y(p)$ evaluated at the three control points using eq.(6) with the motion vectors of the three control points defining a mesh inside which the pixel $p=(x,y)$ resides. Since the refinement process does not change the motion vectors of all the control points inside R_n except p_n, the calculation of eq.(5) can be easily done. This process of refinement is iteratively performed for all the control points until terminated by the convergence of the control point positions. After the refinement, half-pel motion vector is estimated by measuring the matching errors for the eight neighbor half-pixel positions. Once the motion vectors of all control points are identified, these are encoded in the same manner as specified in H.263. In this way, a minimal change of the codec structure can be pursued.

3. Computational Complexity

The computational complexity of the proposed method is somewhat heavier than that of the conventional 16×16 block-based motion compensation. Especially the computation for content-adaptive placement of meshes is not required by the block-based motion estimation. Although the simple address calculation required for the initial mesh distribution is trivial computation (it can be performed even in advance), the repeated evaluation of the effectiveness measure is somewhat the opposite: it requires solving the 3X3 first-order linear equation of eq.(4) for each mesh, three multiplications for each pixel inside the mesh, and finally evaluation of eq.(2). This is computed for each node under consideration of removal, and finally this whole process is repeated until a desired number of control points are finalized. Although it might seem to be an extra burden over the conventional block-based approach, the added feature of the content-based affine motion model can bring far better prediction performance, consequentially leading to more natural and less blocky motion rendition.

The computation for motion compensation is similar to that of the block-based motion compensation except the additional amount to compute the motion vector of each pixel using eq.(6). This is something to pay for object-based motion compensation. Note that effective motion compensation is becoming more important due to the limited bit budget for the residual texture coding especially in low bit rate coding. Furthermore there are many applications that can justify better motion model and its associated motion compensation even with implication of complexity increase.

Ⅳ. EXPERIMENT AND DISCUSSION

To investigate the performance of the proposed method, temporal prediction error is compared in terms of PSNR with that of the conventional block-based motion compensation of H.263. The experiment is carried out using four real video sequences in QCIF format (176 by 144) - the mother & daughter, the clair, the suzie, and the miss america. The number of skip frame is 3. The first 100 frames for each sequence are used. In the experiment, we modify the Telenor H.263 software codec [10] to accommodate the proposed motion estimation and compensation scheme. The other parts including the texture coding are intact. Note that a different motion model will change the statistics of estimated motion vector, therefore a new VLC table customized to the new model will definitely help the overall coding performance. In the experiment, however, we do not endeavor such customization at least just for now. Therefore, overall coding performance has room for further refinement.

1. Effect of Content-based Mesh Design on Mesh Representation

As the first step, we evaluate how much the content-based mesh design can affect the performance of mesh representation and subsequently the motion prediction. To check the effectiveness of content-based mesh design, a predetermined number of control points are set up without considering the image content, and its result is used for reference in comparison. This is denoted by regular mesh: the meshes are of the same size and uniformly cover an entire picture irrespectively of image details. Fig.4(a) shows this mesh structure where the horizontal (and the vertical) length of the triangular mesh (call it as the mesh-size) is 16. Total 120 control points are found. Note the meshes are coarse.

To find the irregular mesh structure optimal to the image content, we successively delete control points - the least effective one first in reducing the representation error until a predetermined number of control points, N is reached. N denotes the desired number of control points in one frame. Large N indicates faithful approximation of the given frame, however, in due course, large amount of motion information to send. We choose N=99 because it corresponds to the same amount of motion information as the H.263 with the advanced prediction mode off (note there are 99 macroblocks in one frame of QCIF size). In the experiment, we do not consider the (secondary) effect of motion vector coding on amount of motion information. Note that an exact amount of motion information is not necessarily proportional to the number of macroblocks or control points—it depends on several inter-related factors such as correlation between estimated motion vector, estimation method, and motion vector coding. Therefore, one cannot obtain exact measure of number of bits spent for motion vector information simply from the number of control points. However, we roughly assume that similar statistical behavior holds as in H.263 and we use same motion vector coding method as in H.263. Customized VLC table for motion vector is necessary in this case for more sophisticated system optimization. An accurate comparison calls for more extensive experiment which also takes into account the different amount of motion information in finding proper number N , which is one of the next steps to extend the result in this paper.

