

Metrics Performance Analysis of Optical Flow

Taha Alhersh¹^a, Samir Brahim Belhaouari²^b and Heiner Stuckenschmidt¹^c

¹Data and Web Science Group, University of Mannheim, Mannheim, Germany

²College of Science and Engineering, Hamad Bin Khalifa University, Education City, Doha, Qatar

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Abstract: Significant amount of research has been conducted on optical flow estimation in previous decades. However, only limited number of research has been conducted on performance analysis of optical flow. These evaluations have shortcomings and a theoretical justification of using one approach and why is needed. In practice, design choices are often made based on qualitative unmotivated criteria or by trial and error. In this paper, novel optical flow performance metrics are proposed and evaluated alongside with current metrics. Our empirical findings suggest using two new optical flow performance metrics namely: Normalized Euclidean Error (NEE) and Enhanced Normalized Euclidean Error version one (ENEE1) for optical flow performance evaluation with ground truth.

1 INTRODUCTION

Optical flow computation is considered a fundamental problem in computer vision. In fact, it is originated from the physiological phenomenon of world visual perception through image formation on the retina, and this refers to the displacement of intensity patterns (Fortun et al., 2015). On the other hand, optical flow can be defined as the projection of velocities of 3D surface points onto the imaging plane of visual sensor (Beauchemin and Barron, 1995). However, the relative motion constructed between the observer and objects of an observed scene only represents motion of intensities in the image plane, and not necessarily represents the actual 3D motion in reality (Verri and Poggio, 1989). A consequent problem emerges that intensity changes are not necessarily due to objects displacements in the scene, but can also be caused by other circumstances such as: changing light, reflection, modifications of objects properties affecting their light emission or reflection (Fortun et al., 2015). Research paradigms in optical flow estimation have advanced from considering it as a classical problem (Horn and Schunck, 1981; Brox and Malik, 2011) to a higher-level approaches using machine learning (Wannenwetsch et al., 2017; Sun et al., 2018; Alhersh and Stuckenschmidt, 2019). For instance, convolu-

tional neural networks (CNNs) is considered to be state-of-the-art method for Optical flow estimation.

Despite the fact that optical flow estimation methods have dramatically evolved, the most common evaluation methodologies are end point error (EPE) (Otte and Nagel, 1994) and angular error (AE) (Barron et al., 1994), noting that AE metric is based on prior work of Fleet and Jepson (Fleet and Jepson, 1990). Even though EPE and AE metrics are popular, it is unclear which one is better. Moreover, AE penalizes errors in regions of zero motion more than motion in smooth non-zero regions. In addition, there exists different cases (Figure 1) where EPE gives same value between various scenarios which will be discussed later in this paper. The purpose of this paper, is not to evaluate optical flow estimation methods, but to create a new evaluation methodology and propose new metrics for optical flow performance evaluation, and compare them with existing evaluation metrics.

2 RELATED WORK

Even though many optical flow estimation algorithms have been proposed, there are few publications on their performance analysis. Two main approaches can be used for evaluating optical flow: qualitative and quantitative. Motion fields of optical flow can be visualized in either arrow or color forms (Figure 2) which provide qualitative insights on the accuracy of

^a <https://orcid.org/0000-0002-3673-5397>

^b <https://orcid.org/0000-0003-2336-0490>

^c <https://orcid.org/0000-0002-0209-3859>

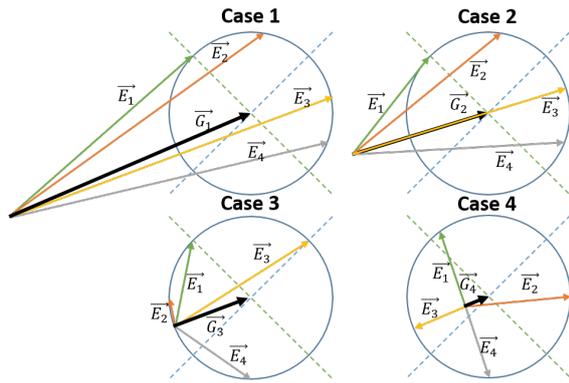


Figure 1: Different cases where the EPE metric gives the same error value between GT represented by the black vector $\vec{G}_i, i \in (\vec{G}_1, \vec{G}_2, \vec{G}_3, \vec{G}_4)$ and other estimated optical flow vectors $\vec{E}_j, j \in (\vec{E}_1, \vec{E}_2, \vec{E}_3, \vec{E}_4)$.

