Measurement and protocol for evaluating video and still stabilization systems

Etienne Cormier, Frédéric Cao[*], Frédéric Guichard, Clément Viard
[a]DxO Labs, 3 rue Nationale, 92100 Boulogne Billancourt, FRANCE

ABSTRACT

This article presents a system and a protocol to characterize image stabilization systems both for still images and videos. It uses a six axes platform, three being used for camera rotation and three for camera positioning. The platform is programmable and can reproduce complex motions that have been typically recorded by a gyroscope mounted on different types of cameras in different use cases. The measurement uses a single chart for still image and videos, the texture dead leaves chart. Although the proposed implementation of the protocol uses a motion platform, the measurement itself does not rely on any specific hardware. For still images, a modulation transfer function is measured in different directions and is weighted by a contrast sensitivity function (simulating the human visual system accuracy) to obtain an acutance. The sharpness improvement due to the image stabilization system is a good measurement of performance as recommended by a CIPA standard draft. For video, four markers on the chart are detected with sub-pixel accuracy to determine a homographic deformation between the current frame and a reference position. This model describes well the apparent global motion as translations, but also rotations along the optical axis and distortion due to the electronic rolling shutter equipping most CMOS sensors. The protocol is applied to all types of cameras such as DSC, DSLR and smartphones.

Keywords: Image quality evaluation, image stabilization, video stabilization, texture acutance, dead leaves chart, digital photography

1. INTRODUCTION

Recent years have seen the very fast development of video applications, driven by the small and inexpensive cameras of mobile devices. The quality of the videos produced by the smart phones improves with each new generation. A feature that has been required is video stabilization. It is well known that the hand-shake of the user (physiological tremor) degrades the quality of video. This is particularly true for light weight devices since it has been observed that the tremor has larger amplitude if the camera is light and held far from the body of the photographer. The result of the tremor on a video is that the objects in the image seem to be moving erratically. For HD videos (1920x1080), the apparent motion can be more than 10 pixels per frame. Image stabilization systems aim to cancel this apparent motion. Expensive stabilization systems rely on sensors measuring the camera motion (gyroscope, accelerometer) and applying the inverse motion to a part of the camera (an optical block, or the sensor for some cameras). Cheaper systems analyze the images and estimate the apparent motion on the fly before applying the necessary compensation. They may use or not gyroscopic sensors to ease motion estimation. The first type of systems is designated as optical image stabilization (OIS) and the latter electronic image stabilization (EIS). Systems moving the sensor are sometimes called mechanical stabilization, but to make it simple, we designate by OIS all the systems involving a moving part. Each type has some advantages and drawbacks. For instance, OIS usually do not compensate for the rotation around the optical axis (roll). Optical stabilization systems have first been conceived for still images in order to compensate for the motion of the user during the exposure of the image. Optics have been stabilized long before most cameras were digital. The same idea is used for other applications as telescope imaging, where the mirrors can be moved. . On the other hand, EIS cannot do

[*] Corresponding author: fcao@dxo.com

Updated 1 March 2012

much to reduce a large amount of motion blur. Another degradation due to motion is the image deformation due to the electronic rolling shutter (ERS) used by almost all CMOS sensors. The readout out the pixel lines over the whole picture height is usually comparable to the frame rate, so the last line is read out about 1/60s to 1/30s later than the first line of the sensor. Even if the scene is still, the image is deformed because of the shaking of the user. This “jello” effect is usually not visible on a single frame but particularly annoying for videos. For this reason, compensation for the average motion at the center of the frame is not enough to obtain a good video stabilization.

Since photography and video applications are now available on most devices on the market, it is necessary to characterize these devices with fast, easy and repeatable protocols.

1.1 Scope

The present paper describes a set-up and defines measurements to evaluate image stabilization systems. The protocols use a moving platform and a single chart. Both image stabilization for still images and for video are covered. We first describe the existing standards, then the chart that we will be using for the measurements. For still photography measurement, we follow the protocol described in a CIPA standard draft. To the best of our knowledge, there is no existing standard for video stabilization, in particular evaluating the deformation due to the electronic rolling shutter. We propose a solution and show test results. The advantages of the proposed method are the following:

- The set-up is easy to install since it uses the same hardware for photo and video.
- The blur measurement we use has been chosen by a standard (CPIQ) and correlates with human perception of blur. It can also take viewing conditions into account.
- The video measurement accounts for deformations due to the electronic rolling shutter.

