Robust Watermarking of Mobile Video Resistant against Barrel Distortion

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Abstract: In head mounted display (HMD), in order to cancel pincushion distortion, the images displayed on the mobile should be pre-warped with barrel distortion. The copyright of the mobile video should be verified on both the original view and the pre-warped virtual view. A robust watermarking resistant against barrel distortion for HMDs is proposed in this paper. Watermark mask is embedded into image in consideration of imperceptibility and robustness of watermarking. In order to detect watermark from the pre-warped image with barrel distortion, an estimation method of the barrel distortion is proposed for HMDs. Then, the same warp is enforced on the embedded watermark mask with the estimated parameters of barrel distortion. The correlation between the warped watermark and the pre-warped image is computed to predicate the existence of watermark. As shown in experimental results, watermark of mobile video can be detected not only from the original views, but also from the pre-warped virtual view. It also shows that the proposed scheme is resistant against combined barrel distortion and common post-processing, such as JPEG compression.

Keywords: mobile video; HMD with mobile; robust watermarking

I. INTRODUCTION

Mobile consumers expect a faster broadband connection to ubiquitous consumption of video contents and services [1-5]. Benefiting from the properties of high-quality display, inexpensive, and compact for mobile devices, head mounted displays (HMDs) have motivated consumers' interest for immersive video, image, and gaming [6]. In HMD, a mobile is placed in front of each eye, and wide-angle optics are used to bring the mobile video into focus, as shown in Fig.1. Unfortunately, wide-angle optics introduce spatial *pincushion distortion* into the video for viewer. In order to cancel pincushion distortion, the video to be displayed on mobile must be pre-warped with *barrel distortion* beforehand. Because the pirate might record and misuse the mobile video for this pre-warped view, copy protection and copyright problems also exist and should be solved for mobile video in HMDs. In this aspect, these newly emerged technologies will bring a serious necessity for the copyright and copy protection problems in the future.

Watermarking is a process of embedding information (watermark) into digital multimedia (image, video, et al), so that the watermark can be detected for a variety of purposes including copy protection, copyright management [7-9]. Robustness, which is an essential characteristic of watermarking, indicates the resistibility to accidental and intentional attacks. These attacks can be classified as common signal-processing attacks and de-synchronization attacks. Common signal-processing attacks (including low-pass filtering, noising, JPEG compression, *et al*) reduce the energy of watermarking rather than introducing synchronization errors. Correspondingly, de-synchronization attacks (including rotation, scaling, and translation transforms, affine transforms, *et al*) reduce watermark energy and introduce the synchronization errors between the encoder and the decoder.

Recently, some new-fashioned de-synchronization attacks to video watermarking have increasingly emerged with the development of novel 3D and free-view video technology as introduced in [10-13]. Subsequently, some robust watermarking schemes resistant against such new-fashioned de-synchronization attacks, are proposed for content protection in these novel multimedia application [10-12].

Many of 3D video are distributed in image-based representations, with their advances of low cost. The copy and copyright protection for image-based 3D video is a new challenge for watermarking systems. The depth-image-based rendering (DIBR) 3D video consists of the depth image and the center image generated by the content provider, which is one of the image-based 3D video. Both left-eye and right-eye images are rendered from the depth image and the center image in the DIBR 3D system. In such a scenario, the watermark of 3D video should be detected not only from the center image, but also from rendered images including both left-eye and right-eye images. Lin *et al* propose a novel watermarking system to counter the copy and copyright problem for DIBR 3D video in [12].

Free-View Television (FTV) has emerged as a new entrainment equipment, which can bring immersive and realistic feelings for TV viewers. In this system, the TV-viewer can watch a virtual arbitrary scene generated via image based rendering (IBR) from a number of real views. Because the TV-viewer can record and misuse a video for this arbitrarily selected view, some watermarking systems are proposed to solve copyright protection problems of FTV [10, 11]. In these watermarking systems, watermark information can be detected not only from the original views, but also from any virtual views.

Similar to newly emerged DIBR-based 3D images and FTV, watermarking should be an effective solution for the copyright problem of mobile video for HMDs. Few watermarking schemes are proposed to counteract barrel distortion for HMDs. Therefore, we proposed a robust watermarking scheme for HMDs in this paper. In order to detect watermark from the pre-warped image with barrel distortion in HMDs, an estimation method of the barrel distortion is proposed, firstly. Then, the same warp is enforced on the embedded watermark mask with the estimated parameters of barrel distortion. Correlation between the warped watermark and the pre-warped image is computed to predicate that the watermark is or isn't existent in the image.