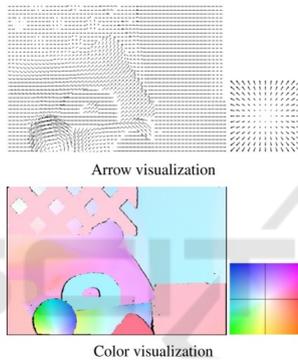


Figure 2: Arrow and color visualization of optical flow (Fortun et al., 2015).

the estimation. Arrow visualization represents motion vectors and provides good intuition about motion. On the other hand, motion field vectors should be under-sampled to prevent arrows overlapping. The color code visualization allows for dense representation of motion field via associating color hue to the direction and saturation to the magnitude of vectors (Fortun et al., 2015). The first direct quantitative evaluation metrics for optical flow were published in 1994 (Otte and Nagel, 1994; Barron et al., 1994) suggesting using EPE (Otte and Nagel, 1994) which can be described as the *Euclidean* distance between two vectors; it is defined in Equation 1:

$$EPE = \sqrt{(u - u_{GT})^2 + (v - v_{GT})^2}. \quad (1)$$

and AE (Barron et al., 1994) which represents the angle between the two extended vectors $(1, u, v)$ and $(1, u_{GT}, v_{GT})$ and defined in Equation 2:

$$AE = \cos^{-1} \left(\frac{uu_{GT} + vv_{GT} + 1}{\sqrt{u^2 + v^2 + 1} \sqrt{u_{GT}^2 + v_{GT}^2 + 1}} \right). \quad (2)$$

AE is very sensitive to small estimation errors caused by small displacements, whereas EPE hardly discriminates between close motion vectors (Fortun et al., 2015). Figure 1 illustrates four different cases when EPE metric gives same error value between ground truth (GT) and estimated motion vector; this drawback is caused by the fact that EPE considers only the difference of vectors and ignores the magnitude of each one.

McCane *et al.* (McCane et al., 2001) has suggested two evaluation metrics, the first one is defined in Equation 3, which is based on AE metric with motion vectors normalization. Nevertheless, AE does not take into consideration the vector magnitude and uses only angles, the normalization step has no actual effect.

$$E_A = \cos^{-1}(\hat{c} \cdot \hat{e}), \quad (3)$$

where E_A is the error measure, c is GT, e is the estimated optical flow, and $\hat{\cdot}$ denotes vector normalization.

The second metric is the normalized magnitude of the vector difference between GT and estimated optical flow which is defined in Equation 4.

$$E_M = \begin{cases} \frac{\|c - e\|}{\|c\|} & \text{if } \|c\| \geq T, \\ \frac{\|e\| - T}{T} & \text{if } \|c\| < T \text{ and } \|e\| \geq T, \\ 0 & \text{if } \|c\| < T \text{ and } \|e\| < T, \end{cases} \quad (4)$$

where E_M is the error measure.

Baker *et al.* (Baker et al., 2011) compared the performance of EPE and AE and argued that EPE should become the preferred optical flow evaluation metric based on a qualitative assessment of an estimated optical flow for Urban sequence.

3 METHOD

In this section, a novel performance evaluation methodology is proposed, this methodology is based on using only optical flow ground truths and modified version for ground truths in terms of shifting horizontally and vertically or magnifying by a certain value, or rotating or a combination for evaluating performance metrics. A description of the used datasets and mathematical modeling of the proposed metrics are provided in the consequent sections.

3.1 Dataset

Three well known datasets have been used for evaluating and analyzing the performance of optical flow. Since this work is not for evaluating optical flow estimation algorithms, only GT datasets are used.

3.1.1 Baker (Baker et al., 2011)

Baker *et al.* has proposed new sequences with non-rigid motion where the ground truth flow is determined by tracking hidden fluorescent texture. The number of available GT files is eight and the data description is shown in Table 1. Three GT files have maximum values more than 10^9 for limited amount of pixels which are Dimetrodon, Hydrangea and RubberWhale. To avoid bias in analysis results, a threshold of maximum 10^7 has been set.

3.1.2 KITTI

KITTI dataset is a real-world computer vision benchmark. The dataset has two versions, the first one was proposed in 2012 by (Geiger et al., 2012), and the second version was proposed by (Menze and Geiger, 2015) in 2015. Compared to KITTI 2012 benchmark, KITTI 2015 covers dynamic scenes for which ground truth was established in a semi-automatic process. In this experiment, only eight random different ground truths were used.

3.1.3 Sintel

Sintel dataset (Butler et al., 2012) is an open source synthetic dataset which is extracted from animated film produced by Ton Roosendaal and the Blender Foundation. It provides optical flow ground truths as part of the training set. In this experiment we have used eight random ground truths for validating proposed and existing optical flow performance metrics.

3.1.4 Modified GT

Different modified versions of GT have been created based on possible error scenarios. Changes in GT are based on the the following assumptions.

Lets $S = \{-30, -20, -10, 10, 20, 30\}$, and for each GT file, one of the following scenarios is applied:

1. Shift GT horizontally by $s \in S$ and replace shifted pixels by zeros.
2. Shift GT vertically by $s \in S$ and replace shifted pixels by zeros.

Table 1: Minimum, maximum and standard deviation for Baker dataset used.

