THE EFFICIENCY OF VIEW SYNTHESIS PREDICTION FOR 3D VIDEO CODING: A SPECTRAL DOMAIN ANALYSIS

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ABSTRACT

We study the coding efficiency of view synthesis prediction (VSP) in 3D video coding. Our spectral domain analysis relates the power spectral density (PSD) of the VSP prediction error to the probability density function (pdf) of the warping error. Our analysis takes into account the warping error induced by (i) depth coding and (ii) rounding error at integer-pel, half-pel and quarter-pel warping accuracy. We also study the interaction between depth coding error and warping accuracy. Our model suggests that the coding gain with using higher warping accuracy diminishes as the depth coding error increases. Our analysis results are validated with empirical data.

Index Terms— view synthesis prediction, disparity error, warping accuracy, power spectral density

1. INTRODUCTION

New coding standards have been developed by Moving Picture Experts Group (MPEG) and Joint Collaborative Team on 3D Video Coding (JCT-3V) targeting at 3D video content [1–4]. These standards are primarily designed for 3D video format known as multiview video plus depth (MVD) [5] with 1D-parallel camera arrangement. With the MVD format, depth-image-based rendering (DIBR) [6] could be employed to generate virtual views among transmitted/coded views for stereoscopic and autostereoscopic displays. The process of generating virtual views is called view synthesis [7].

One of the important new coding tools in 3D video coding standards is *view synthesis prediction* (VSP) [8,9]. In VSP, a synthesized virtual view is utilized as a predictor for predictive coding of the texture image. In particular, with the geometry information provided by depth map, texture picture of a neighboring coded view (reference view) is warped to current coding view (target view). The coding efficiency of VSP depends on the accuracy of the warping. The accuracy of warping in turns depends on several factors. One factor is the quality of the depth map, as depth map usually contains error due to lossy depth compression. Another factor is the accuracy of warping, as integer-pel, half-pel or quarter-pel accuracy can be used for warping. More accurate warping in general improves coding performance but requires more computation.

In this work, we study the effect of depth map error and warping accuracy on the prediction efficiency of VSP. We use the analysis tools developed for conventional motion compensated coding [10] to analyze VSP in 3D video coding. In particular, our analysis relates the power spectral density (PSD) of the VSP prediction error to the probability density function (pdf) of the warping error. We derive the pdf of the warping error due to depth coding and warping accuracy. Our analysis suggests that the prediction gain with using higher warping accuracy diminishes as the depth coding error increases. In particular, above certain depth quantization parameters (Depth QP), the coding improvement of using half-pel and quarter-pel warping accuracy is small. The analysis is validated with empirical data.

Some previous efforts have studied the effect of depth distortion on the quality of the synthesis view, and the analysis for bit allocation between texture and depth images. Kim *et al.* [11] proposed to estimate the distortion of rendered view by spatial correlation coefficient for depth coding optimization and simplify it by first order autoregressive model. Zhang *et al.* [12] and Chung *et al.* [13] proposed to estimate rendering distortion in spectral domain with empirical depth distortion for depth compression. Velisavljevic *et al.* [14] derived a model for synthesis distortion as a function of view location for bit allocation. Fang and Cheung *et al.* [15] proposed an analytical model for synthesized view quality. They decoupled the estimation into texture- and depth-error induced distortion, and used PSD for rendering distortion estimation. Xiang and Cheung *et al.* [16] proposed a model to estimate the depth error induced synthesis distortion taking camera configuration into account. However, there has not been any effort in theoretical analysis of VSP and its prediction efficiency under different depth error and warping accuracy.

The rest of this paper is organized as follows. Section 2 presents the state-of-the-art VSP technique in standard. Section 3 presents the spectral domain analysis of VSP error. Then the pdf of the warping error taking depth coding distortion and warping accuracy into account is derived in Section 4. Experimental results and discussion are provided in section 5 and section 6 concludes this paper.

2. VIEW SYNTHESIS PREDICTION IN 3D-HEVC

The way of using texture and depth of a same neighboring view for VSP picture generation is called forward warping VSP (FVSP), i.e., the disparity vector is forward directed from reference view to target view [17]. On the other hand, the case using texture of reference view and depth of target view is called backward warping VSP (BVSP) [18]. In BVSP, disparity vector of every texture sample is converted from its colocated depth pixel and then utilized to fetch texture pixels from reference view, thus provides capability of parallel processing and free from the hole-filling process [7].