In Section II, we propose a parameter estimation method of barrel distortion. The proposed watermarking scheme of mobile video is presented in Section III. Experimental results of the watermarking scheme for mobile video is given in Section IV. Finally, Section V conclusions the paper.

This paper detects watermark from the warped image by barrel distortion, an estimation methods of the barrel distortion are proposed for HMDs.

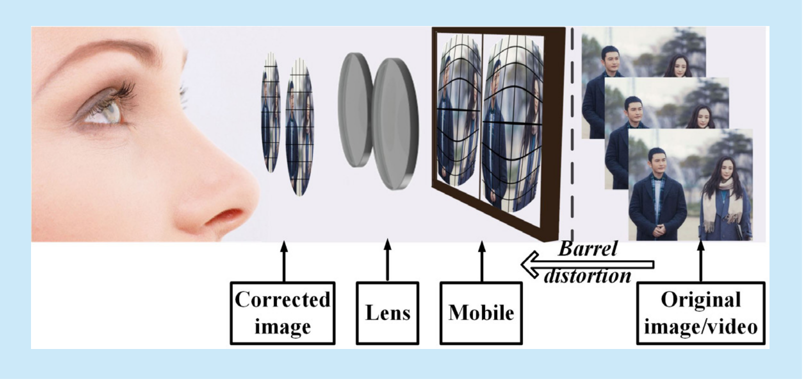


Fig.1 *A low-cost immersive HMD with a mobile*

II. PARAMETER ESTIMATION OF BARREL DISTORTION

2.1 Mathematical Model of Barrel Distortion

The magnification of the lens decreases with axial distance will cause each image point to move radially towards the center of the image. This results in the barrel distortion [14]. The barrel distortion is often modeled by Taylor expansion:

$$\dot{r} = r(1 + k_1 r^2 + k_2 r^4 + \ldots + k_i r^{2i} + \ldots.) \quad (1)$$

where $\dot{r}$ and r are the distances from the center of distortion in the undistorted and distorted images, respectively. k_i is the radial distortion coefficient. The "perfect" approximation would be a polynomial of infinite degree, however, it is not needed. In [15], two coefficients are used to model barrel distortion of wider angle lenses:

$$\dot{r} = r(1 + k_1 r^2 + k_2 r^4) \quad (2)$$

where k_1 controls the general behavior of the distortion. When the distortion is so severe that the 1st order approximation can't give a good enough solution, k_2 will be adjusted.

2.2 Parameter Estimation

As shown in Fig.2, an image is warped with barrel distortion by using of (2). Firstly, we select three boundary points (denoted with P_1, P_2, and P_3) in the warped image. Polar coordinates of the three distorted boundary points are (r_1, θ_1), (r_2, θ_2), and (r_3, θ_3), respectively. Secondly, we compute polar coordinates of undistorted boundary points (denoted with $\dot{P}_1$, $\dot{P}_2$, and $\dot{P}_3$). They are $(\dot{r}_1, \theta_1)$, $(\dot{r}_2, \theta_2)$, and $(\dot{r}_3, \theta_3)$, respectively.

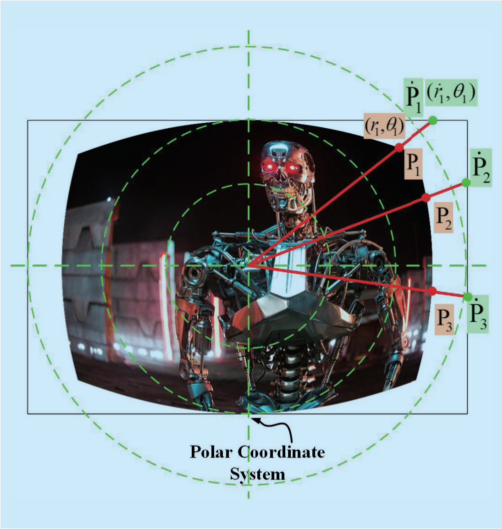


Fig.2 *A warped image with barrel distortion*

According to (2), we can get:

$$\begin{cases} r_1(1 + k_1 r_1^2 + k_2 r_1^4)s = \dot{r}_1 \\ r_2(1 + k_1 r_2^2 + k_2 r_2^4)s = \dot{r}_2 \\ r_3(1 + k_1 r_3^2 + k_2 r_3^4)s = \dot{r}_3 \end{cases} \quad (3)$$