Name	Min	Max	Std
Dimetrodon	-4.33E+00	1.67E+09	3.55E+08
Grove2	-3.31E+00	4.01E+00	3.64E+00
Grove3	-4.09E+00	1.43E+01	2.89E+00
Hydrangea	-7.02E+00	1.67E+09	4.13E+08
RubberWhale	-4.58E+00	1.67E+09	2.09E+08
Urban2	-2.13E+01	8.51E+00	7.96E+00
Urban3	-4.19E+00	1.73E+01	5.15E+00
Venus	-9.38E+00	7.00E+00	2.91E+00

3. Shift GT horizontally and vertically by $s \in S$ and replace shifted pixels by zeros.
4. Rotate GT by $s \in S$ degrees and replace shifted pixels by zeros.
5. Magnify GT by multiplying by $s \in S$.
6. Shift GT horizontally and vertically and then rotate by $s \in S$ and replace shifted pixels by zeros.
7. Shift GT horizontally and vertically and then rotate and magnify by $s \in S$ and replace shifted pixels by zeros.

This will allow us to have 42 different versions of each GT file with total of 336 modified GT files for each dataset.

3.2 Proposed Performance Metrics

To overcome the drawbacks of the existing optical flow metrics, we have proposed five different novel metrics. For each modified optical flow vector \vec{E} represented by (u, v) and ground truth vector \vec{GT} notated by (u_{GT}, v_{GT}) . The following subsections present the proposed metrics:

3.2.1 Point Rotational Error (PRE)

AE is adding another dimension and force it to be equal to 1. From one hand, this will prevent division by zero, but from the other hand, this will affect the measurement of the angle. This is an enhancement on AE, where the angle in 2D space between (u, v) and (u_{GT}, v_{GT}) is considered instead of 3D space as shown in Equation 5:

$$PRE = \begin{cases} \cos^{-1} \left(\frac{uu_{GT} + vv_{GT}}{\sqrt{u^2 + v^2} \sqrt{u_{GT}^2 + v_{GT}^2}} \right), & \text{if } (u^2 + v^2) \neq 0 \wedge (u_{GT}^2 + v_{GT}^2) \neq 0 \\ \pi, & \text{if } (u^2 + v^2) \oplus (u_{GT}^2 + v_{GT}^2) = 0 \\ 0, & \text{if } (u^2 + v^2) = 0 \wedge (u_{GT}^2 + v_{GT}^2) = 0 \end{cases} \quad (5)$$

for example, if we have the following two points (0.1, 0.1) and (3, 3.1), then AE = 1.2025, but PRE = 0.0164.

3.2.2 Generalized Point Rotational Error (GPRE)

PRE metric can be generalized when the angle in 3D space between (α, u, v) and (β, u_{GT}, v_{GT}) is considered instead of 3D between $(1, u, v)$ and $(1, u_{GT}, v_{GT})$ space. From Cauchy Schwarz theory (Steele, 2004), we can prove the following inequalities:

$$-1 \leq \frac{\alpha\beta + (uu_{GT} + vv_{GT})}{\sqrt{\alpha^2 + u^2 + v^2} \sqrt{\beta^2 + u_{GT}^2 + v_{GT}^2}} \leq 1 \quad (6)$$

The metric GPRE can be defined as:

$$GPRE = \begin{cases} \cos^{-1}\left(\frac{\alpha\beta + (uu_{GT} + vv_{GT})}{\sqrt{\alpha^2 + u^2 + v^2} \sqrt{\beta^2 + u_{GT}^2 + v_{GT}^2}}\right), & \text{if } (u^2 + v^2) \neq 0 \wedge (u_{GT}^2 + v_{GT}^2) \neq 0 \\ \pi, & \text{if } (u^2 + v^2) \oplus (u_{GT}^2 + v_{GT}^2) = 0 \\ 0, & \text{if } (u^2 + v^2) = 0 \wedge (u_{GT}^2 + v_{GT}^2) = 0 \end{cases} \quad (7)$$

where α and β can be any real numbers, for instance if $\alpha = \beta = 0$, then GPRE = PRE. On the other hand, if $\alpha = \beta = 1$ this will led to AE in Equation 2.

3.2.3 Linear Projection Error (LPE)

This metric is a kind of mixture between AE and EPE, where the magnitude difference between (u, v) and (u_{GT}, v_{GT}) is added to the perpendicular distance between them Figure3. The perpendicular distance between (u, v) and (u_{GT}, v_{GT}) is defined as follows:

$$\max(\|proj_{\vec{GT}} \vec{E}\|, \|proj_{\vec{E}} \vec{GT}\|) \quad (8)$$

where the perpendicular distance is defined as the angular distance between the two non-null vectors \vec{E} and \vec{GT} . Therefor our metric can be defined as:

$$LPE = \begin{cases} \|\vec{GT} - \vec{E}\| + \max(\|proj_{\vec{GT}} \vec{E}\|, \|proj_{\vec{E}} \vec{GT}\|), & \text{if } \|\vec{GT} \cdot \vec{E}\| \neq 0 \\ \|\vec{GT} - \vec{E}\| + \max(\|\vec{GT}\|, \|\vec{E}\|), & \text{if } \|\vec{GT} \cdot \vec{E}\| = 0 \end{cases} \quad (9)$$

where the projection of vector \vec{b} over \vec{a} is given by the following formula:

$$proj_{\vec{a}} \vec{b} = \frac{\vec{a} \cdot \vec{b}}{|\vec{a}|^2} \vec{a} \quad (10)$$

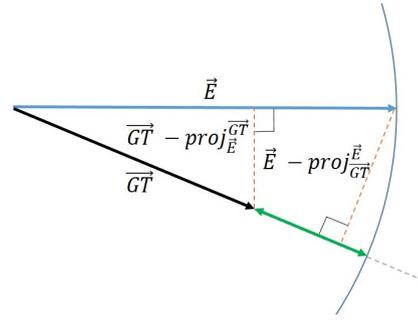


Figure 3: The angular distance between the two non-null vectors \vec{E} and \vec{GT} based on the perpendicular distance between both vectors.

