# Optical Image Stabilization (OIS)

Fabrizio La Rosa, Maria Celvisia Virzì, Filippo Bonaccorso, Marco Branciforte.

STMicroelectronics

## 1. Introduction

For more than a decade, Image Stabilization (IS) technology has been considered essential to delivering improved image quality in professional cameras. More recently, as a result of advancing technology, IS has become increasingly popular to handheld device makers who want to propose high-end features for their products. So, manufacturers like ST have worked hard on its technologies and methods for image stabilization to significantly improve camera shutter speed and to offer precise suppression of camera vibration.

Today, from the technologic point of view, Digital Image Stabilization (DIS), Electronics Image Stabilization (EIS) and Optical Image Stabilization (OIS) are the best understood and the easiest to integrate in digital still cameras and smartphones, though they can produce different image-quality results: in fact, DIS and EIS require large memory and computational resources on the hosting devices, while OIS acts directly on the lens position itself and minimizes memory and computation demands on from the host. As an electro-mechanical method, lens stabilization (optical unit) is the most effective method for removing blurring effects from involuntary hand motion or shaking of the camera.

This paper hosts a technical explanation on the main aspects of Optical Image Stabilization and the actuator technologies and the solutions commonly available in the market. A brief description of the system solution will highlight the main parts and relative considerations on how to design the control algorithm to move the lens precisely. Finally, the last paragraph will also take into account the results obtained from tests carried out on a commercial camera retrofitted with OIS, to verify the performance evaluation method.

## 2. The spread of OIS in the market of recent years

Early on Image Stabilization was an unusual feature in traditional professional cameras and it became more common with the arrival of digital still camera (DSC) on the market. These devices have taken over the digital imaging system market and contributed to drive technological innovation in photography.

Then, in 2010, the mobile revolution started and the use of smartphones exploded. The technological evolution encouraged the major phone makers to propose innovative solutions in hardware design that allowed the integration of miniaturized photographic modules in mobile phones to take pictures with camera-like resolution. This revolution has led to the decline of compact DSCs (Figure 1), deposed by camera-equipped phones (Figure 2). Image Stabilization was a key feature, joining display dimension, Near Field Communication (NFC), the Wireless

Charging and Finger print security options, in contributing to the success of smartphones and enabling the segmentation of high-end models to low cost ones.

From a marketing perspective, according to an IC Insights report [1], sales of stand-alone digital cameras are projected to decline at an annual average rate of -10.5% in the forecast period 2012-2017, while revenues for cellphone-camera integrated circuits are expected to rise by an annual rate of 9.0% in the same period.

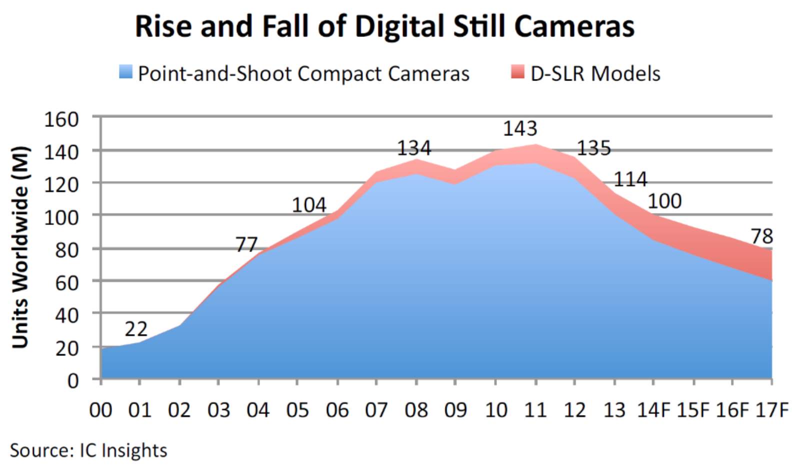
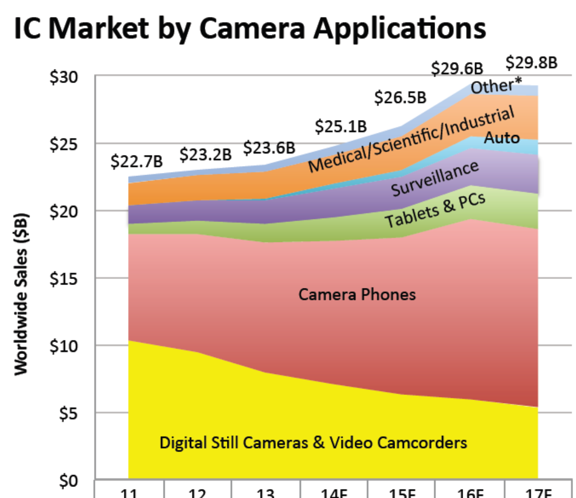



**Figure 1 : Rise and Fall of Digital Still Cameras - Source: IC Insights.**




| | 11 | 12 | 13 | 14F | 15F | 16F | 17F |
|---|---|---|---|---|---|---|---|
| Other* | $0.5 | $0.5 | $0.6 | $0.7 | $0.7 | $0.8 | $0.8 |
| Medical/Scientific/ Industrial | $1.7 | $1.8 | $2.0 | $2.2 | $2.6 | $3.1 | $3.3 |
| Automotive Safety | $0.02 | $0.03 | $0.1 | $0.3 | $0.5 | $0.87 | $1.1 |
| Surveillance Networks | $1.3 | $1.5 | $1.8 | $2.1 | $2.4 | $2.8 | $2.8 |
| Tablets/PCs | $0.8 | $1.0 | $1.4 | $1.8 | $2.1 | $2.5 | $2.6 |
| Camera Phones | $7.9 | $8.7 | $9.6 | $10.6 | $11.6 | $13.4 | $13.2 |
| Stand-alone Cameras | $10.3 | $9.4 | $8.0 | $7.0 | $6.4 | $5.9 | $5.4 |

**Includes military/aerospace, video games and toys, TVs, and other consumer electronics.*

Source: IC Insights

**Figure 2 : Break-out of camera-IC sales by type of camera application.**

As a result of the introduction of these and other innovations, the smartphone market has seen remarkable growth and it is estimated that shipments will exceed 1 billion units in 2014 for the first time.

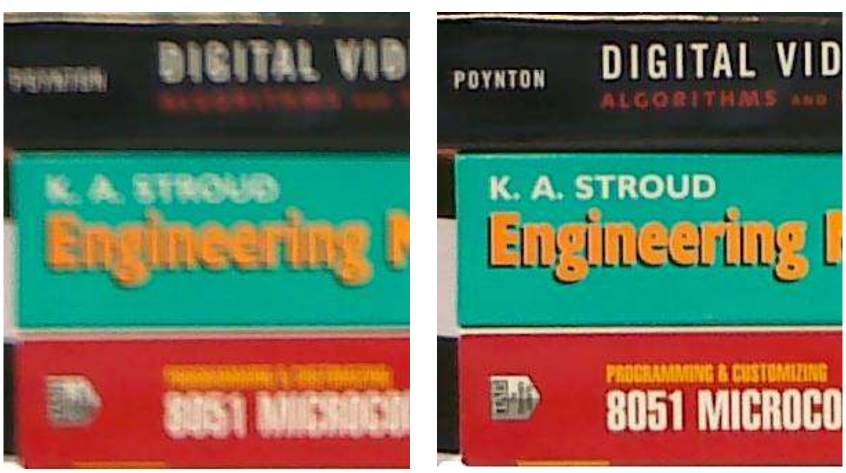
## 3. OIS: features and benefits

The DSC market has moved towards smaller sizes, lower weight and higher resolutions, much as mobile camera modules have followed the same trend after their introduction in smartphones and handsets. A big drawback to this development has been the impact of blurring, caused by involuntary motions, on image quality. In fact, lighter cameras produce greater blurring. In addition, the introduction of larger LCD displays has encouraged users to take pictures with outstretched arms, further increasing blurring.

The introduction of Image Stabilization in several mobile platforms has been a significant added value for photography lovers and especially for younger users, who replaced their traditional and bulky cameras with brand-new smartphones—or had cameras available to record memories simply because those cameras were embedded in the mobile platform they were already carrying. Image Stabilization in smartphones enables pictures and video with quality comparable to digital still cameras in so many operating conditions. As a consequence, the request for Image Stabilization is increasing both in compact DSCs and in smartphones.

Picture blurring caused by hand jitter, a biological phenomenon occurring at a frequency below 20Hz (see Section 4.1), is even more evident in higher resolution cameras. In fact in smaller resolution cameras the blurring may not exceeds one pixel, which is negligible; but in higher resolution ones it may impact many pixels, thus degrading image quality significantly (see Figure 3).

Optical Image Stabilization technology is an effective solution for minimizing the effects of involuntary camera shake or vibration. It senses the vibration on the hosting system and compensates for these camera movements to reduce hand-jitter effects. So, OIS captures sharp pictures at shutter speeds three, four, or five times slower than otherwise possible.




(a) (b)

**Figure 3 : OIS OFF (a) vs. OIS ON (b) in 5Mpixel camera.**

The increase of the shutter opening time permits more brilliant and clear pictures in indoor or low-light conditions. The time during which the shutter remains open, regulates the amount of light captured by the image sensor. Of course, the longer the exposure time, the greater the potential for hand shaking to cause blurring.

In the case of smartphones cameras, because of their small lens apertures and the material used to make unbreakable lenses, the amount of light that can enter and strike the image sensor is significantly less than that of a DSC. This requires a higher exposure time, with the obvious drawback of increasing the effect due to shaking hands.

(a) (b)

Figure 4: OIS OFF (a) vs. OIS ON (b) in outdoor night picture.