1.2 Prior art, existing standards

There is no published standard for stabilization. The most advanced document is a draft by CIPA[1] that covers still picture stabilization. It is essentially a statistical blur measurement. In practice, blur is evaluated on long series of images (about 200 images per series), for different exposure times, with and without stabilization. For a given amount of blur, it is expected that a stabilized system allows longer exposure time than a non stabilized system. This exposure time is beneficial in particular for low light imaging, because it results in images with better signal to noise ratio. The performance of the stabilization is the gain in f-stop of the exposure. Strangely enough, the CIPA draft does not use any standard blur measurement (for instance the SFR method[2] of ISO 12233), but defines a new one as the width of a black/white transition. Some camera tests websites also publish lens testing including stabilization. For instance, SLRgear[3] uses a methodology close to the CIPA standard, although the blur measurement is the BxU measurement[4]. Blur measurement on a Siemens Star chart or the histogram of the image of a binary spatially white noise have also been used[5] as well as the texture MTF on a dead leaves chart[6]. Some papers[7, 8] study the motion that can be expected for real image depending on the type of camera.

2. EXPERIMENTAL SET-UP

2.1 Test chart and lighting conditions

We want to use the same chart for both photography and video stabilization. The chart must have sufficiently diversified content so that an electronic image stabilization system may have a chance to estimate the apparent motion. We also want to measure blur in any direction. Since the chart is going to move, it is also preferable that the blur measurement is independent from the position and orientation of the camera, meaning the chart is translation and rotation invariant.

We use the dead leaves chart that was introduced by Cao et al[9, 10]. as a method to evaluate the quality of texture in digital photography. This chart is composed of overlapping disks of specific random radius distribution and with neutral reflectance of random intensity, and is depicted on Fig. 1. This chart has been chosen by the Camera Phone Image Quality standard[11, 12] (now part of IEEE) to measure texture blur.

The illumination of the chart is uniform (less than 5% non uniformity on the chart) and the illumination level is adjusted so that the sensor exposure remains constant for all the different exposure times. This adaptation is crucial since we want the camera to use the same ISO setting and the same aperture, in order to make the reference sharpness identical for the different exposures. The image processing pipe of the camera is also more likely to use the same set of parameters (in particular for sharpening and noise reduction) since the sensor exposure is going to be the same for all series. For video stabilization measurement, the cameras are tested under different levels of illumination (3000 lux and 400 lux).

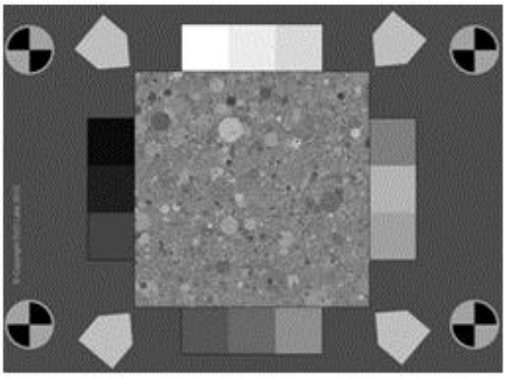

Figure 1. Dead leaves chart for texture blur, photography and video stabilization measurement. The texture part at the center is used to measure sharpness and the markers in the corner are also used to measure the apparent motion.

2.2 Motion platform

In order to fairly compare different cameras, we use a moving platform with a programmable motion. The model of the platform is PI M-840 5PD. It can produce repeatable motions with six degrees of freedom. We use the translation to fix the pivotal point of the camera and then apply rotations around the three axes. Motions have been recorded to reproduce the same motion for all the tested cameras. Different use cases have been considered, from still photography with an experienced user or video shot while walking (typically useful for photo reporter).

Figure 2. Hexapod PI M-840 motion platform used for our evaluation. The six axes are driven by a specific controller to set the position and the orientation of the platform.