For conventional BVSP, the depth picture should be coded prior to texture picture within the same view to provide geometry information for depth-to-disparity conversion. However, in HEVC based 3D video coding standard, i.e., 3D-HEVC, texture picture of each view is always coded first [4, 19].

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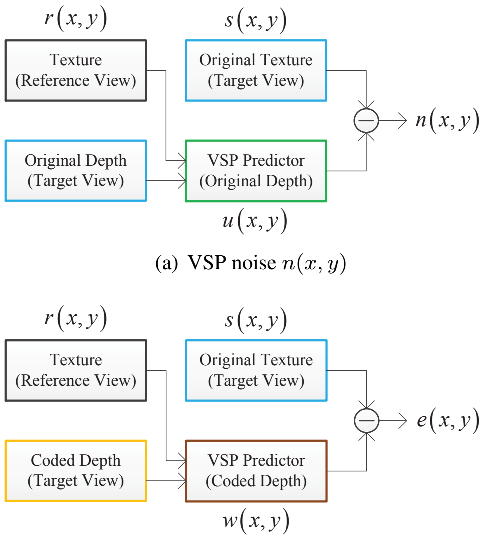


(a) VSP noise $n(x, y)$

(b) VSP error $e(x, y)$

Fig. 1. (a) VSP noise and (b) VSP error.

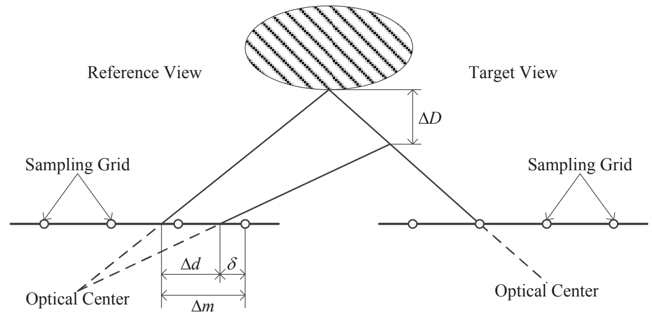


Fig. 2. Warping under distorted disparity. The overall disparity error Δm is the sum of depth coding induced distortion Δd and rounding induced distortion δ.

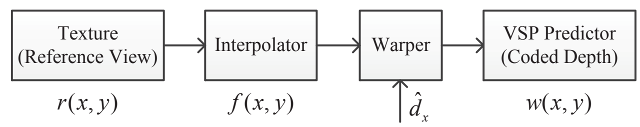


Fig. 3. Generation of VSP predictor $w(x, y)$.

So the adopted BVSP framework in 3D-HEVC approximates the conventional BVSP by fetching a virtual depth block from depth of reference view (already coded) by a disparity vector which is retrieved from spatial neighboring texture blocks (NBDV) [20]. The virtual depth block is then divided into 8x4 or 4x8 sub-blocks based on its gradient. Corresponding texture block in reference view is then warped to target view by disparity converted from maximum of four corner pixels of each depth sub-block.

We assume that with NBDV, the virtual depth block fetched from reference view would be accurate approximation of the corresponding depth block of current texture block in target view.

3. SPECTRAL MODEL FOR VSP ERROR ANALYSIS

Fig. 1 illustrates the BVSP process. Texture picture at the reference view $r(x, y)$ is warped to the target view position to generate the VSP predictor $u(x, y)$, which is used to predict the texture picture at the target view $s(x, y)$. In Fig. 1(a) we consider the case when the "true" disparity is used in the warping, and this generates VSP predictor $u(x, y)$ and results in prediction noise $n(x, y)$. In Fig. 1(b) we consider the case when the distorted disparity is used in the warping, and this generates a degraded VSP predictor $w(x, y)$ and results in prediction error $e(x, y)$. We consider disparity distortion induced by depth coding and disparity rounding in this work.