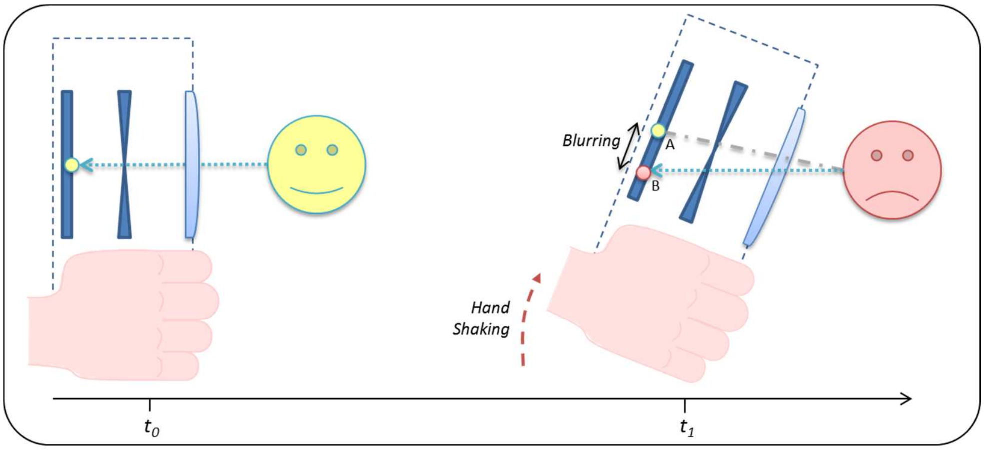
Besides the optical requirements, two main challenges in the development of OIS in smartphones are size and cost. The additional hardware required to implement OIS (see Section 5 on camera-module technology), increases the total cost of camera, and increases the camera's size. This runs counter to the constant market demand for smaller and thinner devices.

## 4. OIS: the working principle and the specification

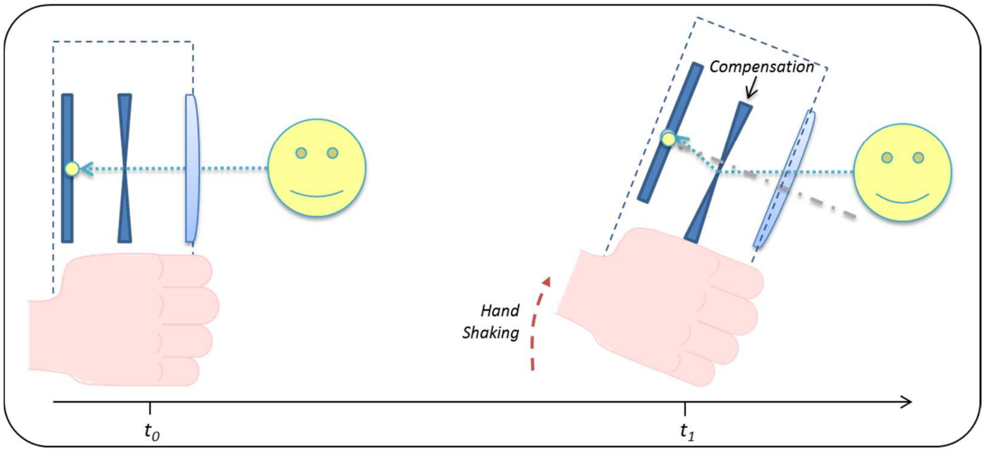
In contrast to DIS, OIS doesn't require post-processing algorithms on the captured frames [2]. OIS controls the optical path between the target and the image sensor by moving mechanical parts of the camera itself: so, even if the camera shakes, the OIS ensures that light arriving to the image sensor does not change trajectory, since we can assume any pixel color-value is the composition of a single cone of light.

The basic principle underlying OIS is simplified in Figure 5, where the movement effects are amplified and represented on a single axis, for the sake of clarity. Let's suppose we take a picture of a non-moving object in which the shutter remains open for a time interval equal to $\Delta t$; if no compensation occurs (Figure 5a), the involuntary rotation of the camera generates a distribution of the light cone, over a single pixel, splattered on a segment indicated in Figure 5a by A-B. Clearly, this phenomenon occurs across the whole image sensor, causing a blurred image.

Otherwise, when optical stabilization occurs (Figure 5b), the lens moves opposite to the direction of the camera shake and the image results to be stabilized (i.e. the subject acquired in $t_1$ coincides with image acquired in $t_0$).




(a)




(b)

**Figure 5: OIS compensation.**

As stated above, the hand movements indicated in Figure 5 were simplified to explain the compensating effect of the lens movements on the picture. In reality, hand tremors affect two axis (as depicted in Figure 6), where the light cone generated by a single white LED is distributed in the two dimensional space of the image sensor [3].

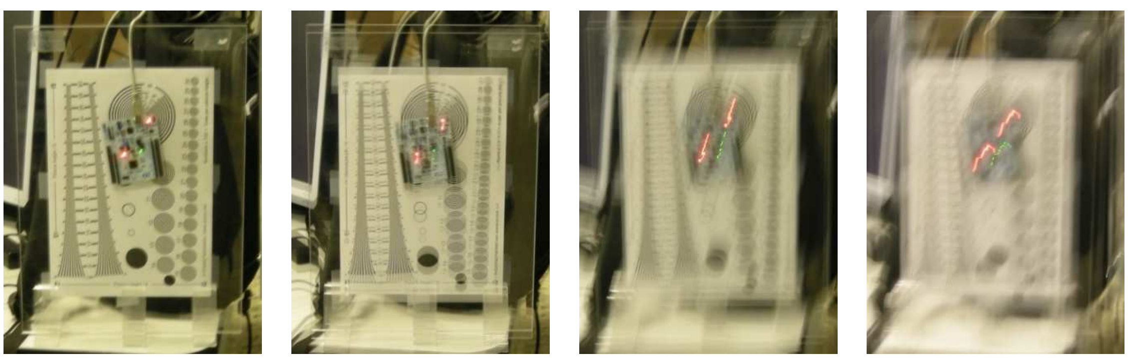


**Figure 6: Pictures captured at different shutter speeds (respectively at 1/8th, 1/4th, 1 and 2 seconds) without image stabilization.**

This clearly demonstrates that the interval time $\Delta t = t_1 - t_0$ captures more than a single rotation. In fact, the curves in Figure 6 are the convolution of the LED light distribution. Comparing these curves with segment A-B in Figure 5a makes clear hand tremor is not a predictive effect.

Finally, we need to make clear that OIS can stabilize image blur due to photographer hand trembling, but it cannot compensate for blur caused by scene motion (Figure 7).

**Figure 7: Blur due to scene motion.**

### 4.1. Physiological tremor define the OIS specification

While the tremor is not a pathology, it is a common physiological phenomenon present in all humans. It's an involuntary oscillatory movement of body parts directly generated by muscles during their activities when they contract and relax repetitively [4].

From its nature, the physiological tremor is not so clearly visible to the naked eye and is independent of age though it may depend on the capability of the body muscles to maintain a position against the force of gravity. For example, standing up and holding a camera with outstretched arms definitely produces physiological tremor in arm muscles. The consequences of this phenomenon are visible as the blurring effect in pictures: this effect is what OIS aims to reduce.

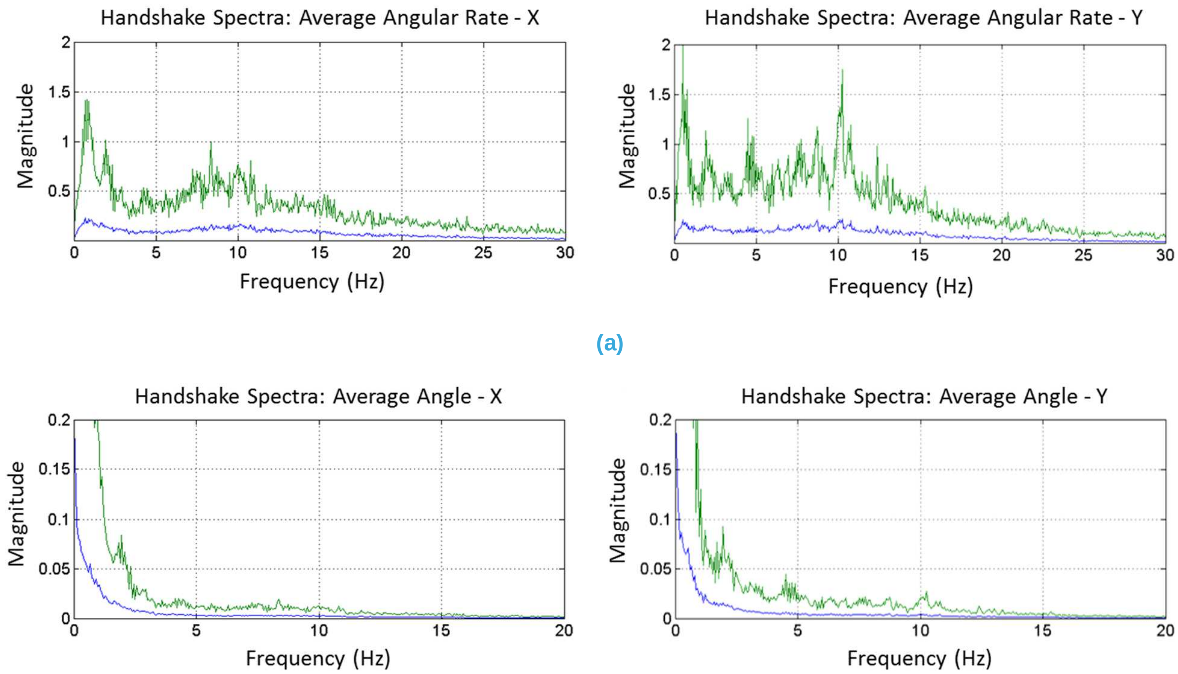
Also, for the tremor, as for many physical phenomena, statistical modeling has played an important role in understanding and identification of its characteristics.

An acquisition campaign has been conducted, over a representative population, to measure the handshake, identifying the spectrum characteristics and defining OIS specifications in amplitude and frequency.

As results of the campaign, vibration has been identified as an oscillating signal with:

- An amplitude typically less than 0.5 degrees;
- A frequency compatible with the vital signs of humans, with a spectrum in the range 0 – 20 Hz.