where s is a scale factor used to zoom the warped image to the size of the original image. After s is eliminated, obtaining:

$$\begin{cases} (r_2^3 \dot{r}_1 - r_1^3 \dot{r}_2)k_1 + (r_2^5 \dot{r}_1 - r_1^5 \dot{r}_2)k_2 = r_1 \dot{r}_2 - r_2 \dot{r}_1 \\ (r_3^3 \dot{r}_1 - r_1^3 \dot{r}_3)k_1 + (r_3^5 \dot{r}_1 - r_1^5 \dot{r}_3)k_2 = r_1 \dot{r}_3 - r_3 \dot{r}_1 \end{cases} \quad (4)$$

We define:

$$A = \begin{bmatrix} r_2^3 \dot{r}_1 - r_1^3 \dot{r}_2 & r_2^5 \dot{r}_1 - r_1^5 \dot{r}_2 \\ r_3^3 \dot{r}_1 - r_1^3 \dot{r}_3 & r_3^5 \dot{r}_1 - r_1^5 \dot{r}_3 \end{bmatrix}, \quad (5)$$

$$Z = \begin{bmatrix} r_1 \dot{r}_2 - r_2 \dot{r}_1 \\ r_1 \dot{r}_3 - r_3 \dot{r}_1 \end{bmatrix}, \quad (6)$$

$$k = \begin{bmatrix} k_1 \\ k_2 \end{bmatrix}. \quad (7)$$

Then,

$$Ak = Z \quad (8)$$

Therefore, parameters of barrel distortion can be estimated as:

$$\widehat{k} = A^{-1} Z \quad (9)$$

There are many distorted boundary points in the warped image, therefore we can select more groups of distorted boundary points to obtain more estimations of $\widehat{k}$. Finally, mean of such $\widehat{k}$ is set as the parameter of barrel distortion.

III. WATERMARKING SCHEME

There are two strategies to detect watermark from the warped image of HMD. 1), do geometric correction on the warped image, then compute the correlation between the watermark mask and the corrected image to predicate the existence of watermark. 2), estimate the parameters of barrel distortion, then warp watermark mask with the estimated parameters. Finally, the correlation between warped watermark mask and warped image is computed to predicate the existence of watermark.

However, there are two shortcomings for the first strategy. Firstly, geometric correction for the barrel distortion is still an open problem. Secondly, geometric correction is, once again, a geometric attack for the watermark energy in the watermarked image. Therefore, the second watermarking strategy is adopted in this paper.

Framework of our proposed robust watermarking scheme for HMD is shown in Fig.3. It consists of watermarking embedding and detection. In the watermarking detection phase, distortion coefficients $\widehat{k}$ is estimated from the image of HMD, firstly. Then, the same warp is enforced on the watermark mask with the estimated parameters of barrel distortion. Correlation between warped image of HMD and warped watermark mask is computed to predicate that the watermark is or isn't existent in the image.

Traditional watermarking strategies (e.g., spread spectrum [16] and quantization index modulation [17]) can be integrated into our proposed watermarking framework to construct a robust watermarking scheme for HMD. Without loss of generality, the improved spread spectrum (ISS) method [18] is considered in this work. Below we present a robust HDM watermarking scheme within the framework.

In watermarking embedding phase, the ISS-based method is used to embed watermark into original image. The watermarking embedding procedure includes:

1) Generate a watermark sequence W_1, which is a binary pseudo random sequence. The element of sequence W_1 takes values from {-1, 1}, its length is N, and the mean of the sequence W_1 is zero.

2) In a pre-selected zigzag scan, the 1-D sequence W_1 is converted into a 2-D sequence W_2. Intermediate frequency DCT coefficients are not changed; other coefficients are changed as zero;

3) IDCT (inverse discrete cosine transform) is implemented on W_2 to produce W;