As shown in Fig. 1(a), when generating VSP predictor, even when the true disparity is used, i.e., the depth of target view is original and there is no rounding error, there still exists difference between the generated predictor $u(x, y)$ and original texture of target view $s(x, y)$, such difference is named as "VSP noise" $n(x, y)$ in this paper. In general, VSP noise contains inter-view difference introduced by reference texture coding distortion, non-Lambertian view-dependent effects, occlusion or any aspect of geometry compensation [21], etc. In spatial domain, $n(x, y)$ can be described as

$$n(x, y) = s(x, y) - u(x, y) = s(x, y) - r(x - d_x, y). \quad (1)$$

where d_x is the true disparity which is converted from original depth, used for warping $r(x, y)$ from reference view to target view to be $u(x, y)$. While in spectral domain, $n(x, y)$ could be represented by

$$\begin{aligned} N(\omega_x, \omega_y) &= S(\omega_x, \omega_y) - U(\omega_x, \omega_y) \\ &= S(\omega_x, \omega_y) - e^{-j\omega_x d_x} \cdot R(\omega_x, \omega_y), \end{aligned} \quad (2)$$

where the term $e^{-j\omega_x d_x}$ corresponds to spatial shifting of $r(x, y)$.

Fig. 1(b) depicts the case when distorted disparity is used. In the current work, disparity is distorted (i) when depth map of target view is lossy compressed or (ii) when there is rounding error in the warping process. In this case, a degraded VSP predictor $w(x, y)$ is generated, and its difference with $s(x, y)$ is defined as "VSP error" $e(x, y)$, which is

$$e(x, y) = s(x, y) - w(x, y). \quad (3)$$

As $e(x, y)$ indicates the predictor error, we will use $e(x, y)$ to characterize the coding gain of VSP.

The depth distortion ΔD in coded depth would result in disparity difference Δd in reference view. In addition to Δd, due to limited accuracy of pixel warping, the deviated disparity has to be rounded to match the sampling grid in reference view, as shown in Fig. 2. The overall disparity error Δm between original disparity d_x and distorted disparity $\hat{d}_x$ is

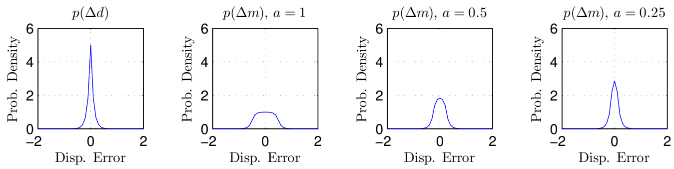
$$d_x - \hat{d}_x = \Delta m = \Delta d + \delta \quad (4)$$

where δ is the rounding error. We assume Δd and δ are independent in this work.

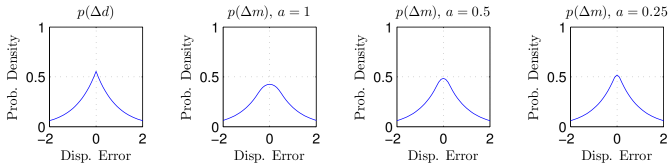
Then the VSP predictor with coded depth map, i.e., $w(x, y)$, is shifted from reference texture $r(x, y)$ by distorted disparity $\hat{d}_x$ and interpolated by filter $f(x, y)$, as Fig. 3 shows. Meanwhile, in frequency domain, the generation process could be interpreted as

$$W(\omega_x, \omega_y) = e^{-j\omega_x \hat{d}_x} \cdot F(\omega_x, \omega_y) \cdot R(\omega_x, \omega_y) \quad (5)$$

where $W(\omega_x, \omega_y)$ and $F(\omega_x, \omega_y)$ denote the Fourier transform of the degraded VSP predictor $w(x, y)$, and frequency response of the



(a) $\sigma_{\Delta d} = 0.1$



(b) $\sigma_{\Delta d} = 0.9$

Fig. 4. $p(\Delta d)$ and $p(\Delta m)$ with different rounding range a. For situation with small depth coding error (a), warping accuracy has more pronounced effect.

interpolation filter, respectively.