The relevant results of the identification test on the tremor as a signal are graphically shown in Figure 8.




(a)

(b)

**Figure 8: Mean (blue) and +3σ (green) bound on hand tremor spectra: a) angular rates measured on X and Y axis; b) angles measured on both axes**

## 5. OIS camera-module technology

As described above, the technology used to build the camera module is a fundamental factor for OIS implementation. They increase the complexity of the camera modules, which introduces new fixed and moving items, increases its dimensions and cost. OIS contains actuators that are able to move the lens, and sensors, that allow following the position.

The technology characterizes OIS-enabled modules both for the driving method and for position data sensors, greatly influencing the performance of the OIS system.

The actuator for mobile phone cameras may be built in different technologies as adaptive liquid lens (LL) [5], shape memory alloy (SMA), or a piezo-electric motor. Today, the most widespread actuators are based on the Voice Coil Motor (VCM).

Voice coil actuation exploits the interaction between a current-carrying coil winding and the field generated by a permanent magnet; the coil and the magnet, one in front of the other, are attached to two sides of the camera-module housing can. When a current is applied to the coil the interaction between the fixed and electrically-generated magnetic fields by the coil generates a force that enables the camera body to move by a distance directly proportional to the current applied.

Actually, in smartphones camera modules, the lens isn’t always the moving part.

Depending on the architecture used to build the camera modules [6], there are two main methods for OIS compensation taking its name from the mechanical structures (Figure 9) [7] [8]:

- **Barrel Shift** (also called Lens Shift) where the image sensor is fixed to the bottom of the camera case and the lenses move with a translational movement (Figure 9b);

- **Camera Tilt** where the image sensor is integrated in the same body with the lenses, and both move angularly to compensate for involuntary shaking (Figure 9c).

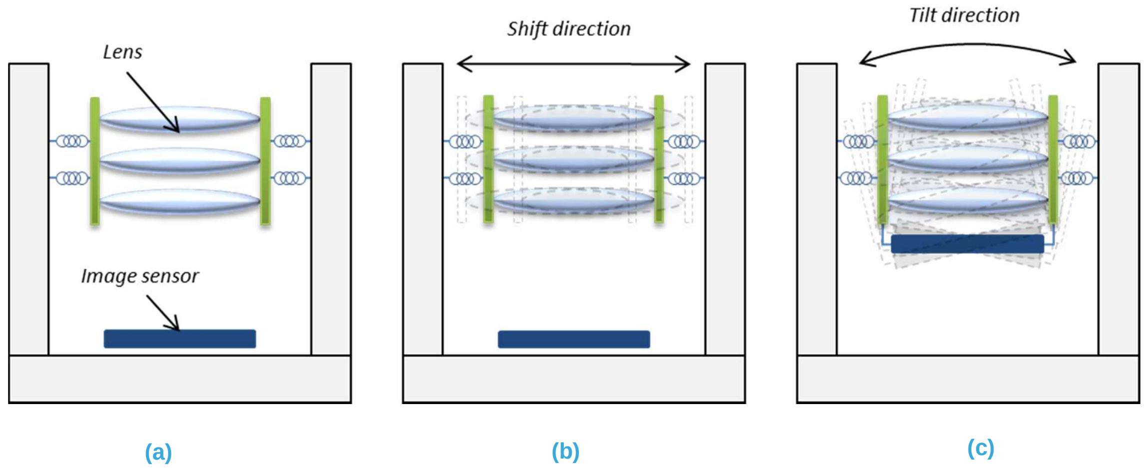



Figure 9: Camera module architecture: Lens shift (b) vs. camera tilt (c).

Another important constructive aspect of the camera module is represented by the position sensors, which are fundamental to detecting the lens movements. These sensors can be placed inside the module in either of two approaches to retrieve the position information (Figure 10):

- using Hall sensors, an approach mainly suitable for Barrel-Shift architecture;
- using photo sensors, appropriate for the Camera-Tilt architecture.

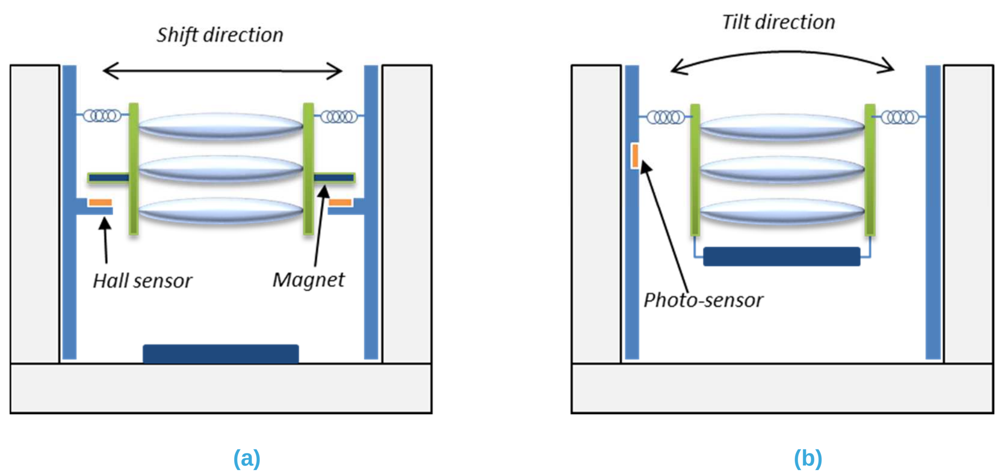



Figure 10: Camera module equipped with Hall sensors (a) and photo-sensor (b).

As previously stated, the dimensions of an OIS camera module depends on its structure and its technology, and may be slightly more bulky when compared with those of fixed-lens camera modules. On the other hand, the integration in smartphones or handsets forces designers to reduce the size of the entire OIS system (camera module + electronics), which should cover an area approximately equal size to 100mm$^2$. A common trick usually used for integrating the OIS system and saving space in smartphone platforms, is to place both the camera module and the OIS circuitry on the same flexible PCB, and then to fold it to arrange the devices alongside the camera module (Figure 11).

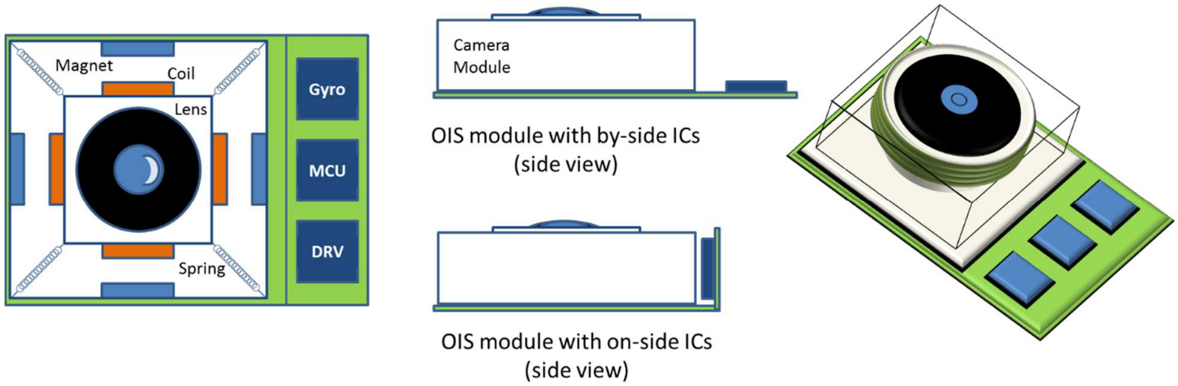



Figure 11: OIS Camera module and system in different views.

Another important consideration related to the placement of the OIS system in the mobile is the identification of the reference system that defines the orientation of movements of the entire platform: this reference is determined by the gyroscope.

The gyroscope is suited to measure the hand jitter better than the accelerometer because the blur effect caused by linear translations of camera is negligible in comparison with that caused by the component of angular rotation: this means that human jitter can best be measured by observing angular displacements.

The gyro measures angular rates along its reference axes; these angular movements along axes are known as pitch, yaw and roll. Referring to Figure 12, roll refers to the rotations around the longitudinal axis (Z), pitch to rotational movements about the lateral axis (X), and yaw to rotations around the vertical axis (Y). If the gyroscope is integral to the camera module, it detects and measures the same movements of the camera (Figure 12 and Figure 13).

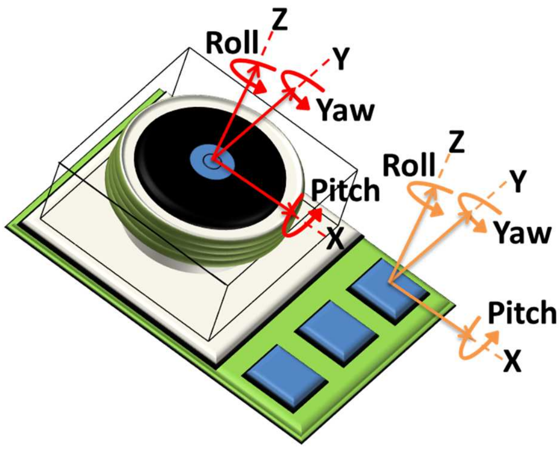



Figure 12: OIS Camera module and system with emphasis on its axes of rotation.

Figure 13 shows how the gyroscope reference system becomes the reference system of the entire platform after the placement of the OIS system inside the mobile platform.