The platform is both used to evaluate photography stabilization and video stabilization. The motion specifications are sufficient to reproduce the motion of a hand held camera in typical situations. The maximal travel range is more than 15° around all three axes and the maximal velocity is 600mrad°/s with repeatability of 20µrad. It can be used for smartphones but also DSLR as the maximal load is 3kg. The performance of the platform was validated by sending sine waves of different frequencies and checking that the attenuation is negligible for an input signal characteristic of human motion, both for still hand-held camera or a walking situation, and for different loads.

3. STABILIZATION FOR STILL PHOTOGRAPHY MEASUREMENT

3.1 Description of the problem

In still photography, the interest of a stabilization system in photography is the opportunity of using exposure times that are longer than those one should use to obtain sharp images without stabilization. Optical stabilization systems use gyroscopes to measure the angular displacement of the camera around pitch and yaw axes. Then, a lens or a group of lenses is displaced in order to keep the image of an object at the same location on the sensor, regardless of the shakiness of the camera. The lens can only be tilted in two directions so it is impossible for this type of stabilization system to compensate motions around the roll axis (that is, the optical axis). In-body or sensor stabilization systems use the same operating principle except that the moving part is not a lens but the image sensor itself. The sensor is mounted on a stage that can be translated and even rotated, thus allowing compensating for motions around all three axes of rotation.
Software stabilization systems (or Digital Image Stabilization) can be as simple as just increasing ISO sensitivity in order to allow the use of higher shutter speed to reduce motion blur. On the other hand, they can be very complex, decreasing global image motion as well as rolling-shutter-induced distortions by performing an advanced motion estimation based on gyroscopes and/or the video stream from the sensor.
One of the keys of still picture stabilization system evaluation is to measure the motion blur in an image.

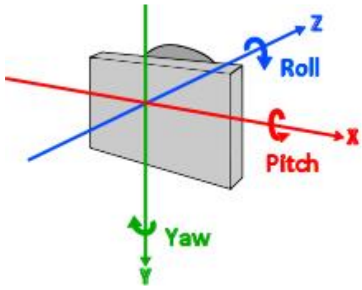

Figure 3. Rotation axes of a camera.

3.2 Measurement definition and protocol

A complexity of motion blur is that it may be highly unpredictable. The blur kernel is much dependent on exposure time and the shaking frequency of the photographer (assuming the scene is still with no moving object) and not repeatable from one shot to another. The shape of the blur kernel is usually elongated in one direction, but this direction changes over time, depending on the motion. ISO standard 12233[2] describes the computation of MTF (modulation transfer function) with the SFR (spatial frequency response) algorithm, which analyzes the response of the camera to a slanted edge. Since the direction of the blur kernel is unknown and may vary in the image field, there is a chance that an edge cannot capture motion blur if the motion is almost parallel to the edge. Therefore, we prefer to use a test chart that does not have any particular direction.

The dead leaves chart statistics has been studied in the literature, and the ratio of the power spectrum of the picture and the theoretical power spectrum of the chart defines the squared texture MTF[9, 10], exactly as an optical MTF can be defined. Since the power spectrum is computed by the 2D Fourier transform of an image, the texture MTF can also be defined in 2D. It is then averaged on angle sectors, for instance of size 45° around the average positions 0°, 45°, 90° and 135°. Given some viewing conditions (defined by a display size and a viewing distance), the texture acutance[11] can be calculated in the four directions mentioned above. It was proven by subjective analysis using the image quality rulers of ISO 20462[14] that the texture acutance correlates very well with the perception of sharpness[15].

The direction with the smallest acutance determines the principal direction of the blur. In presence of motion blur, one direction is usually far more blurry than the other ones. When we measure the sharpness on a picture, the acutance loss is due to several factors: motion blur, but also the native blur of the optics and the image processing of the camera. For the purpose of image stabilization evaluation, it is necessary to separate the motion blur from the rest. Indeed, if a lens is blurry (for instance because it is wide open, or has a lot of aberrations, or the focus is not perfectly accurate), acutance loss alone cannot be used as an indication of image stabilization performance. Therefore, the acutance with no motion (camera set on a tripod) is taken as a reference, and the variation of acutance with respect to this reference is used to measure image stabilization performance. A complete protocol of photo stabilization was proposed by CIPA[1]. It consists in comparing the sharpness of a camera with and without image stabilization for different exposure time. When exposure becomes longer, images become more blurry. Thanks to the stabilization system, the camera is supposed to be able to achieve the same sharpness for a longer exposure time than without stabilization. Photographers are used to measuring time difference in f-stop which is simply the base 2 logarithm of the ratio between two durations. The relevant information is contained in a measure of sharpness as a function of exposure time.