3.2.4 Normalized Euclidean Error (NEE)

EPE metric is takes into consideration the magnitude of the difference between two vectors and ignores the magnitude of each vectors in the sense that the EPE metric gives the same value for case 1 and case 2 where the radius of two circles is the same (refer to Figure 1). The following metric is an enhancement of the magnitude error E_M proposed by (McCane et al., 2001):

$$NEE = \begin{cases} \frac{\sqrt{(u-u_{GT})^2 + (v-v_{GT})^2}}{\min((u^2 + v^2), (u_{GT}^2 + v_{GT}^2))}, & \text{if } \min((u^2 + v^2), (u_{GT}^2 + v_{GT}^2)) > \epsilon \\ \frac{\sqrt{(u-u_{GT})^2 + (v-v_{GT})^2}}{\epsilon}, & \text{if } \min((u^2 + v^2), (u_{GT}^2 + v_{GT}^2)) = 0 \end{cases} \quad (11)$$

where, ϵ is a threshold around 0.01.

3.2.5 Enhanced Normalized Euclidean Error (ENEE)

Another way to get over EPE drawbacks is to calculate the relative distance between \vec{E} and \vec{GT} vectors and to use different normalization methods as the following:

$$ENEE1 = \begin{cases} \frac{\sqrt{(\|P_{GT}\|)^2 + \tau(\|N_{GT}\|)^2}}{\min((u^2 + v^2), (u_{GT}^2 + v_{GT}^2))}, & \text{if } \min((u^2 + v^2), (u_{GT}^2 + v_{GT}^2)) > \epsilon \\ \frac{\sqrt{(\|P_{GT}\|)^2 + \tau(\|N_{GT}\|)^2}}{\epsilon}, & \text{if } \min((u^2 + v^2), (u_{GT}^2 + v_{GT}^2)) = 0 \end{cases} \quad (12)$$

If the normalization is performed by only \vec{GT} vector, then:

$$ENEE2 = \begin{cases} \frac{\sqrt{(\|\vec{P}_{GT}\|)^2 + \tau(\|\vec{N}_{GT}\|)^2}}{\sqrt{u_{GT}^2 + v_{GT}^2}}, & \text{if } (u_{GT}^2 + v_{GT}^2) \neq 0 \\ \sqrt{u^2 + v^2}, & \text{if } (u_{GT}^2 + v_{GT}^2) = 0 \end{cases} \quad (13)$$

If the normalization is performed by the average of \vec{GT} and \vec{E} vectors, then:

$$ENEE3 = \begin{cases} \frac{2\sqrt{(\|\vec{P}_{GT}\|)^2 + \tau(\|\vec{N}_{GT}\|)^2}}{\sqrt{u_{GT}^2 + v_{GT}^2} + \sqrt{u^2 + v^2}}, & \text{if } (u_{GT}^2 + v_{GT}^2) \neq 0 \\ \sqrt{u^2 + v^2}, & \text{if } (u_{GT}^2 + v_{GT}^2) = 0 \end{cases} \quad (14)$$

If normalization is ignored, then:

$$ENEE4 = \sqrt{(\|\vec{P}_{GT}\|)^2 + \tau(\|\vec{N}_{GT}\|)^2} \quad (15)$$

where τ is strictly positive value and it works as steering power for normal component N_{GT} and P_{GT} and N_{GT} are defined as:

$$\vec{P}_{GT} = \frac{(uu_{GT} + vv_{GT})}{(u_{GT}^2 + v_{GT}^2)} \vec{GT} - \vec{GT} \quad (16)$$

$$\vec{N}_{GT} = \vec{E} - \frac{(uu_{GT} + vv_{GT})}{(u_{GT}^2 + v_{GT}^2)} \vec{GT} \quad (17)$$

4 EXPERIMENTS AND RESULTS

Systematic experiments have been conducted to evaluate optical flow performance. As we are evaluating 10 different metrics, a total number of 3360 experiments have been performed for each dataset. Behavior and sensitivity of every metric have been reported for motion variations in horizontal, vertical, rotational and magnification or a combination. Parameter settings used in all experiments are summarized in Table 2.

As a rule of thumb, a good metric has to produce an error value proportional to the absolute values in step sequence S described in Section 3.1.4. A general overview of mean error curves for existing and proposed error metrics in log scale are illustrated in Figure 4. It is obvious that some metrics are outperforming others but yet it's not clear which metrics are more suitable for optical flow performance measure.

More detailed explanations and results are reported in the following sections.