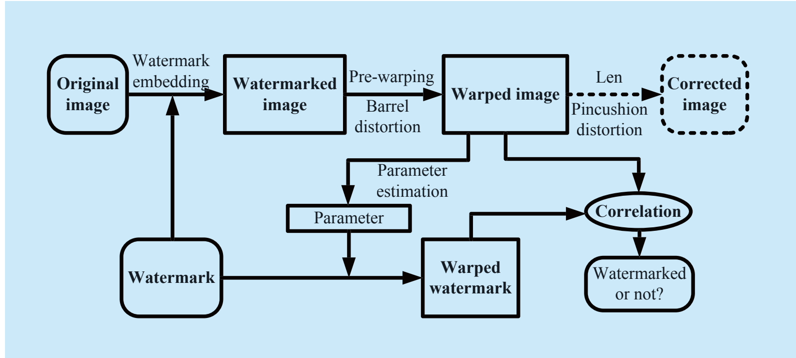


Fig.3 *The framework of the proposed watermarking scheme*

4) Using formula (10), the final watermark mask W is embedded into the original image I to produce the watermarked image I^*:

$$I^* = I + (\alpha - x)W, \tag{10}$$

where α is the watermarking strength which controls the distortion level. x is set as:

$$x \triangleq \langle I, W \rangle / \|W\| . \tag{11}$$

After the four steps, the watermark W_1 is embedded into the intermediate frequency DCT domain of the image.

As shown in Fig.3, the watermarking detection procedure is summarized as follows:

1) Regenerate the same W_1 as that in watermarking embedding phase.

2) 1D sequence W_1 is converted into a 2D sequence W_2 in a pre-selected zigzag scan (e.g., intermediate frequency DCT coefficients); other coefficients are changed to zero;

3) Apply IDCT to W_2 to produce W;

4) According to (9), distortion coefficients $\widehat{k}$ of barrel distortion are estimated from the warped image I_d using the proposed parameter estimation method, which has been introduced in Section II;

5) According to (2), watermark mask W is distorted to obtain barrel distorted watermark mask $\dot{W}$ with the estimated parameter $\widehat{k}$;

6) Compute the correlation between $\dot{W}$ and I_d, $corr(I_d, \dot{W})$. If $corr(I_d, \dot{W}) > T$, the warped image has been watermarked; vice versa. $corr(\cdot)$ is used to compute the correlation coefficient of two vectors and T is a threshold.

IV. EXPERIMENTS

In order to evaluate the performance of the proposed watermarking scheme, we build a database[1] with 440 images from 25 films. The size of every image in the database is 960×640 pixels. All experiments are conducted on this database, and all values of experiment results are the means of 440 images. Some example images in the database are shown in Fig. 4.

1 Database can be found at https://sites.google.com/site/watermarkforhmd

4.1 Watermark Imperceptibility

PSNR (peak signal-to-noise ratio) [19, 20] between the original image and watermarked image is used to measure watermark imperceptibility. The correlation response $Corr$ between $\dot{W}$ and warped image I_d is used as the criterion for watermark robustness.

Generally, the watermark imperceptibility can be controlled by α, which is the watermarking strength. If α is too small, the robustness of the watermarking scheme decreases, and the watermark imperceptibility increases; whereas if α is too large, the imperceptibility decreases, and the robustness increases. Fig.5 shows the relationship between imperceptibility (measured by PSNR value) and robustness (measured by $Corr$ value).