As described in the previous section, the sharpness loss with respect to some reference measurement (with no motion) is the relevant value. In the CIPA protocol, the sharpness measurement is given as the width of a black to white transition, which is not related to any other standard, to the best of our knowledge.

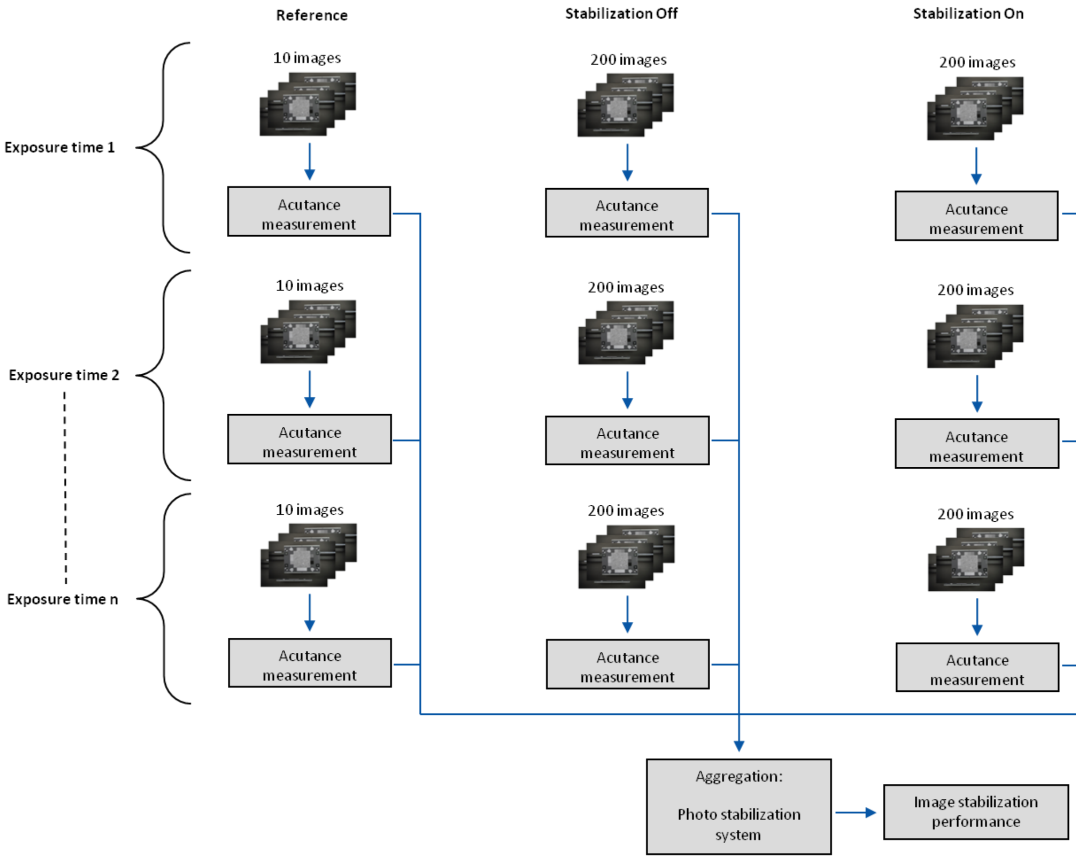

Figure 4. Workflow of still image stabilization measurement. For each exposure time, 10 pictures are shot to measure the reference sharpness of the camera; 200 pictures are shot with stabilization; 200 pictures are shot without stabilization.