Table 2: Metric settings used in all experiments.

Metric	Setting
GPRE	$\alpha = \beta = 0$
NEE	$\epsilon = 0.01$
ENEE1	$\epsilon = 0.01, \tau = 3$
ENEE2	$\tau = 100$
ENEE3	$\tau = 100$
ENEE4	$\tau = 5$

4.1 Metrics Evaluation on Baker Dataset

Metrics are calculating errors between GT and modified GT. The most general example for a modified GT is when GT values are shifted horizontally and vertically then rotated after magnification by a value. For instance, Figure 5 is showing mean error metric curves for Baker dataset. X – axis is representing values used to shift, rotated and magnify actual GT, while Y – axis is the mean error values.

Based on our rule of thumb, Figure 5 is showing that LPE, ENEE4 and EPE metrics are more sensitive to motion variation when GT is modified with negative values, while NEE and ENEE1 is more sensitive to motion variation when GT is modified with positive values.

According to the approach used in modifying GT, no motion pixels are replaced with zero values when GT is rotated, hence, this will increase zero values in modified GT and mean error would be biased. To overcome this issue, The third quartile of the error can be used instead of mean error. The third quartile is denoted by $Q3$, which is the median of the upper half of the data set. This means that about 75% of the numbers in the data set lie below $Q3$ and about 25% lie above $Q3$.

Since it is not clear from mean error which metric is better, $Q3$ mean error gives a more clear idea about the best metrics. Figure 6 illustrates $Q3$ mean error for all metrics. It is obvious that NEE and ENEE1 metrics are outperforming other metrics. In the second place, ENEE4, EPE and LPE metrics. On the third place ENEE2 and Em metrics.

Visualization of optical flow error for Hydrangea sample which is part of Baker dataset is shown in Figure 9 and indicates that NEE and ENEE1 metrics are compromised metrics between EPE which highly penalize errors and AE which less penalize errors.

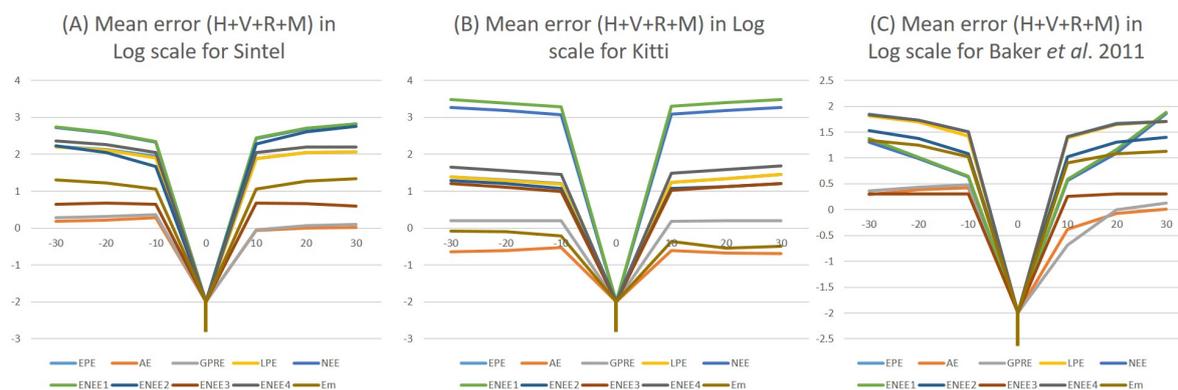


Figure 4: Mean error ($y - axis$) in log scale for all metrics between GT and modified GT in different scenarios: (I) when GT are shifted horizontally(H) by number of pixels in $x - axis$, (II) GT are shifted vertically (V) by number of pixels in $x - axis$, (III) GT are magnified (M) by values in $x - axis$, (IV) GT are shifted horizontally and vertically by number of pixels in $x - axis$, (V) GT are rotated (R) by angle degree in $x - axis$, (VI) GT are shifted horizontally and vertically then rotated by values of $x - axis$. For (A) Sintel dataset, (B) Kitti dataset and (C) Baker dataset. Note that $\log(0^+) = -\infty$ which is represented by the lowest point in the graph.

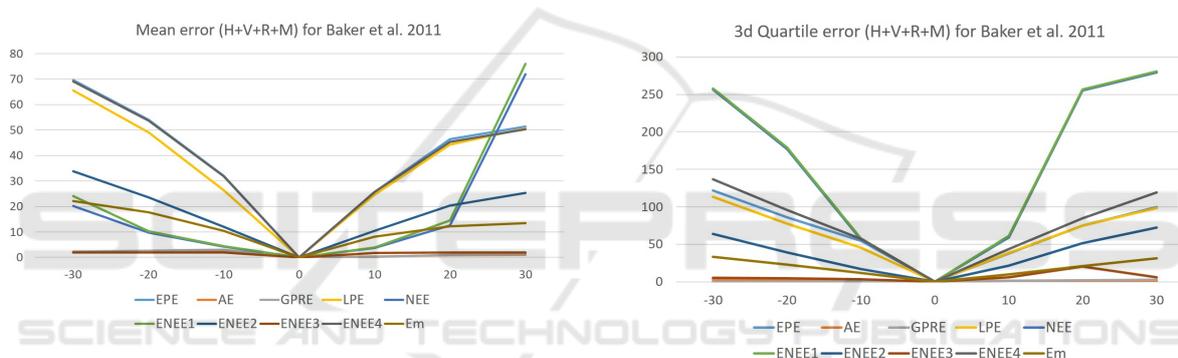


Figure 5: Mean error ($y - axis$) for Baker dataset for all metric calculations between GT and modified GT when they are shifted horizontally and vertically then rotated after that magnified by values of $x - axis$.