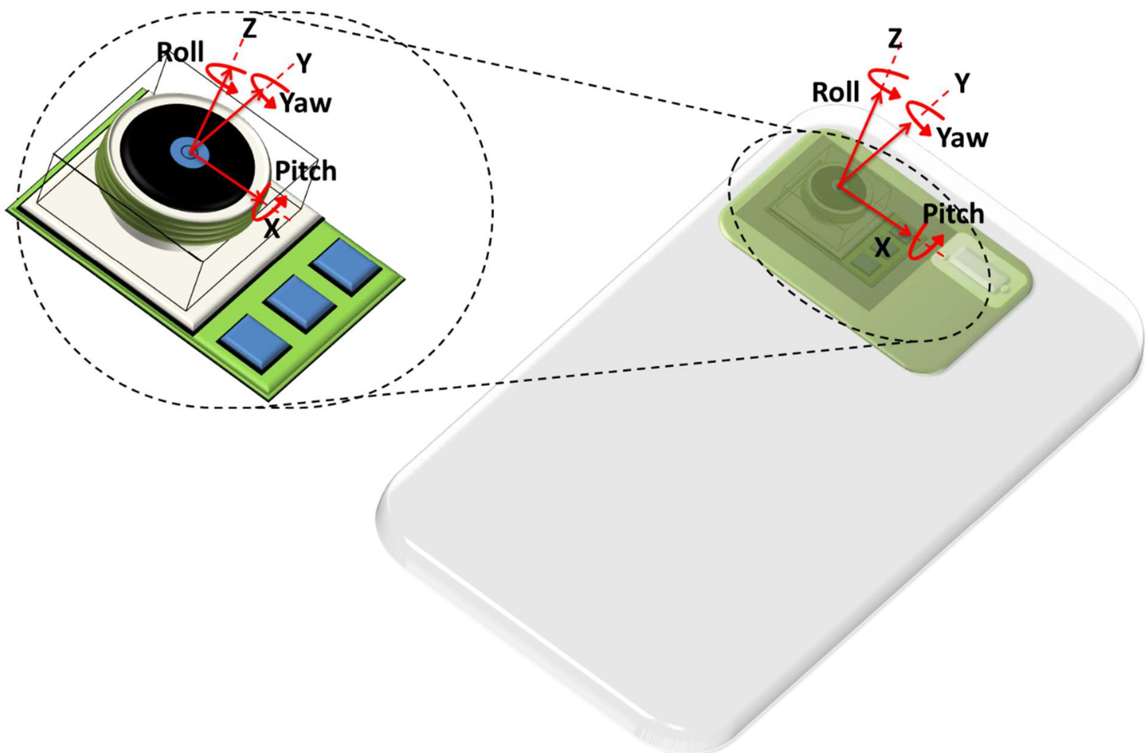



**Figure 13: Axes of motion in a smartphone, where roll is the rotation around the axis perpendicular to the image sensor plane.**

The module architectures described so far are capable of correcting the effects of camera shaking in two dimensions, pitch and yaw: in these two presented topologies it's not possible to compensate for any roll motion because no translation or rotation of the lens along the axis perpendicular to the image sensor can contribute to correct it. An action able to compensate for roll can be made by the image sensor itself only if it is able to move freely inside the camera module.

Although the camera-tilt architecture guarantees higher performance, its construction complexity has limited its adoption in commercial camera modules. Therefore, from this point, we will refer to a generic VCM-based Barrel-Shift architecture, built using Hall Sensors to manage the Lens-Shift compensation.

## 6. OIS Architecture description

The electronic circuitry implementing the optical image stabilization, partially described in the previous Section 5, is composed by four main components:

a) A ***Gyroscope,*** able to sense the movements or the vibrations inflicted on the system;
b) ***Hall Sensors,*** able to sense the lens movements, from within the camera module (as depicted in Figure 10a).
c) A ***Driver*** that performs two functions: it pilots the camera module into the right position, as calculated by a control algorithm, while, on the other hand, it retrieves the information on the camera-module position from the Hall sensors mounted inside it;

d) A ***Microcontroller*** that executes the control algorithm to correct for camera displacements.

This architecture has a notable benefit: it permits a system to operate independent of the hosting mobile platform, which autonomously compensates the camera module, thus performing OIS.

The block diagram of the control loop [9] [10] is shown in Figure 14 (the orientation refers to the system in Figure 13).

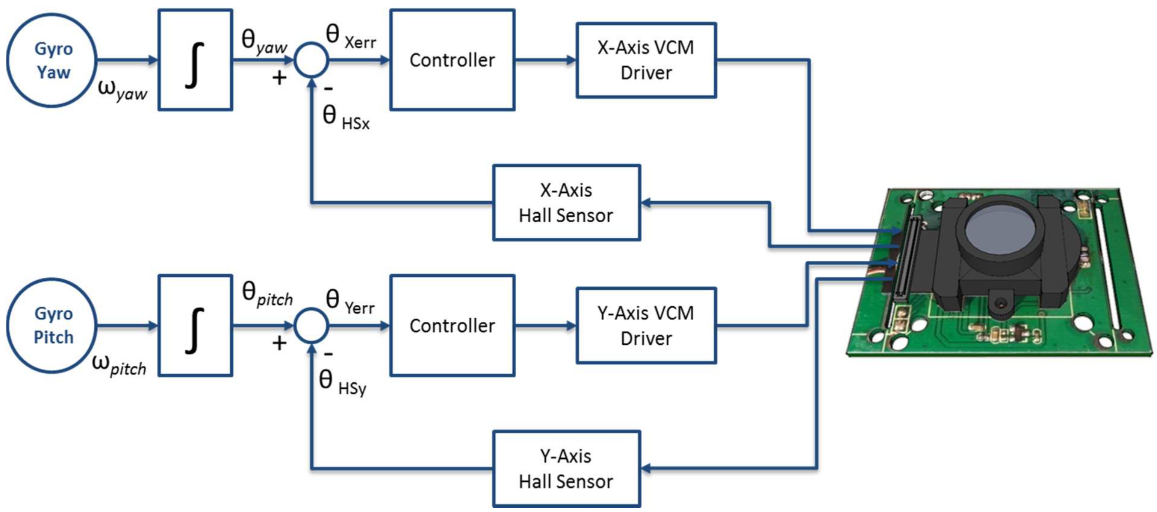



**Figure 14: OIS Control-Loop block diagram, where "$\theta_{yaw}$" and "$\theta_{pitch}$" respectively indicate yaw and pitch angles.**

According to the Control-Loop block diagram (Figure 14), the angular rates detected by the gyroscope along two main axes (pitch and yaw) are integrated to achieve the relative angular displacements. The current position of the camera module is achieved through its Hall sensors, since these are compared to retrieve the error angle which is elaborated by the control algorithm of the on-board microcontroller to set the VCM actuators' new positions. So the driver moves the camera in order to compensate for the involuntary jitter. The control algorithm should also manage the pre-processing of the acquired signals and the Hall sensors calibration compensate for the temperature drift.

The camera module makers invest a lot of effort to design modules where there is no cross-correlation between the axis movements. In other words, the VCM actuator along the X axis shouldn't generate movements on the Y axis, and vice versa. The correct placement of the Hall Sensors is equally important, since they have to detect only the movement along the single axis where they are mounted. In case there is cross-correlation on the axes' movements, the control algorithm must take this into account and introduce another input in the single-axis controller related to the reading of the other axis' Hall sensor.

### 6.1. Gyroscope

As stated, the gyroscope is the most important element in the control chain because it is the reference used to retrieve the information on angular displacement. Both the electrical and mechanical characteristics [13] of the gyro should mark out the control synthesis strategy and, in general, the overall OIS performance; for example, gyroscope accuracy is a key feature that defines the performance of the entire system; it is fundamental for controlling precision.

Other influential factors in the choice of a gyroscope for OIS are:

- phase delay: must be reduced to the minimum to avoid inserting a delay in control-loop timing;
- zero-rate offset: must be near zero in order to reduce the integration error;
- output data rate: must be higher than double the frequency of the system to be controlled (oversampling);
- measurement range: up to ±250dps must be guaranteed;
- rate noise density: this parameter must be very low to maximize the signal accuracy;
- power consumption: must be extremely low both in normal mode and stand-by mode to suit a mobile application.

The gyroscope can be directly integrated inside the housing can of the camera module: this guarantee the most faithful reference for detecting the same displacements applied on the camera module. For this reason, one of the most important considerations of a gyroscope suitable for OIS is its form factor, which must allow to be easily integrated in the thinnest camera modules.

Finally, it’s critical that the gyroscope uses a robust and quick communication peripheral to send angular data to the application processor, avoiding inserting noise or further delay in the control-loop execution timing. For this reason, an SPI peripheral is preferable to an I2C one for transferring data up to 6Mbit/sec to the MCU block.

### 6.2. Voice Coil Motor Driver and Hall Sensors position acquisition

Specific drivers are usually used for piloting lens movement of the VCM camera module and acquiring its relative positions thought the Hall sensors embedded in the camera. These mixed-signal devices may be divided in two stages, usually integrated in a unique IC: the driving stage and the acquiring one. The former houses two full H-bridges (one per axis) and two Digital-to-Analog Converters (DACs), suitable for driving the VCM actuators (i.e. assimilating to an inductance) of the camera module and producing a displacement of the lens. The latter is equipped with two Analog-to-Digital Converters (ADCs) able to read the Hall sensors on its own to retrieve the lens’ exact position.

On the driving stage, two operational modes are designed for driving VCM-based camera module in the most accurate and efficient way:

a. PWM-mode driving;
b. Linear-mode driving.

Depending on the camera-module technology, the two modes contribute in different ways to the performances of an OIS system; in fact the first mode aims to manage the power efficiency, while the second one is reduces the noise of the driven part. Concerning the first mode, the selection of the PWM operative frequency is fundamental. In fact, when the PWM frequency is in the range of audio frequencies, the mechanical parts of the camera module emit an audible whistle. Obviously, this aspect can be easily overtaken if the second driving mode is chosen, although the power contribution of this driving method could have a greater impact on the power consumption quotes.

Another important feature characterizing the driving stage is anti-ringing compensation. On the camera module, the lens is directly connected to a mechanical support anchored by springs to the fixed chassis. These springs may cause mechanical oscillation when the VCM actuators operate and may be read by the Hall sensor as a dampened ringing signal. The anti-ringing compensation reduces the settling time for every lens position adjustment and avoids any oscillation on the sudden changes of position (Figure 15).