We implement the CIPA protocol but take the texture acutance loss as sharpness measurement. Therefore, we compute the function

$$\text{Acutance loss} = f(\text{exposure time})$$

and find the exposure time with and without stabilization leading to the same acutance loss. The acutance loss has to be measured when the camera moves. Motion blur depends on the amplitude of the motion, but also on the particular instant the picture is shot, because motion is essentially random and may alternate essentially still phases with fast moving phases. Therefore, the sharpness measurement has to be averaged over many shots. The CIPA document recommends 200 shots for a given exposure. The exposure difference between the stabilized and non stabilized series is considered for a given acutance loss due to motion blur. This means that we also need a reference measurement, when the platform is still. The reference measurement needs fewer shots, but other parameters may vary as well, since some cameras only work in a fully automatic mode. Therefore, about 10 shots are used for the reference measurement. The workflow of the measurement is depicted on Fig. 3. We consider that the images are not acceptable when the acutance loss with respect to the still series is above 0.1.

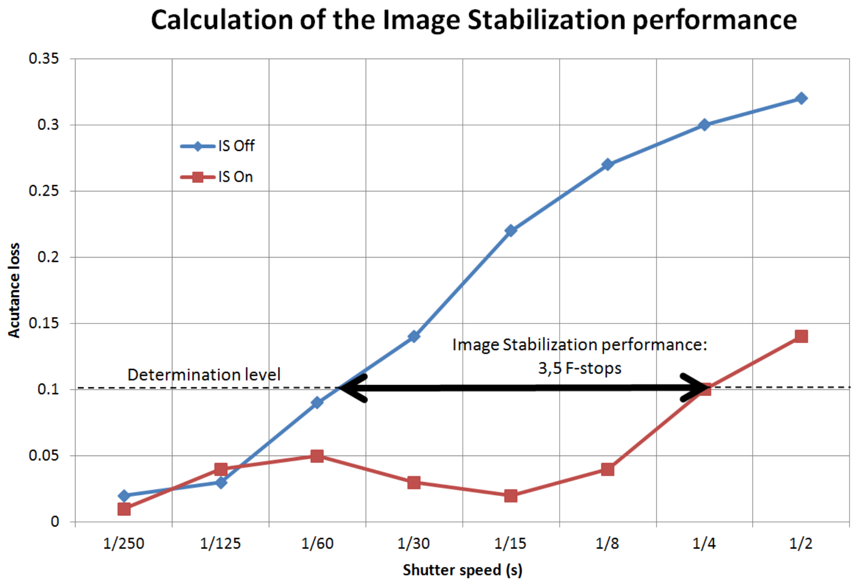

Figure 5.Calculation of the Image Stabilization performance. Without stabilization, the acceptable motion blur (0.1 acutance loss) is attained for exposure time 1/60s. With stabilization, it is possible to use 1/4s exposure time. Therefore, the stabilization system gains 3.5 f-stops. The tested lens is a Canon 15-85 IS USM at 50mm mounted on an APSC- sensor (Canon EOS 600D).

4. VIDEO STABILIZATION

4.1 Measurement definition

Video stabilization also intends to remove shaking effects, but these latter do not have the same effect on videos as on still images. In video, the purpose is basically to maintain the position of the subject at a stable position in the image field. Because of the user shaking, the subject has an apparent motion. At first order, this motion is a translation, at least at the image center. It is worth noticing that this apparent translation is actually related to small rotations of the cameras around the yaw and pitch axes. For typical focal lengths (as the ones used for smartphones), the effect of translation is negligible as soon as the subject is far enough from the camera (a few meters), but a rotation of 0.1° results in several pixels apparent translation. Rotation around the optical axis (roll) can also be seen in a lesser extent. For CMOS cameras, the electronic rolling shutter (ERS) also degrades the image quality. Because of the sequential readout of the pixels values, the lines of the sensor are not exposed synchronously and the motion of the camera during the acquisition yield a slight deformation of the scene. It is usually not a problem for still images, except in some extreme cases (the reader will easily find on the internet remarkable pictures of fast moving objects like propellers as viewed by a camera with an ERS). For video, the deformation due to the ERS is usually much more visible because it is inconsistent between one frame and another. The subject deforms as if it were elastic, hence the generic name jello effect for the deformations due to the ERS.