We use the analysis tools in [10] originally proposed for conventional motion compensation. In particular, following [10], the power spectral density (PSD)of VSP error $e(x, y)$ is given by:

$$\begin{aligned}\Phi_{ee}(\omega_x,\omega_y) = \Phi_{ss}(\omega_x,\omega_y)\cdot\left(1+|F(\omega_x,\omega_y)|^2\right.\\ -2\Re\left\{F(\omega_x,\omega_y)\,P(\omega_x,\omega_y)\right\}\Big)\\ +\Phi_{nn}(\omega_x,\omega_y)\cdot|F(\omega_x,\omega_y)|^2\end{aligned} \tag{6}$$

where $\Phi_{ee}(\omega_x, \omega_y)$, $\Phi_{ss}(\omega_x, \omega_y)$, $\Phi_{nn}(\omega_x, \omega_y)$ denotes PSD of VSP error, original texture of target view and VSP noise, respectively; $\Re\{\cdot\}$ denotes the real part of a complex number; $P(\omega_x, \omega_y)$ is the band-limited 2D Fourier transform of the pdf $p(\Delta m)$ of disparity error Δm.

Lossy coding of depth map, rounding operation of disparity, and selection of maximum depth sample for a certain depth subblock would all result in disparity error and could be summarized by $p(\Delta m)$. So we propose to model the $p(\Delta m)$ including the effect of depth coding and disparity rounding in the next section.

4. MODELING OF DISPARITY ERROR

In this section we model the disparity error Δm, which is the sum of depth coding induced distortion Δd and rounding induced distortion δ. For 1D-parallel camera arrangements, there is no vertical disparity, so pixels are only warped in horizontal direction, i.e., only horizontal disparity error need to be modelled. Following [16], we assume ΔD, the depth distortion (distortion in the depth map due to lossy coding) is Laplacian distributed with mean zero and standard derivation σ. ΔD and Δd are related linearly [16]: $\Delta d = kb\Delta D$, where $k = \frac{f}{255}\left(\frac{1}{z_{near}} - \frac{1}{z_{far}}\right)$, b is distance between target view and reference view, f is focal length, and z_{near} and z_{far} are nearest and furthest physical depth values, respectively. Thus, Δd is also Laplacian distributed:

$$p\left(\Delta d|0,\sigma_{\Delta d}\right) = \frac{1}{2\sigma_{\Delta d}}\exp\left(-\frac{|\Delta d|}{\sigma_{\Delta d}}\right), \tag{7}$$

where $\sigma_{\Delta d}$ equals to $kb\sigma/\sqrt{2}$, i.e., the standard deviation of depth-coding induced disparity error.

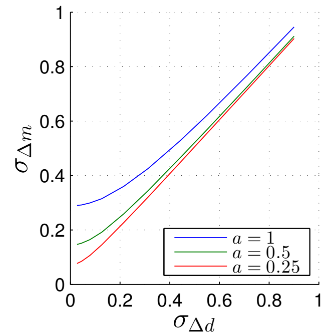


Fig. 5. Change of $\sigma_{\Delta m}$ over $\sigma_{\Delta d}$.

The rounding error δ is assumed to be uniformly distributed within rounding range $[-\frac{a}{2}, \frac{a}{2})$ [22], which is

$$p\left(\delta\right) = \begin{cases} \frac{1}{a} & -\frac{a}{2} \leqslant \delta < \frac{a}{2} \\ 0 & other \end{cases} \tag{8}$$

where a is the distance between sampling points, i.e., $a = 1$ for integer-pel warping accuracy, $a = 0.5$ for half-pel, $a = 0.25$ for quarter-pel.

From (4) and assume Δd and δ are independent, the pdf of the overall disparity error Δm, i.e., $p(\Delta m)$, is then given by convolution integrals of $p(\Delta d)$ and $p(\delta)$ in (9):

$$\begin{aligned} p_{\Delta m}(x) &= \int_{-\infty}^{\infty} p_{\Delta d}(y)\, p_\delta(x-y)\,dy \\ &= \begin{cases} \frac{1}{2a}[\exp(\frac{2x+a}{2\sigma_{\Delta d}}) - \exp(\frac{2x-a}{2\sigma_{\Delta d}})], & for\ x < -\frac{a}{2}; \\ \frac{1}{2a}[2 - \exp(\frac{2x-a}{2\sigma_{\Delta d}}) - \exp(-\frac{2x+a}{2\sigma_{\Delta d}})], & for\ -\frac{a}{2} \leqslant x \leqslant \frac{a}{2}; \\ \frac{1}{2a}[\exp(-\frac{2x-a}{2\sigma_{\Delta d}}) - \exp(-\frac{2x+a}{2\sigma_{\Delta d}})], & for\ x > \frac{a}{2}. \end{cases} \end{aligned} \tag{9}$$