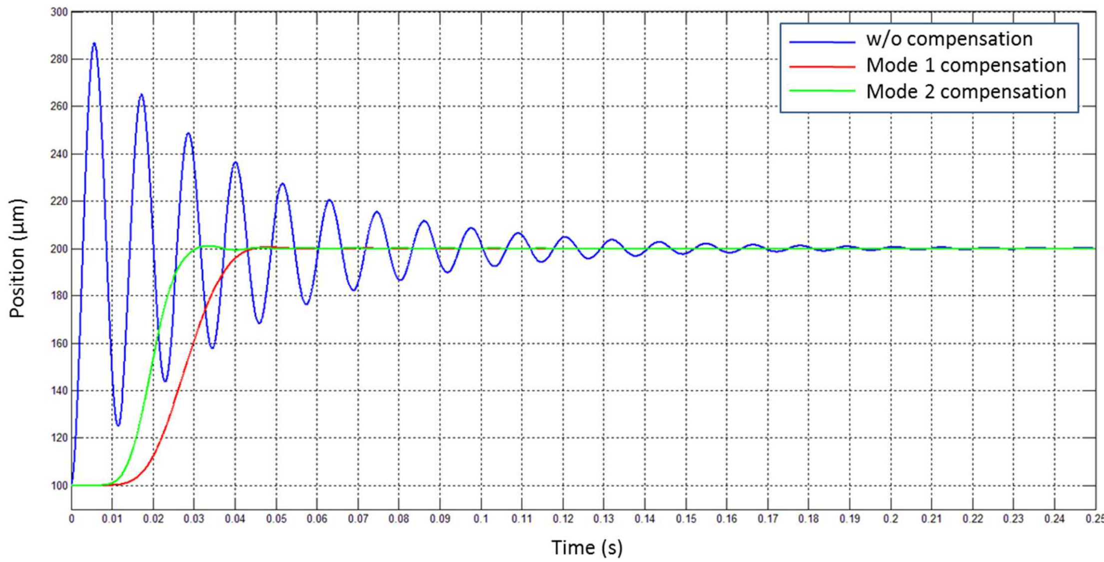



**Figure 15: Anti-ringing compensation: simulation of different modes.**

The acquisition stage is equally important in terms of accuracy, since it manages the data acquired from the Hall sensors and provides the position of the camera module lens. Obviously the Hall sensors must be accurate in detecting the slightest movement of the lens.

For the same reasons described for the gyroscope, the driver must be equipped with an SPI peripheral to be aligned with the common communication protocol of the other main blocks of the OIS system.

### 6.3. Microcontroller

The microcontroller (MCU) operates independently as the application processor cyclically executes several operations that constitute the routine of the firmware application:

– it manages the communication with the two devices (gyroscope and driver), for retrieving their data;
– it prepares and elaborates all the incoming information to adapt to the same measurement unit;
– it executes the main algorithm for controlling the entire system;
– it tells the driver the new reference condition to be actuated on the camera module.

All these operations, that constitute the main tasks of the control algorithm, impose two important technical requirements on the MCU: computational power and communication capabilities.

On the first requirement, the data must be conditioned before being processed by the control function. The MCU has to execute the routine in the fastest time possible, while managing 32-bit floating-point variables, if necessary. On the other hand, higher computing capacity capable of handling floating point may be too expensive for the application, so a 32-bit ARM® Cortex™-

based MCU could be a good choice: this technology also offers other characteristics that fit perfectly with OIS requirements, like small silicon area, low power consumption and minimal code footprint.

From the communication point of view, the MCU has to guarantee a stable link with the gyro and driver as normal operation, but another communication channel with the mobile baseband is also conceivable. So, in addition to the SPI peripherals necessary to ensure communication with the gyro and the driver as described above, an additional serial peripheral, also supporting a specific communication protocol, may be used to enable communication with the mobile baseband.

### 6.4. Control Algorithm

The control algorithm links all the hardware blocks described so far, with the control law used to manage the entire OIS system.

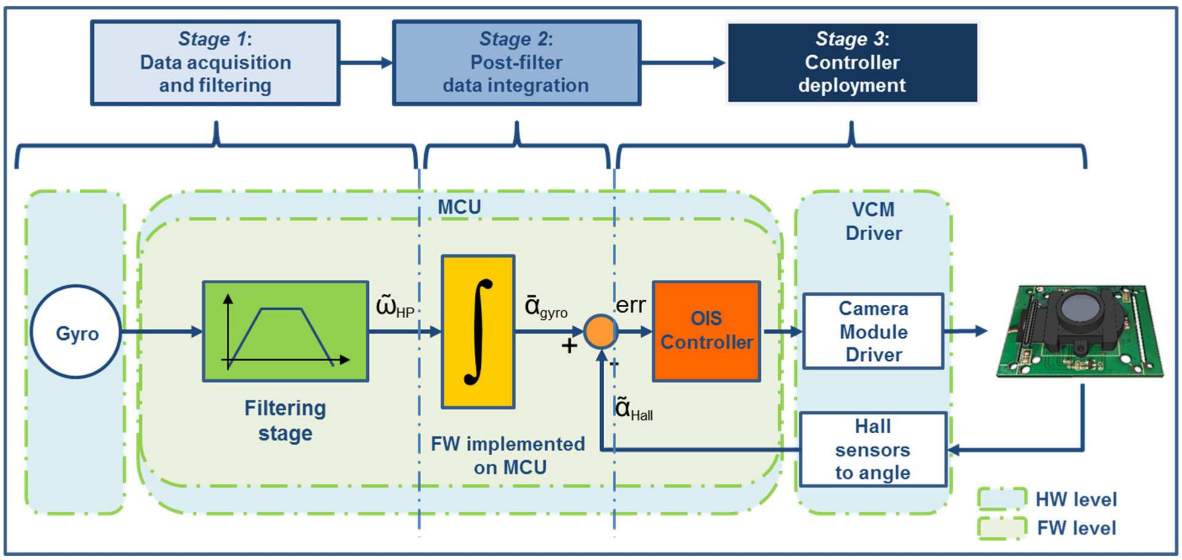



Figure 16: OIS platform: FW block scheme

Referring to Figure 16, the firmware structure may be divided in three stages representing the main tasks the system must perform to successfully run the OIS application [10]:

1. Data acquisition and filtering;
2. Post-filter gyro data integration;
3. Controller deployment;

In the first stage, angular rate data are acquired by the gyroscope and the lens position is obtained by the driver through the Hall sensors; the angular rate data are first filtered to reduce offset drift contribution. Then, in the second stage, the filtered angular rate data are integrated, obtaining the relative angular displacement caused by jitter [15]. Finally, the OIS control function processes the angular displacement and the camera-module position data, elaborating the new set-point: this value is assigned to the driver (VCM actuators) to compensate for the jitter effect.

The execution time of these operations is a key-feature of the control algorithm. It depends not only on the MCU, gyroscope and driver capabilities, but also on the response time of the camera module. This imposes one of the most essential requirements of the OIS application: the control-loop operative frequency. An effective control loop should operate with a frequency in the 500Hz to 5kHz range: this guarantees effective driving of the camera module having a standard resonance frequency around 100Hz.

To guarantee the maximum precision of the controller and reduce to the minimum the error propagation, it's essential that each data measurement and its relative elaborations are executed with the highest level of accuracy.

The angular displacement is calculated on the MCU by the following Euler integration formula:

$$\theta_{\text{gyro}}(t_1) = \theta_{\text{gyro}} + \Delta t * \omega_{\text{gyro}} \quad \text{where} \quad \Delta t = (t_1 - t_0)$$

Each error related either to the angular rate $\omega_{\text{gyro}}$ measured by gyroscope, or to the time interval $\Delta t$ measured by the MCU, may degrade the accuracy of the controller. These effects should be properly compensated to increase reliability of the whole OIS system.

### 6.5. OIS system characteristics

The most important specifications that define the OIS system are:

a) the accuracy of the controlled actuation (i.e. driver);
b) the controller resolution and the loop frequency;
c) the precision of the sensing part (i.e. gyroscope);

Every single piece must fit the specifications prescribed by the application to contribute to the perfect operation of the system. To explain how all the features of the individual blocks can define and affect OIS performance, let's manage a camera module with 8MPxl CMOS sensor, where each pixel is around 1.5µm, and able to move up to ± 200µm along its axes X and Y in a barrel-shift mechanical topology.

The pixel size provides a first level indication for the controller definition. Indeed, to guarantee excellent precision, control accuracy equal to at least one tenth of a pixel (0.15µm) is the target; this represents the smallest shift that the controller should be able to correct.

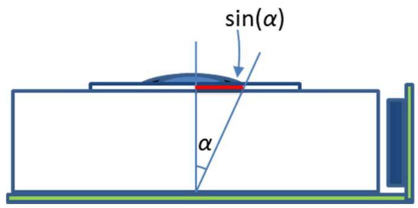
Starting from this data, we can define the resolution of the controlled actuation (i.e. driver resolution).

As stated in Section 4.1, the amplitude of human tremor is less than 0.5deg, so 1deg allows good compensation to suppress jitter. For this, it's necessary to move the camera module with a stroke of ±100µm to obtain a shift of ±1deg. It's easy to define the resolution of the driving control as:

$$Resol._{DRV} = \frac{total\ displacement}{minimum\ shift} = \frac{200\mu m}{0.15\mu m} \cong 1300\ points$$

This result means that the driver must have 11-bit resolution (i.e. $2^{11} = 2048\ points$), at least, to move the camera module along its range with a precision of 0.15µm.

It's also easy to retrieve the minimum compensation angle managed by the driver. In mobile camera modules where the focal distances are tiny, it's possible to approximate the linear shift to its relative angular shift according to the expression:




$$\frac{\sin(\alpha)}{\alpha} \cong 1$$

Figure 17: Camera module sketch-up: approximation from angle displacement to linear shift.

This yields:

$$\alpha_{DRV} \approx sin(\alpha) \approx 0.15\mu rad = 8.6\mu deg$$

A value which represents the minimum correction angle that the controller (and so the driver) should manage to ensure precision of one tenth of a pixel (0.15µm for this example).