At first order, jello effect bends the angles between straight lines. At second order, straight lines also become curvy. We implemented a first order method that computes the deformation of the polygon given by four points. Since we ignore second order deformations, the most general transformations keeping straight lines straight is a homography.

A planar homography is represented by a 3x3 matrix H. The image of a 2D point (x, y) is calculated in homogeneous coordinates as the image of the vector $(x, y, 1)^t$ by H. This matrix H can be uniquely decomposed as

$$H = \begin{pmatrix} A & t \\ w^T & v \end{pmatrix} = \begin{pmatrix} I & t \\ 0 & 1 \end{pmatrix} \begin{pmatrix} K & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} sR & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} I & 0 \\ w^T & v \end{pmatrix},$$

where $t = \begin{pmatrix} t_x \\ t_y \end{pmatrix}$ corresponds to a 2D translation, and

$$A = sKR = s.\begin{bmatrix} 1 & \alpha \\ 0 & 1+\beta \end{bmatrix}.\begin{bmatrix} \cos(\theta) & -\sin(\theta) \\ +\sin(\theta) & \cos(\theta) \end{bmatrix}.$$

Writing $A = \begin{bmatrix} a & b \\ c & d \end{bmatrix}$, the other parameters can be expressed as follows (see the below figure for visualization of the parameters):

- The roll or rotation around optical axis Z is given by $\theta = Arctan\left(\frac{c}{d}\right)$
- The zoom ratio is given by $s = \frac{ad-bc}{\sqrt{c^2+d^2}}$
- The vertical stretch/shrink is given by $\beta + 1 = \frac{c^2+d^2}{ad-bc}$
- The shear is given by Shear $= \text{Arctan}\left(\frac{\alpha}{1+\beta}\right)$ with $\alpha = \frac{ac+bd}{ad-bc}$
- Writing $w^T = (w_1\ w_2)$, the keystoning parameters are given by:

$$\theta_{w_1} = \text{Arctan}(w_1.Y), \theta_{w_2} = \text{Arctan}(w_2.X)$$

where Y is the half height and X is the half width of the chart in the reference image.

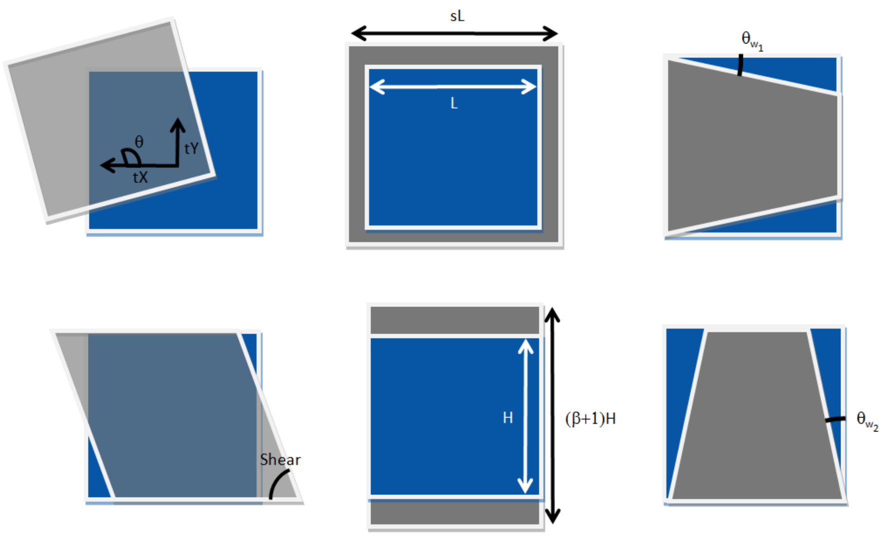

Figure 6.Representation of the parameters of the deformation induced by the camera motion and an electronic rolling shutter.