Furthermore, the Fourier transform of $p_{\Delta m}(x)$, i.e., $P_{\Delta m}(\omega_x)$, would be the product of the Fourier transform of $p(\Delta d)$ and $p(\delta)$,

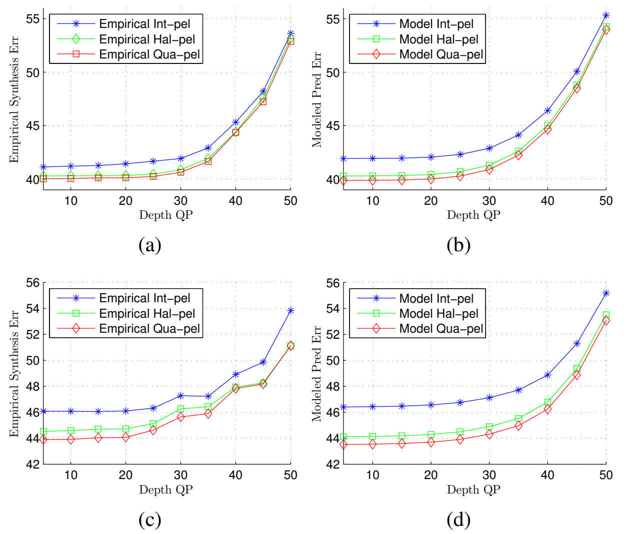
$$P_{\Delta m}(\omega_x) = P_{\Delta d}(\omega_x)\cdot P_\delta(\omega_x) = \frac{1}{1+(\omega_x\sigma_{\Delta d})^2}\cdot\frac{2\sin\left(\frac{a\omega_x}{2}\right)}{a\omega_x}. \tag{10}$$

The convolution result (9) is shown in Fig. 4 with different standard deviation of disparity error and rounding accuracy. When $\sigma_{\Delta d}$ is smaller, i.e., $p(\Delta d)$ is more concentrated around zero disparity error, the effect of rounding range a on $p(\Delta m)$ is more significant than that for $p(\Delta d)$ with larger $\sigma_{\Delta d}$. This can also be reflected by (11) and its corresponding curves shown in Fig. 5. Therefore, for situations with small depth coding error, warping accuracy has more pronounced effect.

$$\sigma_{\Delta m} = \sqrt{\int_{-\infty}^{\infty} x^2\cdot p_{\Delta m}(x)\,dx} = \sqrt{\sigma_{\Delta d}^2 + \frac{a^2}{12}}. \tag{11}$$

5. EXPERIMENTAL RESULTS AND DISCUSSION

In this section, the view synthesis prediction error is estimated by the spectral model described in section 3 and the model of disparity error with different rounding range described in section 4. Depth images are compressed by the HEVC reference software HM 14.0 at QP ranging from 5 to 50 and texture images of reference view are



(a) (b) (c) (d)

Fig. 6. VSP error (a)(c) measured from totally empirical VSP picture, and (b)(d) estimated by model for sequence Shark and Gtfly.

encoded at QP 30.

In the spectral estimation model, there are four terms need to be addressed: the empirical PSD of original texture of target view $\Phi_{ss}(\omega_x, \omega_y)$, the empirical PSD of VSP noise $\Phi_{nn}(\omega_x, \omega_y)$ with the encoded reference texture are used; for Fourier transform $P(\omega_x, \omega_y)$ of pdf of the disparity error Δm, the model established in section 4 is applied here with different rounding range and various standard deviation computed from depth coding error; the frequency response of the HEVC interpolation filter [23] is used as $F(\omega_x, \omega_y)$.

Then the energy of the estimated VSP error is computed by

$$\sigma_e^2 = \frac{1}{4\pi^2} \int_{-\pi}^{\pi} \int_{-\pi}^{\pi} \Phi_{ee}(\omega_x, \omega_y)\, d\omega_x d\omega_y. \tag{12}$$

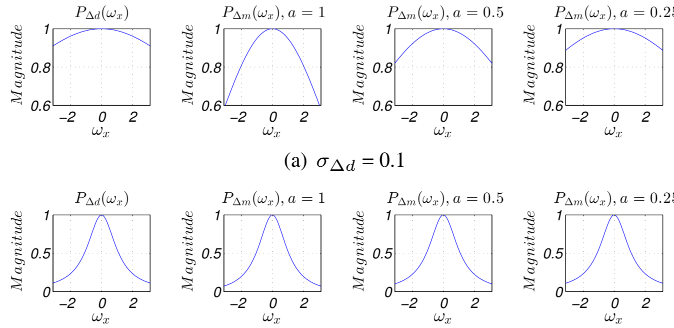
The overall simulation results of sequence Shark and Gtfly are shown in Fig. 6(b) and Fig. 6(d).