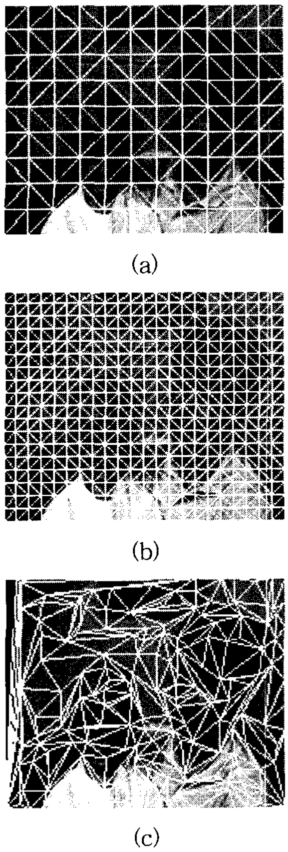
Table 1. PSNR Comparison of Mesh Representation Error.
표 1. 메쉬 표현오류에 대한 PSNR비교

[dB]

Image Sequence Coding Method*	Mother & Daughter	Clair	Suzie	Miss America
R120	19.99	17.60	21.25	23.19
R437	24.17	22.16	26.16	28.40
IR99	25.96	25.11	27.01	30.11

*R120 (Regular Meshes with N=120); R437 (Regular Meshes with N=437); IR99 (Irregular Meshes with N=99).

To find the best 99 control points in one frame, we started initially with 437 of them and successively reduced the number to 99. Fig.4(b) shows the regular meshes with 437 control points (mesh-size=8), and the Fig.4(c) shows the resultant 99 of them with irregularly-shaped meshes. As shown in Fig.4(c), the irregular meshes are smaller and the control points are well concentrated in regions containing salient features such as edges. Thus, the subjective quality of the reconstructed images is significantly improved in these regions compared with the regular mesh case.



(a)

(b)

(c)

Fig. 4. Sample results of mesh design with the "mother and daughter" sequence; (a) Regular Mesh (N=120). (b) Regular Mesh (N =437). (c) Irregular Mesh (N=99).

그림 4. "mother and daughter" 영상에 대한 메쉬설계의 실례; (a) 정형메쉬 (N=120). (b) 정형메쉬 (N =437). (c) 비정형메쉬 (N=99).

Table 1 shows the representation errors of eq.(2) averaged over the 100 frames in PSNR, and it verifies that eq.(2) is indeed effective as a criterion in deleting control points. The PSNR comparison itself is not a direct indication of coding performance, however, it circumstantiates the importance of the content-based mesh design. As quite expected, the irregular mesh structure (IR99) improves by more than 4dB than the regular one (R120), therefore, one can see that the irregular mesh representation scheme outperforms the regular one even with a smaller number of control points. This observation re-iterates the importance of the content-adaptive mesh design. It is even more interesting to see that the irregular structure (IR99) has better representation performance than the regular meshes with 437 control points (R437) even though the IR99 structures are obtained by successively deleting the control points of R437. This is due to the re-triangulation of the regions after the center control points are removed. It suggests that more refined re-triangulation is worthwhile to investigate further in order to improve the performance of mesh representation.

2. Effect of Content-based Mesh Design on Motion Prediction

Now the mesh structures designed in Fig.4(c) are used in motion prediction; the PSNR's of temporal prediction error are averaged over 100 frames and the results are compared in Table 2 in which one can observe that the performance of motion prediction depends on the quality of mesh design. Although similar numbers of control points are used, the motion prediction PSNR differs as much as 0.43 dB depending on the mesh structure. This is actually what one can foresee if the Fig.4(a) and Fig.4(c) are scrutinized: more mesh elements are located near edges to represent the objet boundary more faithfully, while less mesh elements (therefore, larger meshes) over the smooth area. Therefore, the irregular mesh structure gives better motion prediction performance. In fact, it is what inspires the mesh-based motion compensation as a promising tool in the object-based coding.

Table 2. PSNR Comparison of Motion Prediction Error.

표 2. 움직임예측오류에 대한 PSNR비교

[dB]

Image Sequence / Coding Method	Mother & Daughter	Clair	Suzie	Miss America
R120	35.64	38.34	30.49	38.49
H.263	36.12	37.43	30.70	37.98
IR99	36.49	39.67	30.85	39.65

Now, the performance of motion prediction with the irregular mesh structure is compared with the conventional block-based coding method of H.263.