The variation of any of these parameters induces a motion or deformation of the polygon containing four vertices. Any video stabilization system intends to keep the image still and rigid. However, some systems may correct or prevent some of these deformations intrinsically better than others. For instance, Optical Image Stabilizations (OIS) used in lenses measure the rotation of the camera thanks to motion sensors (gyroscope or accelerometer) and apply the reverse motion to some movable optical element. These systems usually do not correct the rotation around the optical axis (roll). However, they limit the jello effect and also motion blur. On the contrary, Electronic Image Stabilization (EIS) systems apply some deformation on the image after it has been acquired. The deformation may be estimated from sensors (gyroscope) but also from the image itself by image processing methods. Therefore, any type of deformation can be corrected in theory, although the estimation is obviously more difficult for complex deformation models. Moreover, motion blur and its variations through time cannot be easily corrected.

The measures we calculate are the standard deviation of the horizontal and vertical translations, the rotation angle around the optical axis, the keystoning parameters and the shear. For the translations parameters only, the standard deviation is calculated after removing the low frequency. In practice, we apply a high pass filter that is 0 below 1Hz, linearly increasing from 0 to 1 between 1Hz and 2Hz, and equal to 1 above 2Hz. The reason is that we are sensitive to a sudden change of the apparent scene position in the image, but not to the absolute value of the translation. This is particularly relevant for panorama for instance, since in this case the requirement is that the motion is fluid, not that the stabilization cancels the apparent motion.

4.2 Protocol

The different cameras were positioned at fixed distance to the chart (the same for all the cameras). The cameras had slightly different focal length, so the same rotation angle yields slightly different apparent motion. However, if we normalize the apparent motion by the apparent size of the chart in the image, we can make the measurement independent of the focal length. It is necessary for some EIS systems when toggling the stabilization, because a crop is applied when the image is stabilized, therefore slightly changing the focal length.

4.3 Test results

We tested several cameras, using different types of video stabilization: optical or electronic, based on gyroscope and/or accelerometer or on the image only. The optical stabilization that we tested performs well for some motions, but seems limited for larger amplitudes. Stabilization based on gyroscopes perform equally well in bright light and low light. They also may take advantage that the sampling frequency of the gyroscope is usually much higher than the frame rate, so several motion measurements can be taken into account for correcting the image frames. Stabilizations that are not using gyroscopic data can be fooled in certain situations as moving one’s hand in front of the camera. In such cases, the camera may choose to try to stabilize the moving foreground while the still background will appear as moving in the video. This type of situation does not appear in our results since the cameras are actually moving on the platform.

Table 1. Results of video stabilization measurement. The use case is a slight motion.

Low motion	**Stabilization type**	**Translation X (pixels)**	**Translation Y (pixels)**	**Rotation (degree)**	**Shear (degree)**
No stabilization	N.A.	2.0	1.3	0.21	0.08
Apple iPhone 5	EIS	0.6	0.3	0.13	0.05
HTC 8X	EIS	1.5	1.0	0.21	0.09
Samsung Galaxy S3	EIS	0.8	0.4	0.19	0.07
Canon S100	OIS	0.7	0.5	0.21	0.08
Nokia Lumia 920	OIS	0.5	0.3	0.21	0.37
Sharp Aquos SH01D	OIS	0.5	0.3	0.22	0.20
Panasonic LX3	OIS	1.1	0.4	0.21	0.03

Table 1 shows some measurement stabilization for some recent cameras when the motion applied to the camera has low amplitude. A camera with no stabilization is taken as reference. Note that some EIS perform as well as OIS systems. The HTC 8X correction is very slight. The best systems correct approximately 70% of the camera shaking.

If we now use the same cameras with a harder use case, simulating a walking photographer, the results degrade significantly and the difference between the cameras is enhanced. Again, there are good and bad performers for both OIS and EIS. The best systems still correct about 70% of the motion in translation. The HTC 8X confirms the results with low motion. The Sharp Aquos system cannot follow this motion amplitude and barely corrects anything. The Canon S100 remains excellent. The best smartphone is the Nokia Lumia 920 using an OIS. The Samsung Galaxy S3 and the iPhone 5 obtain similar results. Beyond the translation correction, the rotation and shear deformation due to the ERS are also very interesting. Note that the ERS effect on the image also depends on the sensor characteristics, as the readout speed. That is why the reference camera with no stabilization may have better results that some other cameras with stabilization.

Table 2. Results of video stabilization measurement. The use case is a walking motion.