On the other hand, before correcting jitter with that precision, the sensing part should have an accuracy that permits it to reach this kind of performance: for this reason, the minimum measurable angle is critical to complete the description of the performance.

Finally, gyroscope sensitivity is one of the most important factors for an angular sensor that represents the relationship between 1LSb and the angular rate expressed in milli-degrees per second (mdps); for a common OIS gyroscope, this characteristic is about 250LSb/dps, which means each 1 LSb represents 4 mdps.

If we establish a control frequency at 2kHz (i.e. control loop period $\Delta t_c = 0.5ms$), and execute the integration of the angular rate for each control period — considering the measurement noise as negligible—it's possible to calculate the minimum measured angle as:

$$\theta_{GYRO} \approx \omega * \Delta t_c = 4mdps * \ 0.5ms = 2\mu deg$$

This result fully satisfies the minimum angle that the driver needs to manage to have a precision of one tenth of a pixel as described before [18].

## 7. OIS performance evaluation

To evaluate OIS performance, the same methods for the lens-performance appraisal in DSCs can be used since they are based on an estimate on the image taken. Yet, evaluation of camera performance is based on a comparison between the target and an image, while two images of the target are taken with OIS OFF and OIS ON to compare.

One of the most widely used among methods for lens performance evaluation is based on the Modulation Transfer Function (MTF) [19] [20], also known as Spatial Frequency Response (SFR), which takes into account both the resolution and the contrast of the image. It measures how accurately the lens reproduces (or transfers) the details of the object to the image produced by the lens.

In image stabilization, it's essential to estimate the difference between the stabilized image and the unstabilized one. Image sharpness is the fundamental quality factor for defining OIS performance because it shows how much OIS reduces image blurring.

To better explain how the MTF is measured, it's useful to describe the factors that characterize perceived sharpness, taking into consideration the black and white bands (called Pattern) shown in Figures 18 and 19, where black is represented as 0 and white as 255.

Perceived sharpness is a mixture of two characteristics:

- Acutance: defines the slope of transitions at the borders (Figure 18). It's high when the image is represented by clearly defined borders.
- Resolution: defines the ability to distinguish the details between closely spaced elements (as the black and white lines in Figure 19).

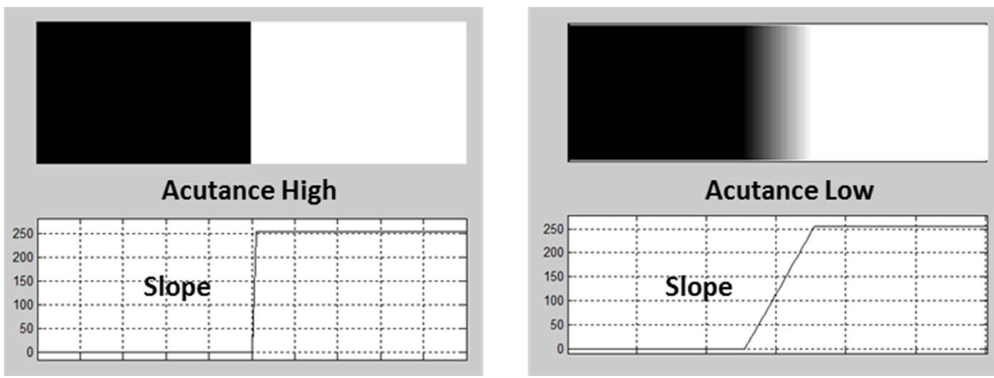



**Figure 18: Acutance: high acutance results in sharp transitions, i.e. defined borders.**

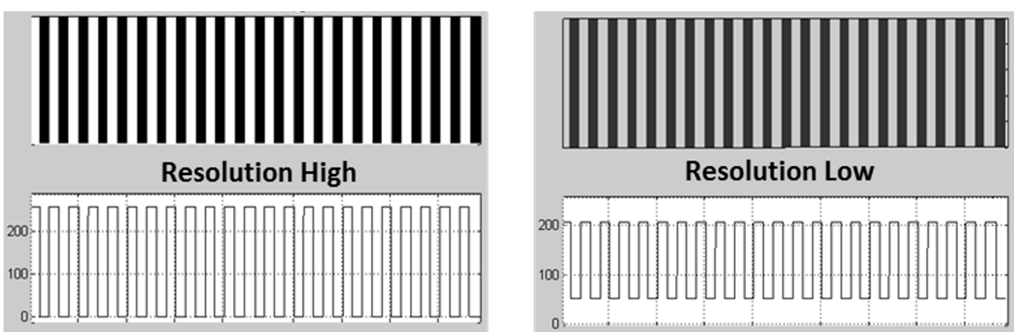



**Figure 19: Resolution: black and white stripes of the target fade into gray in case of low resolution.**

If an OIS system equipped with a camera module with high quality lens that is capable of minimizing the optical distortion of the captured image, the resolution is closely connected to the choice of the CMOS sensor whereas the acutance depends on the suppression rate that the controller applies on the jitter effect. So, the acutance is the main characteristic of sharpness which can be directly managed with the control. For OIS evaluation analysis, MTF is mainly related to the acutance estimation.

The MTF could be defined as the ratio between the relative image contrast and the relative object contrast; by convention the MTF is expressed as a percentage. For describing the MTF evaluation, Figures 20 and 21 are used as a reference. Figure 20 shows a pattern (Pattern A) of differently spaced black and white bars: four zones can be recognized according to the duration of the bars (i.e, to the spatial frequency). Assigning values ‘0’ and ‘255’ to totally black and totally white areas, respectively, generates the plot in Figure 20. When the Pattern A image passes through a camera lens and is captured by a CMOS sensor, the image is modified into something similar to Pattern B and this produces the corresponding profile in graph B.

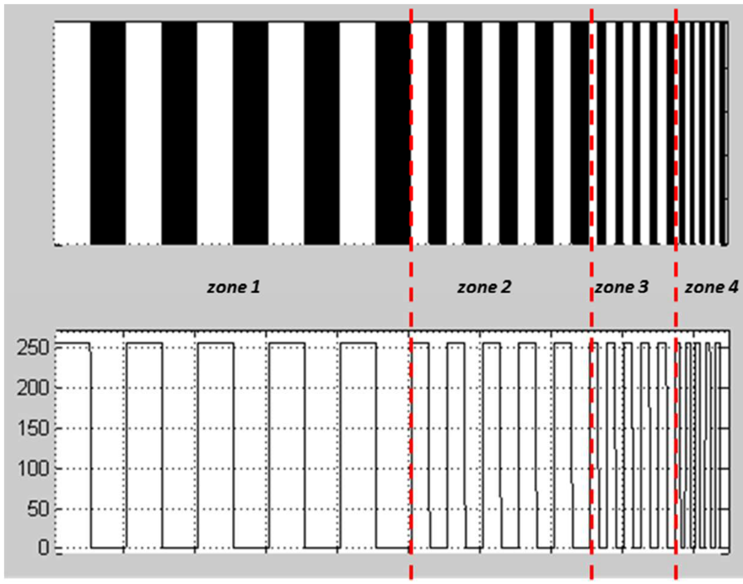



**Figure 20: Pattern A (representing object).**

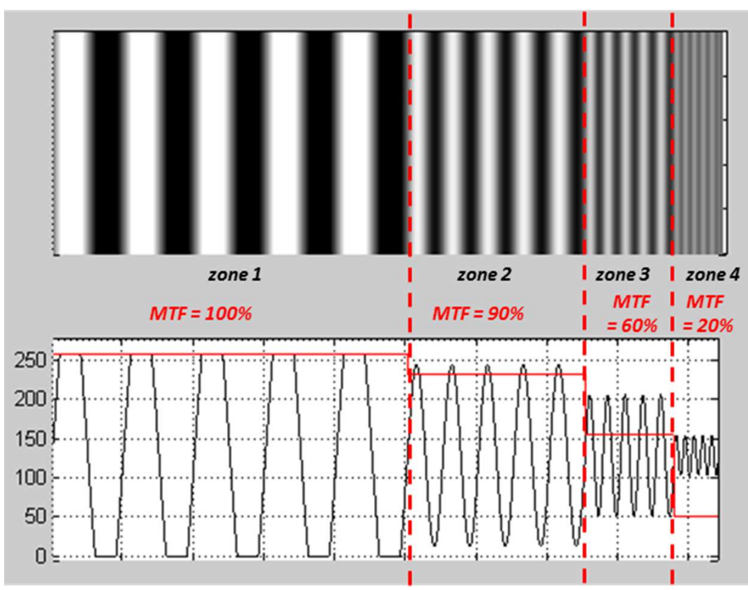



**Figure 21: Pattern B (representing image). The horizontal red line is the MTF percentage plot.**

In Pattern B, the wider spaced bars (zone 1) maintain their amplitude (still varying from ‘0’ to ‘255’) and duration but as the bars get thinner, the grey areas appear: in these sectors (zone 2, 3 and 4) the line profile no longer reaches values ‘0’ or ‘255,’ degrading the quality of the starting profile. In these zones, the original image is no longer reproduced with the initial spatial frequency.

As the stripes get closer together, the visible difference between bars decreases and edges start to blur into each other. The plot changes from a periodic signal to the average value of 127.

As previously described, in Figures 20 and 21 four zones at four different frequencies are distinguishable; the MTF is closer to 1 (or to 100%) for low frequencies (zone 1), while it drops to 20% when bars are almost indistinguishable (zone 4).

The higher the MTF, the sharper the image. In OIS-performance evaluation, the higher the MTF, the lower the blurring, and the better the image stabilization.

A variety of charts, called SFR charts, can demonstrate the quality of the image (i.e. the quality of stabilized image in OIS). These charts contain an amount of black and white or grey scale bars, lines, and circles oriented differently in space. Specific imaging software is available to compute MTF once the image of one of these SFR charts has been captured by a camera.

The target used in OIS-system evaluation is an SFR chart, as shown in Figure 22 [21].