Figure 6: Third quartile of mean error ($y - axis$) for Baker dataset for all metrics calculating error between GT and modified GT when motion is shifted horizontally and vertically then rotated after that magnified by values of $x - axis$.

4.2 Metrics Evaluation on KITTI Dataset

The second evaluation was conducted on KITTI dataset. The mean error of existing and proposed metrics are shown in Figure 7. It's clear that ENEE1 and NEE metrics are more sensitive to motion variation than other metrics.

Optical flow error visualization for sample image of KITTI dataset is shown in Figure 10. A compromised visualization between EPE and AE metrics are represented by NEE and ENEE1 metrics.

4.3 Metric Evaluation on Sintel Dataset

The last evaluation for metrics was performed on Sintel dataset. The mean error of all metrics is plotted in Figure 8. Based on our rule of thumb, NEE

and ENEE1 metrics are producing error values more proportional to the absolute value of motion change. Hence, NEE and ENEE1 metrics are more sensitive to errors and performing better than other metrics.

Visualization of optical flow error as sample image of Sintel dataset is shown in Figure 11. This indicates that NEE and ENEE1 metrics are moderate versions between EPE which highly penalize errors and AE which less penalize errors.

4.4 Discussion

A qualitative assessment (Baker et al., 2011) has been conducted on two common error metrics EPE and AE, and suggested using EPE rather than using AE based on only one sample from Baker dataset from Urban sequence. However, there is a need for a sys-

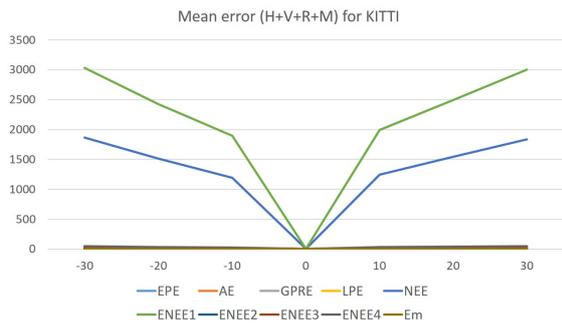


Figure 7: Mean error ($y - axis$) for KITTI dataset for all metric calculations between GT and modified GT when they are shifted horizontally and vertically then rotated after that magnified by values of $x - axis$.

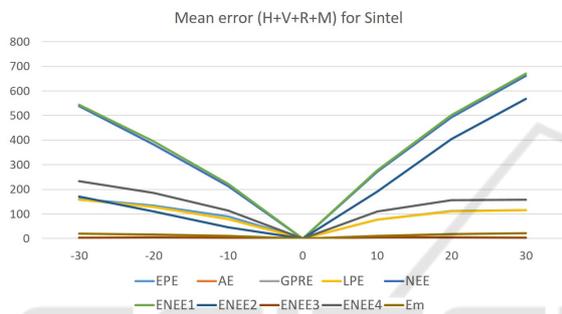


Figure 8: Mean error ($y - axis$) for Sintel dataset for all metric calculations between GT and modified GT when they are shifted horizontally and vertically then rotated after that magnified by values of $x - axis$.

tematic evaluation of optical flow performance, hence this experiment has been conducted on three popular datasets using ten different error metrics. A good metric is considered to be more sensitive to errors. For example, producing error values proportional to the change of motion between modified GT and GT.

Existing metrics such as EPE, AE and EM have sensitivity differ slightly from one dataset to another. For instance, EPE and EM performed good on Baker. While AE and Em are less sensitive on Kitti and AE is not sensitive on Sintel. EPE best sensitivity was on Kitti, on the other hand, AE sensitivity was the worse among all three metrics.

A detailed look into metrics behavior related to motion change is illustrated in Figure 12. The following observations have been derived:

- It is observed from Figure 12 (A,B and C) that almost all metrics except ENEE2 and Em are sensitive to horizontal, vertical and (horizontal and vertical) motion variation, with some differences in magnitude. ENEE2 and Em metrics are more sensitive for horizontal variation Figure 12(B) and

Table 3: A summarized results for our rule of thumb method to choose best metric based on metric sensitivity to motion variation in horizontal (H), vertical(V), rotational(R) and magnification (M) or a combination.