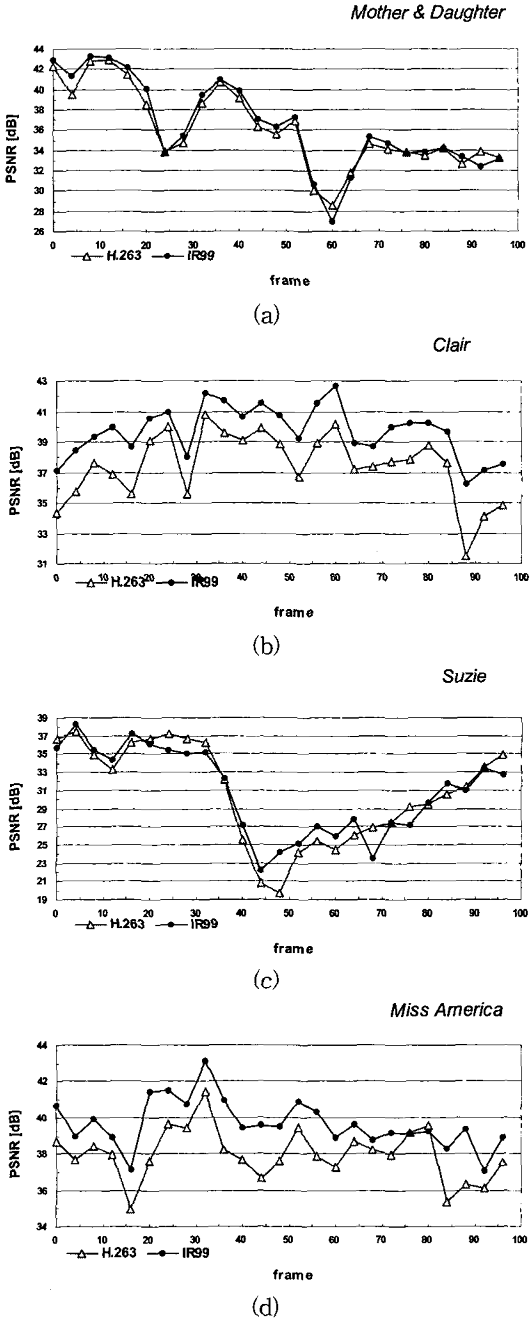


Fig. 5. Comparison of motion prediction in PSNR; (a) Mother & Daughter. (b) Clair. (c) Suzie. (d) Miss America.

그림 5. 움직임예측에 대한 PSNR 비교 (a) Mother & Daughter. (b) Clair. (c) Suzie. (d) Miss America

We turn the advanced prediction mode off. The averaged motion compensation PSNR of 100 frames is also tabulated in Table 2. The motion prediction with irregular meshes (IR99) shows consistent improvement over the H.263. In case of the clair sequence, the proposed method has 2.24 dB improvement over the H.263. Therefore, one can conclude that with similar amount of motion vector information, the proposed scheme achieves better motion compensation. Furthermore, the proposed scheme reduces blocking artifacts in the motion field, and thus gives superior visual quality. It is interesting to see the regular mesh structure (R120) achieves better motion prediction than the conventional block-based method of H.263 in the mother and daughter sequence.

Note that the proposed irregular mesh-based motion compensation can be easily employed by the conventional block-based codec such as H.263 if only the motion compensation part is substituted by the proposed method. The motion compensated error signal can be coded using the conventional block-based DCT or some other coding method as wished. The full implementation of this kind of codec and its evaluation is useful step of further investigation. In a practical situation of a very low-bit rate, the poor quality of a reconstructed frame may hinder proper establishment of meshes faithful to object boundaries as intended by the proposed method. Therefore, one needs further research to evaluate the efficiency of the suggested effectiveness measure function for content-based mesh design on images having a very poor quality

V.CONCLUSION

In this paper, we have introduced irregular mesh-based motion compensation method to apply for the low bit rate coding of video. We have shown that the content-based mesh design is important in enhancing the performance of motion prediction. For the content-based mesh design, we have successively removed control points adaptively to the image contents. Once the content-based mesh structure is obtained, the current picture is predicted based on image warping of the previous picture. Since the mesh structure is designed using the reconstructed previous picture, there is no need to send the information concerning the mesh structure, thus no additional overhead due to the proposed motion compensation method. The decoder can carry out the same mesh design using the reconstructed previous picture stored in the frame buffer. The experiments with the irregular mesh design have shown that approximately 0.2 ~ 0.4dB of motion compensation PSNR improvement can be achieved compared with the conventional method based on the regular meshes. Compared to the block-based approach of H.263, we have observed also 0.15~ 0.37dB of motion compensation PSNR improvement. Since the meshes can be defined on an object basis, the proposed method is well suited to the object-based image processing which most of the image coding applications specify as an important functional requirement.

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