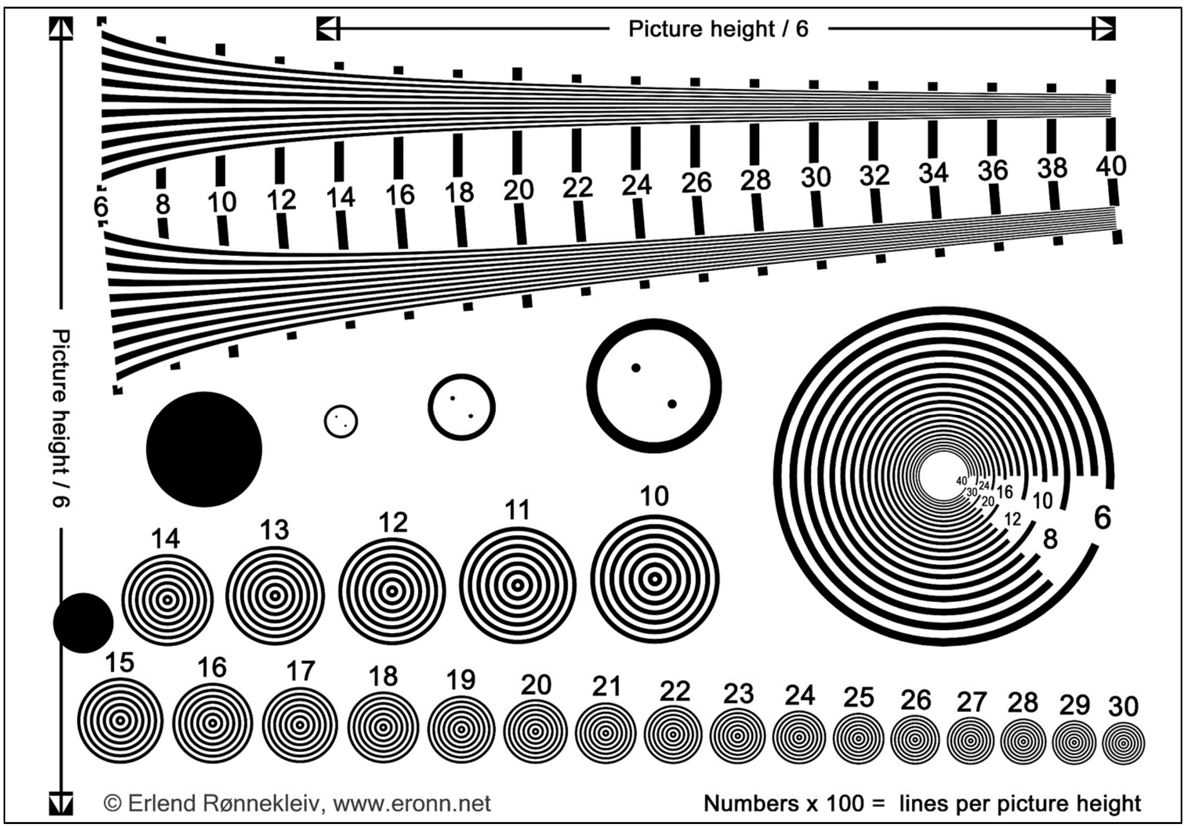



**Figure 22: SFR chart used in experiments to evaluate OIS results (Courtesy of Erlend Rønnekleiv).**

## 8. Experimental results

We have set up an experiment to test the performance of an OIS system under real-world conditions: this set-up uses a 5MPxl camera equipped with an OIS system controlled by a PC, an electro-mechanical test rig also controlled by PC, and the SFR test chart in Figure 22.

The 5MPxl camera equipped with the OIS system has been mounted on the test rig and positioned in front of the test chart.

The test rig can reproduce, with high precision, the movement trajectories previously defined on the PC, including both sinusoidal movements (i.e. single or composed frequencies oscillations), and the random movements that recreate human jitter. For this, data retrieved from a dedicated acquisition campaign for modeling human shake characteristics was passed to the test rig.

So, when the test rig “vibrates”, the images can be acquired by the camera when OIS is switched OFF and ON in order to evaluate the difference in the acquired data.

Two analytic methods have been applied to study the performance:

1. The first one is based on the data acquisition from the OIS system and the analysis of its relative signals;
2. The second method directly involves the acquisition of the SFR chart images, used for image-quality evaluation.

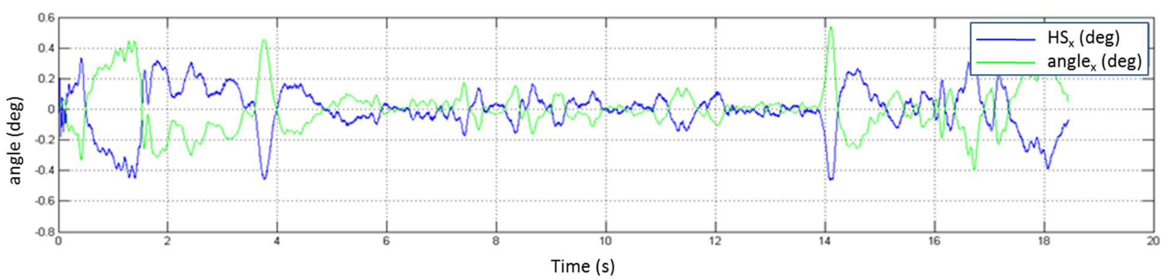
The following sections describe the two analyses.

### 8.1. OIS signals analysis

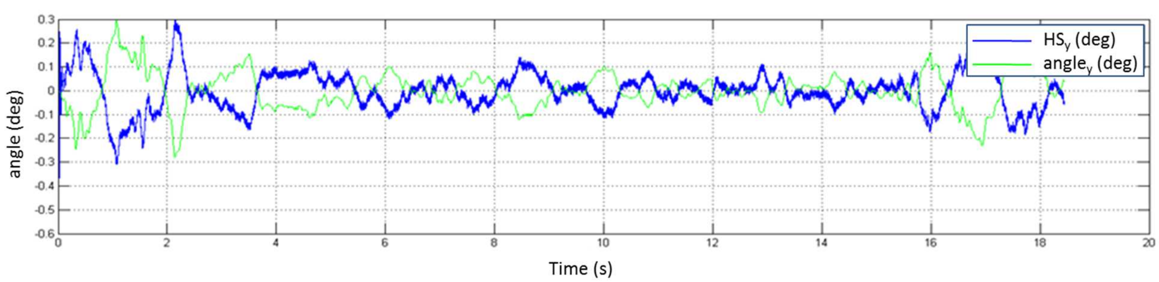
In the first analytic method, the test rig reproduces movements similar to human-caused jitter while the OIS is ON.

During the course of the test, the principal signals were acquired from the gyroscope and the Hall sensors of the camera module. The gyro data represents the test rig movements, while the Hall-sensor data is related to the camera-module movements, managed by the OIS controller.

The two pertinent signals have been analyzed and shown in Figure 23: axes are compared separately, to eliminate cross-axis error.




(a)



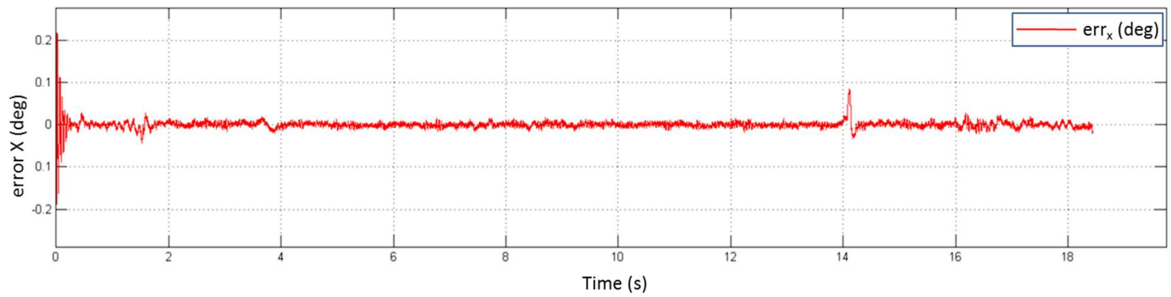

(b)

**Figure 23: OIS signals on X-axis (a) and Y-axis (b): in green gyro filtered/integrated angles (degrees), in blue Hall sensor positions (converted in degrees).**

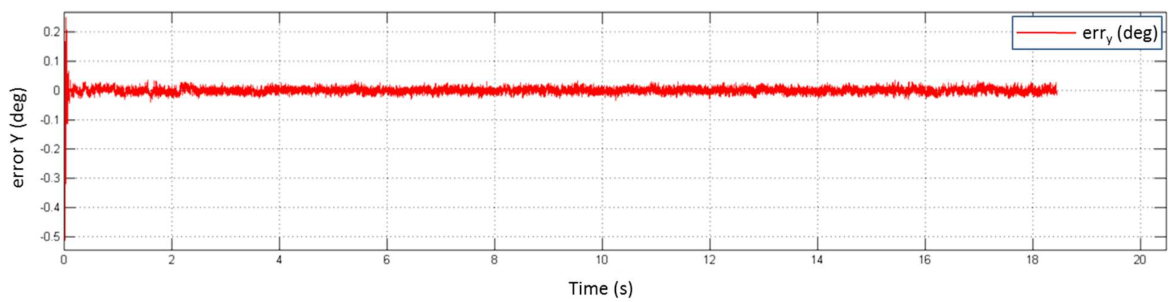
Figures 23a and 23b show how the OIS compensation works; output signals from controller (i.e. HS output in blue) act opposite to camera movements (in green).

Starting from the acquired data, to better appreciating the OIS accuracy, the error function has been calculated as the difference between the gyroscope angles and Hall sensors data converted in angles:

$$err_x = \ angle_y - HS_x;$$
$$err_y = \ angle_x - HS_y.$$




(a)




(b)

**Figure 24: The control error is the difference between the reference angle obtained by the gyro and the relative one calculated by the control algorithm ((a) X-axis, (b) Y-axis).**

The standard deviation calculated on the previous error signals is approximately 15mdeg; this means the system can compensate to around ten thousandth of degree, over a maximum angular displacement ±1 degrees, due to hand jitter.