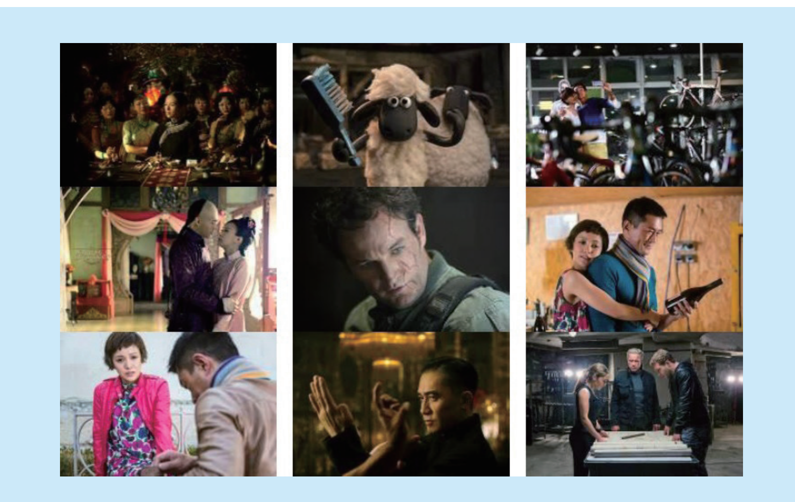


Fig.4 *Some example images in the experimental database*

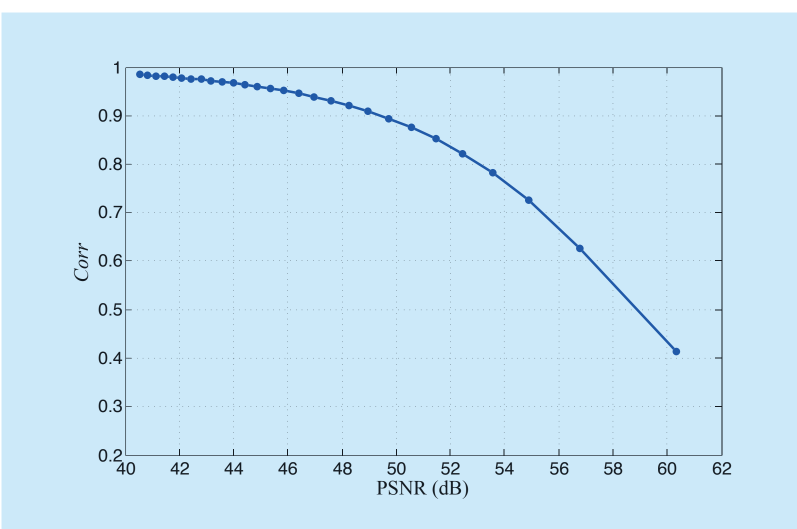


Fig.5 *The relation between PSNR and correlation response*

4.2 Watermark Robustness

We use 199 private keys, which are different to the key used in watermark embedding, as seed to randomly generated 199 watermarks. In addition, the same key used in watermark embedding is used to generate 1 watermark. These 200 watermarks are embedded into 440 images of the above mentioned database. Experimental results are shown in Fig. 7. In Fig. 7(a), the average PSNR values between the original and watermarked images is 40.5dB and it is 49.7dB in Fig. 7(b). Fig. 7 shows the correlation response of the watermark detector to 200 watermarks, only one watermark matches the watermark generated with the correct key. It shows that the false positive response rates of the proposed watermarking scheme is very low.

To evaluate the robustness of proposed watermarking against barrel distortion for HMDs, we use 9 different level distortion coefficients k to attack the watermarked images. These coefficients include [0.3, 0.4], [0.3, 0.6], [0.3, 0.8], [0.6, 0.4], [0.6, 0.6], [0.9, 0.8], [0.9, 0.4], [0.9, 0.6], and [0.9, 0.8].The robustness tests of the 9 different level distortion coefficients evaluated with the average correlation response $Corr$ of 440 images are shown in Fig. 8. Fig. 8 also shows the comparison between the proposed scheme and the ISS watermarking scheme [18]. In Fig. 8, both the average PSNR values of the proposed watermarking scheme and ISS scheme are 40.5dB. As shown in Fig. 8, the proposed watermarking scheme is resistant against barrel distortion for HMDs. Furthermore, the robustness against barrel distortion of the proposed scheme is better than that of ISS watermarking scheme. ISS is one of the most successful and classical watermarking schemes which is robust against many kinds of attacks including noising, filtering, compressing, printing and scanning, cropping, scaling, and *et al*. However, ISS is not resistant against barrel warp. Since it introduces the synchronization errors between encoder and decoder. In the proposed watermarking scheme, the same warp is enforced on the watermark mask with the estimated parameters of barrel distortion. Therefore, synchronization errors can be avoided in the proposed scheme.

The robustness of the proposed watermarking scheme against JPEG compression attacks is also evaluated. Experimental results are shown in Fig. 9, in which the JPEG quality coefficients include 30, 50, and 90. As shown