	V	H	H+V	R	M	H+V+R	H+V+R+M
EPE	✓	✓	✓		✓		
AE	✓	✓	✓	✓			
GPRE	✓	✓	✓	✓			
LPE	✓	✓	✓		✓		
NEE	✓	✓	✓	✓	✓	✓	✓
ENEE1	✓	✓	✓	✓	✓	✓	✓
ENEE2	✓	✓	✓		✓		
ENEE3	✓	✓	✓		✓		
ENEE4	✓	✓	✓		✓		
Em	✓	✓	✓		✓		

horizontal and vertical variation Figure 12(C).

- All metrics except AE, GPRE and ENEE3 are sensitive to magnitude of motion variation. AE, GPRE and ENEE3 metrics can not detect variations in motion magnitude as shown in Figure 12(E).
- NEE and ENEE1 metrics are sensitive for angle variation as seen in Figure 12 (D,F), while AE, GPRE, and Em are sensitive only for small rotational variation.

Based on the previous observations, we conclude that all metrics are sensitive to horizontal, vertical and (horizontal and vertical) variation. AE, GPRE, NEE and ENEE1 metrics are sensitive to rotational variations. All metrics except AE and GPRE are sensitive to magnitude changing in motion. And only NEE and ENEE1 metrics are sensitive for all horizontal, vertical, rotational, magnitude or a combination. These results are summarized in Table 3.

5 CONCLUSION

In this paper, a novel performance measure of optical flow have been proposed. Moreover, a systematic evaluation of optical flow performance have been conducted. Drawbacks of existing performance metrics have been identified. Among the five proposed optical flow performance metrics, NEE and ENEE1 error metrics have outperformed all other metrics including the existing ones. The sensitivity of NEE and ENEE1 to motion variation is very high, indicating that NEE and ENEE1 error metrics are strongly recommended to be used for measuring the performance of estimated optical flow with regard to ground truth.

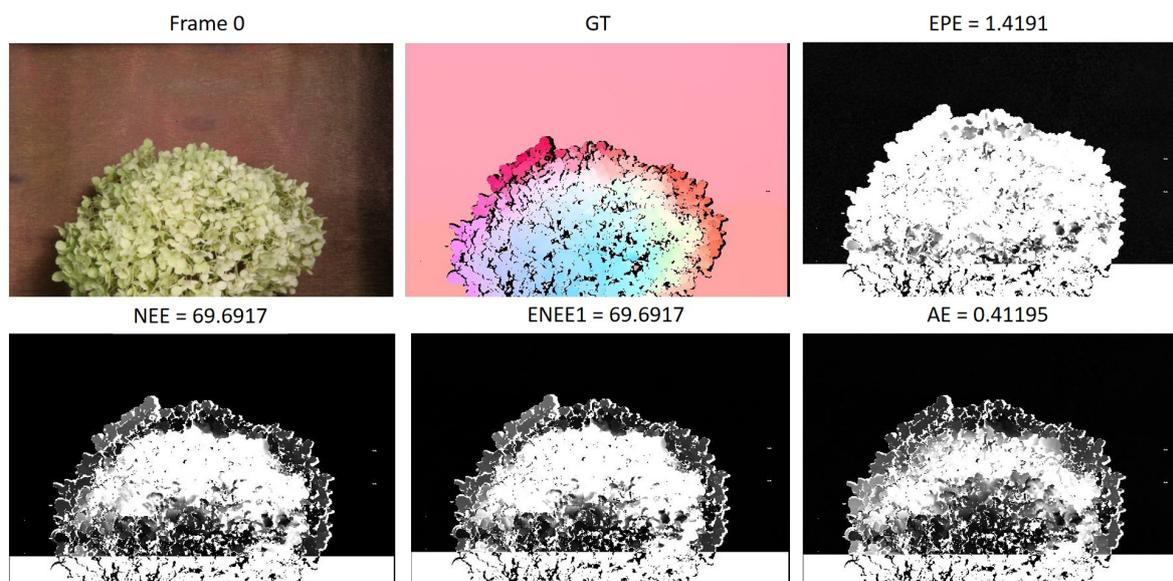


Figure 9: Sample image from Bakers' (Hydrangea) dataset, the corresponding ground truth and the visualization of motion error for four different error metrics (EPE, AE, NEE and ENEE1) between ground truth and modified ground truth when GT pixels are shifted vertically by -50 pixels.