Walking motion	**Stabilization type**	**Translation X (pixels)**	**Translation Y (pixels)**	**Rotation (degree)**	**Shear (degree)**
No stabilization	N.A.	7.7	16.8	0.63	0.32
Apple iPhone 5	EIS	3.5	8.7	0.51	0.17
HTC 8X	EIS	6.0	13.8	0.64	0.30
Samsung Galaxy S3	EIS	3.2	8.6	0.51	0.20
Canon S100	OIS	1.7	3.6	0.67	0.17
Nokia Lumia 920	OIS	2.2	5.9	0.62	0.55
Sharp Aquos SH01D	OIS	6.8	14.5	0.65	0.78
Panasonic LX3	OIS	7.3	16.2	0.67	0.06

5. CONCLUSION AND PERSPECTIVES

We presented methods to measure photography and video stabilization. They both use the same set-up (same chart and moving platform). The photography measurement uses a protocol described by CIPA, although the measurement itself is slightly different. We used a texture acutance which has been proved to correlate very well with perceptual sharpness. The measurement needs to compare the sharpness with and without stabilization. This is completely legitimate for DSLR cameras for which all the settings can manually be changed. For some cameras, it is not possible to deactivate the stabilization, so there is no reference metric. However, knowing the motion of the platform and the camera focal length, it is possible de precisely model the blur spot due to the camera motion. This is also a suggestion of the CIPA draft, and the subject of further works.

The video measurement accounts for the apparent translation of the scene in the image but also for the deformation induced by the electronic rolling shutter in the case of CMOS sensors. In a further study, the deformation due to rolling shutter could be more precisely modeled. In particular, intra-frame deformation could be measured by optical flow like methods. The accuracy of the measurement has to be weighted with the processing complexity since the deformation field in full details is probably not useful to evaluate the performance of the stabilization system.

REFERENCES

[1] CIPA Standard DC-X011-2012, "Measurement and Description Method for Image Stabilization Performance of Digital Cameras (Optical Method)," http://www.cipa.jp/english/hyoujunka/kikaku/pdf/DC-X011-2012_E.pdf.

[2] ISO 12233. Photography -- Electronic still picture imaging -- Resolution and spatial frequency responses.

[3] Etchell D., "Image stabilization testing on SLRgear", http://www.slrgear.com/articles/is_1iswp/iswp.htm.

[4] Buzzi J. and Guichard F., "Uniqueness of Blur measure," ICIP, 2985-2988 (2004).

[5] Golika B. and Wüller D., "Measuring methods for image stabilizing systems," Proceeding of Electronic Imaging (2007).

[6] Zhu K., Li S. and Saupe D., "An objective method of measuring texture preservation for camcorder performance evaluation," Proceeding of Electronic Imaging (2012).

[7] Xiao, F. Pincenti J., John G. and Johnson K., "Camera motion and mobile imaging," Proceeding of Electronic Imaging (2007).

[8] Xiao F., Silverstein A. and Farrel J., "Camera motion and effective spatial resolution," Proceedings of the International Congress of Imaging Science (2006).

[9] Cao, F, Guichard, F. and Hornung H., "Measuring texture sharpness of a digital camera," Proceeding of Electronic Imaging (2009).
[10] Cao, F. Guichard F. and Hornung H., "Dead leaves model for measuring texture quality of a digital camera," Proceeding of Electronic Imaging (2010).
[11] Baxter D., Cao F. Eliasson H., Phillips J., "Development of the I3A CPIQ spatial metrics," Proceeding of Electronic Imaging (2012).
[12] Standard for Camera Phone Image Quality (CPIQ). http://grouper.ieee.org/groups/1858/index.html. IEEE P1858.
[13] Yu J. and Craver S., "A fast, automatic camera image stabilization benchmarking scheme," Proceeding of Electronic Imaging (2012).
[14] ISO 20462-3: 2012. Photography -- Psychophysical experimental methods for estimating image quality -- Part 3: Quality ruler method.
[15] Phillips J., Coppola S., Jin E., Chen Y., Clark J. and Mauer T., "Correlating objective and subjective evaluation of texture appearance with applications to camera phone", Proceeding of Electronic Imaging (2009).