5.1. Discussion on the Modeling Results of VSP Error

The modeling result in Fig. 6 shows:

- With lower depth coding QP, i.e., smaller coding distortion of target view depth map, VSP error is decreased significantly compared to that of higher depth QP. However, the prediction error saturates when depth QP goes down to 20, meaning that reducing depth coding QP after such threshold, i.e., spending more bits on coding depth maps has negligible contribution to improvement of VSP error.
- VSP error could be reduced by using higher warping accuracy. The improvement of prediction error for higher warping accuracy is consistent along all depth coding QP. Besides, the error gap of "*Hal vs Int*" is larger than "*Qua vs Hal*".
- The impact of elevating warping accuracy on prediction error is more significant for lower depth QP. The gap between prediction error of quarter-pel accuracy and integer-pel accuracy on lower QP end is larger than that of higher QP end.

We may get a insight on the above observation from interaction between standard deviation of disparity error $\sigma_{\Delta d}$, rounding range



(a) $\sigma_{\Delta d} = 0.1$

(b) $\sigma_{\Delta d} = 0.9$

Fig. 7. $P_{\Delta d}(\omega_x)$ and $P_{\Delta m}(\omega_x)$ with different rounding range a.

a, and Fourier transformed pdf of disparity error $P_{\Delta m}(\omega_x)$:

- As Fig. 7 shows, for smaller depth QP (smaller $\sigma_{\Delta d}$, corresponded to Fig. 7(a)), the relatively more spread $P_{\Delta m}(\omega_x)$ shows stronger attenuation effect on both low and high horizontal frequency texture signals after being substituted to the term "$1 + |F(\omega_x, \omega_y)|^2 - 2\Re\{F(\omega_x, \omega_y) P(\omega_x, \omega_y)\}$" in (6), i.e., vertically inverted, this results in significant reduction of prediction error when using lower depth QP. Furthermore, when $\sigma_{\Delta d}$ is sufficientlt small, $P_{\Delta m}(\omega_x)$ changes only slightly with $\sigma_{\Delta d}$, thus explains the prediction error saturation on low depth QP end.
- As rounding accuracy being degraded or depth coding QP being raised, the attenuation effect on high horizontal frequency texture signals is weakened, and the change from "integer-pel" to"half-pel" is larger than that of from "half-pel" to "quarter-pel", which leads to the above second observation.
- The impact of $P_\delta(\omega_x)$ is more significant on $P_{\Delta d}(\omega_x)$ with smaller $\sigma_{\Delta d}$. $P_\delta(\omega_x)$ is independent of $\sigma_{\Delta d}$, so $P_\delta(\omega_x)$ with a certain rounding range is fixed. When $P_{\Delta d}(\omega_x)$ is concentrated by raising $\sigma_{\Delta d}$, the affection of $P_\delta(\omega_x)$ on higher frequency part of $P_{\Delta d}(\omega_x)$ become much smaller, which explains the third observation.

Fig. 6(a) and Fig. 6(c) shows the totally empirical VSP error measured from the difference between original texture of target view and the VSP picture generated by a practical synthesizer using backward warping method. The empirical results are consistent with the modeled one in Fig. 6(b) and Fig. 6(d).

6. CONCLUSION

A model of disparity error is proposed to address the interaction of both depth coding distortion and disparity rounding accuracy on view synthesis prediction error. The proposed model is applied to a spectral model to estimate the VSP error in frequency domain. The analysis is done in both spatial and frequency domain. The experimental result shows that the prediction error saturates when depth coding distortion goes lower than a certain point, using higher warping accuracy brings larger prediction error reduction for depth map with less distortion, and the improvement on prediction error of half-pel accuracy over integer-pel is larger than that of quarter-pel accuracy over half-pel.

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