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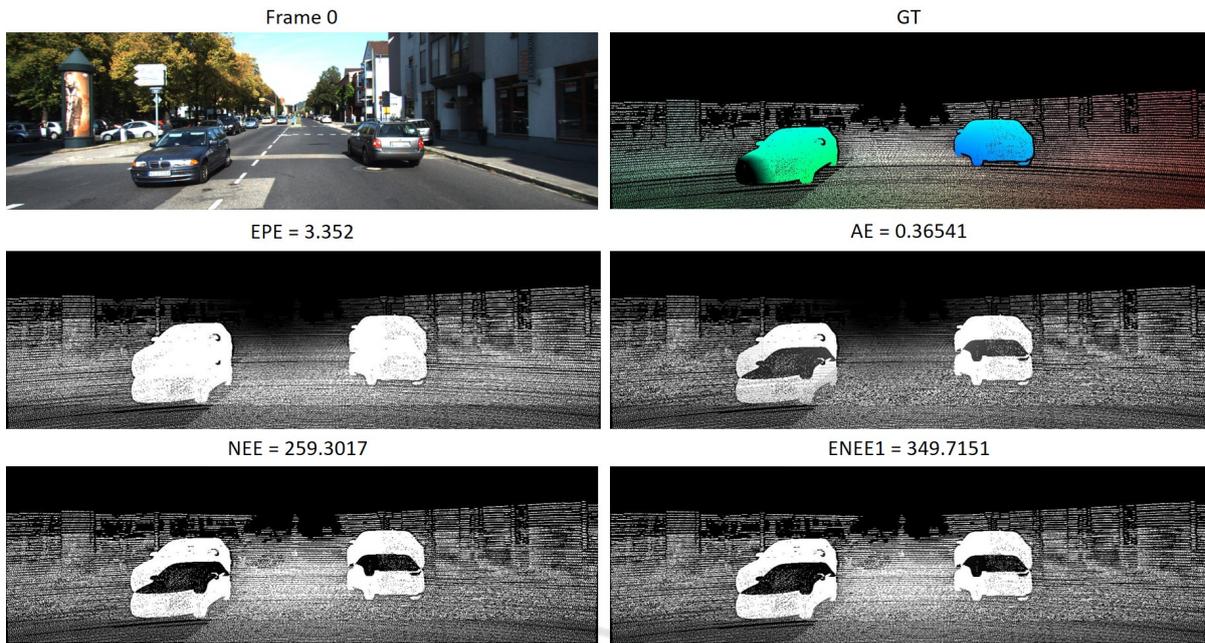


Figure 10: Sample image from KITTI's dataset, the corresponding ground truth and the visualization of motion error for four different error metrics (EPE, AE, NEE and ENEE1) between ground truth and modified ground truth when GT pixels are shifted vertically by -50 pixels.



Figure 11: Sample image from Sintel's dataset, the corresponding ground truth and the visualization of motion error for four different error metrics (EPE, AE, NEE and ENEE1) between ground truth and modified ground truth when GT pixels are shifted vertically by -50 pixels.

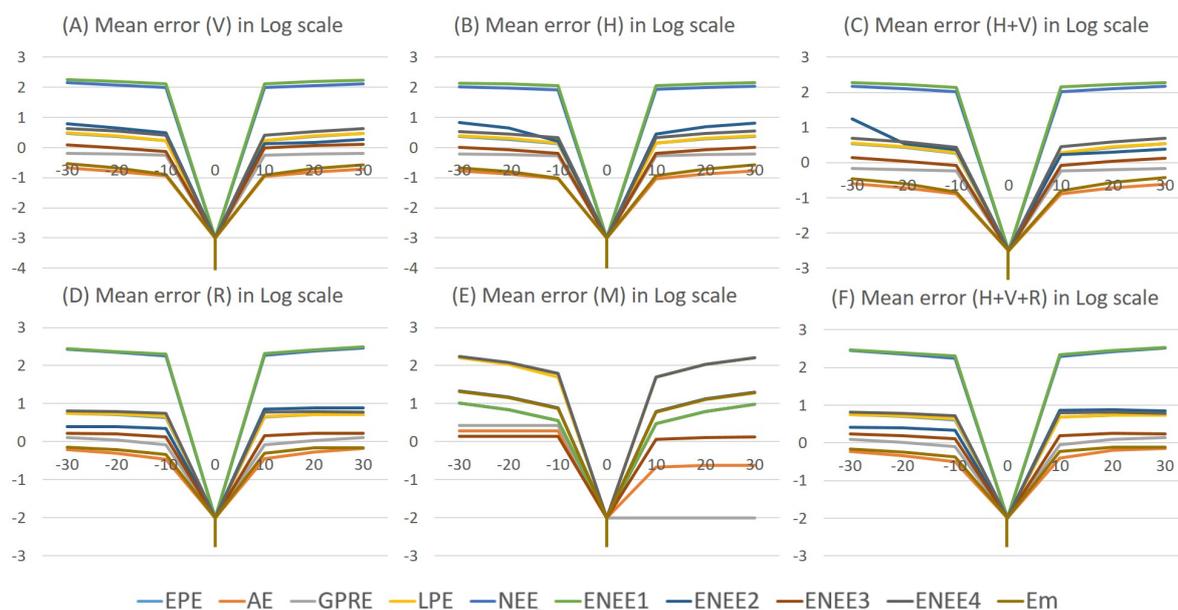


Figure 12: All datasets mean error (y – axis) in log scale for all metrics between GT and modified GT in different scenarios: (A) when GT are shifted horizontally(H) by number of pixels in x – axis, (B) GT are shifted vertically (V) by number of pixels in x – axis, (C) GT are magnified (M) by values in x – axis, (D) GT are shifted horizontally and vertically by number of pixels in x – axis, (E) GT are rotated (R) by angle degree in x – axis, (F) GT are shifted horizontally and vertically then rotated by values of x – axis. Note that $\log(0^+) = -\infty$ which is represented by the lowest point in the graph.