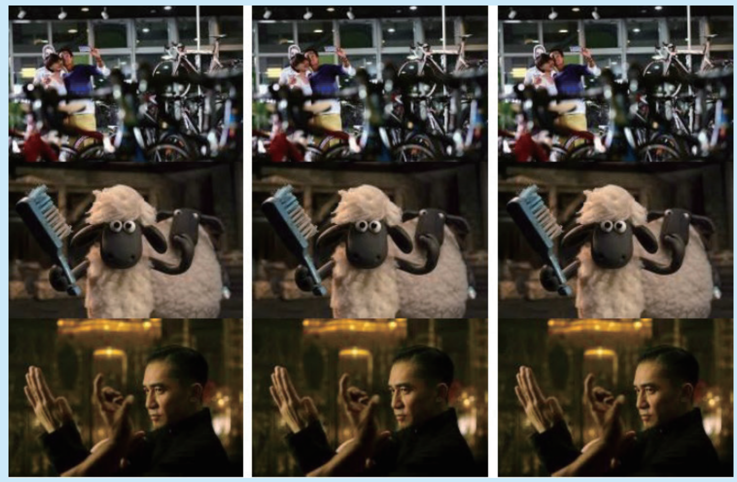
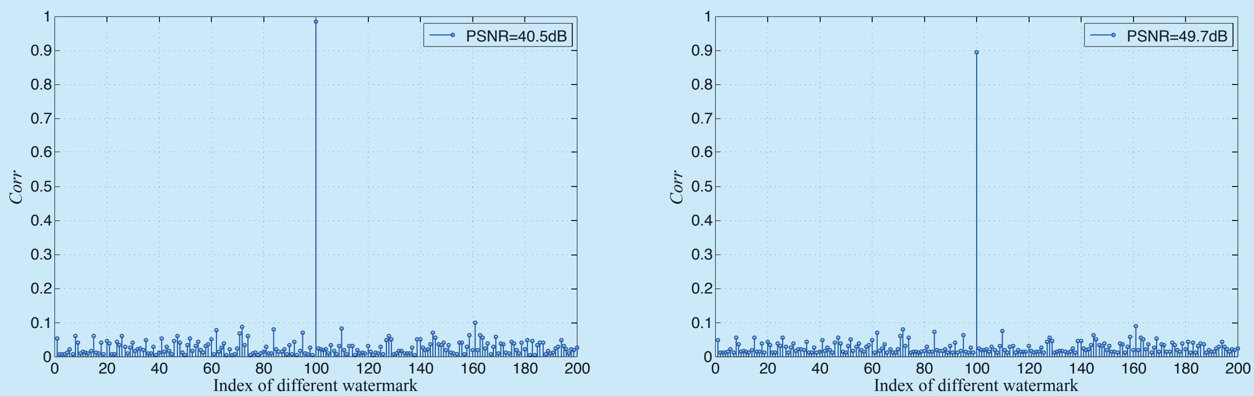


Fig.6 *Watermark imperceptibility. (a) Original images. (b) Watermarked images with PSNR=49.7dB. (c) Watermarked images with PSNR=40.5dB*



(a) PSNR=40.5dB (b) PSNR=49.7dB

Fig.7 *Correlation responses of the watermark detector to 199 random watermarks and 1 correct watermark*

Fig.8 *Watermarking robustness experiments against 9 different level barrel distortions and the comparison with ISS scheme*

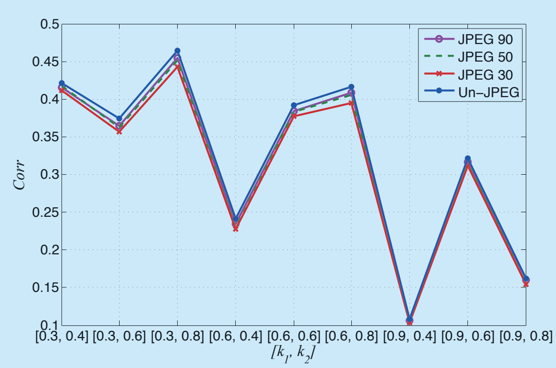


Fig.9 *Watermarking robustness experiments against the combined attack of barrel distortion and JPEG compression*

in Fig. 9, the proposed watermarking scheme of mobile video can resist the combined attack of barrel distortion and JPEG compression.

V. CONLUSION

Few mobile video watermarking schemes are proposed to counteract barrel distortion for HMDs. A robust watermarking scheme of mobile video is proposed for HMDs, in this paper. In order to detect watermark from the warped image by barrel distortion, an estimation methods of the barrel distortion are proposed for HMDs. Then, the same warp are carried out on the embedded watermark with the estimated parameters of barrel distortion. The correlation of pre-warped image and warped watermark is computed to predicate that the watermark is or isn't existent in the image. Experimental results show that our watermarking scheme of mobile video for HMDs is effective. The watermark can be detected not only from the original views, but also from the pre-warped virtual view. The proposed scheme can resist the combined attacks of JPEG compression and barrel distortion.

ACKNOWLEDGEMENTS

This work was partially supported by Fundamental Research Funds for the Central Universities of China (2016JKF01203) and National Natural Science Foundation of China (61401408, 61402484, and 61502160).

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