### 8.2. Image acquisition

The second test allows direct visual feedback on the operation of image stabilization, by acquisition of the image itself. This test has been carried out with the test rig reproducing different sinusoidal signals at the frequencies 1Hz, 5Hz, 9Hz, 12Hz and 15Hz, respectively; the camera acquired the SFR chart image when OIS was OFF and ON and the pictures compared.

Satisfying results of the optical image stabilization are clearly visible in Figures 25 - 29.

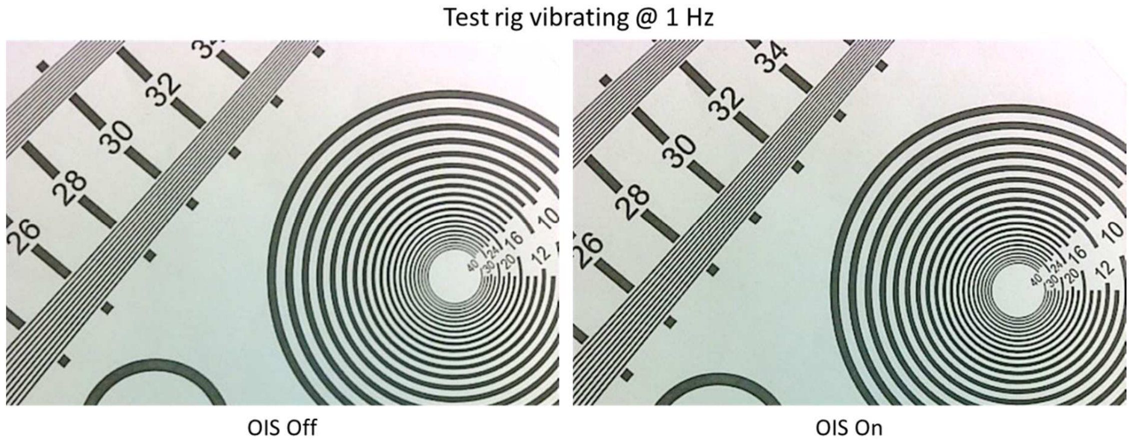



Figure 25: OIS Off/On with test rig vibrating at 1Hz.

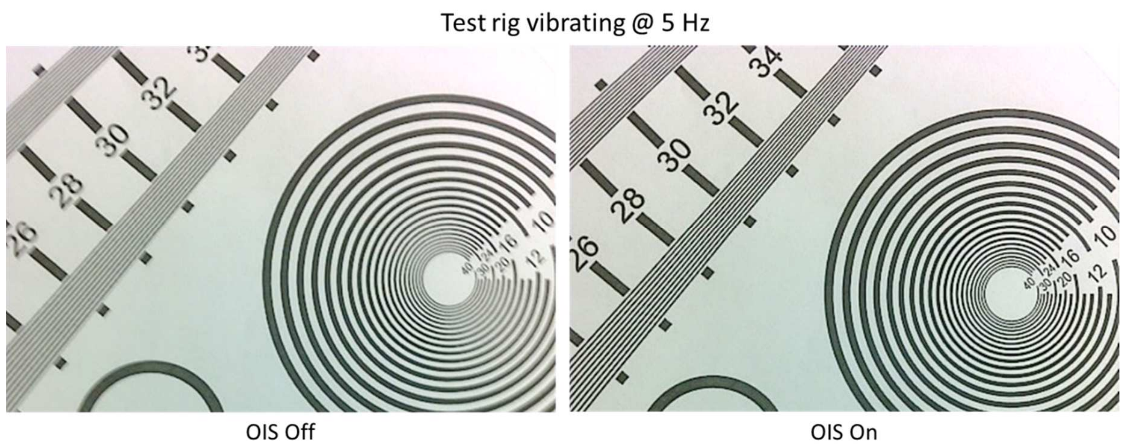



Figure 26: OIS Off/On with test rig vibrating at 5Hz.

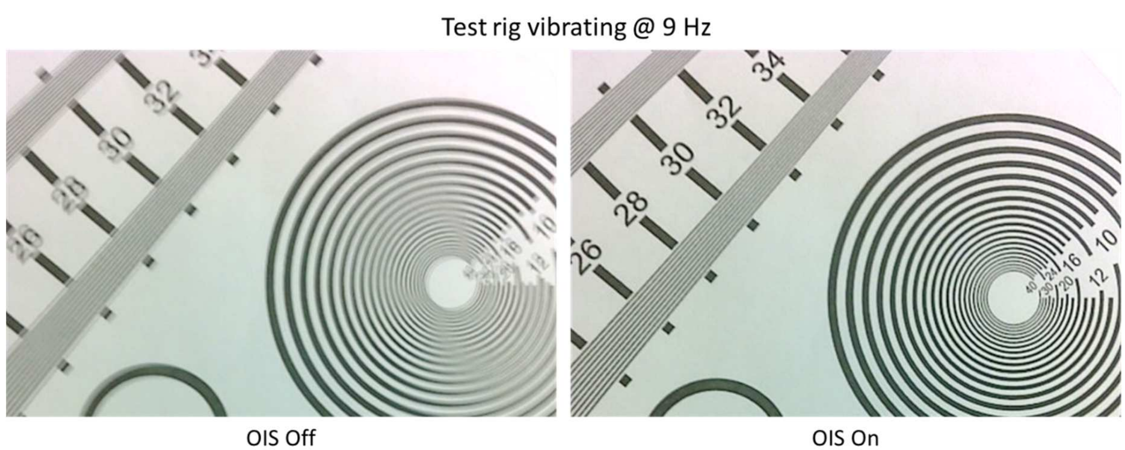



Figure 27: OIS Off/On with test rig vibrating at 9Hz.

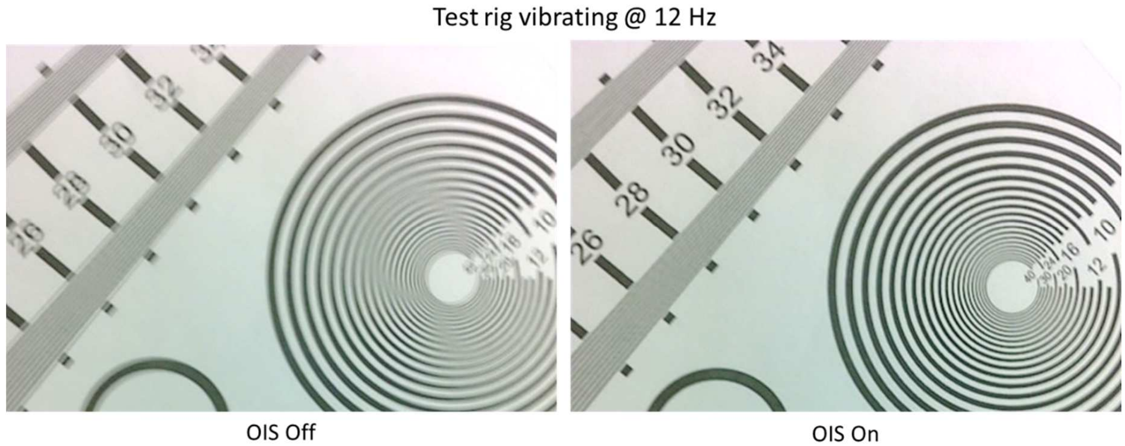



**Figure 28: OIS Off/On with test rig vibrating at 12Hz.**

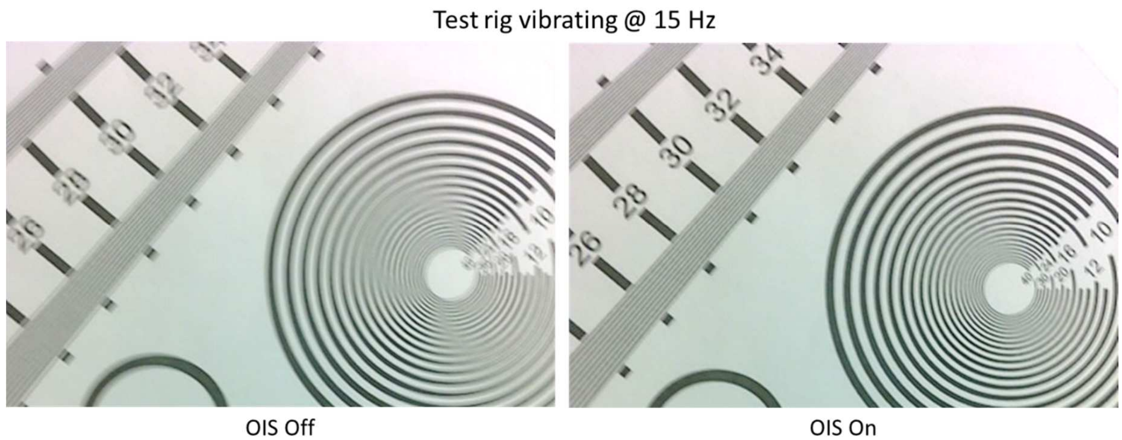



**Figure 29: OIS Off/On with test rig vibrating at 15Hz.**

## 9. Conclusions

Optical Image Stabilization is a mature technology that minimizes blur caused by camera shake. For a long time, it's been the essential feature of professional cameras and digital still cameras. More recently, thanks to mobile technology evolution, it has rapidly become an essential feature across flagship smartphones.

This paper describes the OIS system and the relative camera module application, as implemented on smartphones and handsets. We've also presented the OIS camera module technology that corrects the variation of the lens position to compensate for accidental movements that cause blurring.

The OIS system has been described as the union of a gyroscope sensor for detecting vertical (pitch) and horizontal movement (yaw), a microcontroller executing a control algorithm that determines how much compensation is needed to correct the camera's shake, and a driver controlled by the MCU that retrieves the lens position information from the camera module's Hall sensors and sets the corrected position via the two voice coil motors embedded in it.

In this way, the system can compensate for the detected motion, moving the lens elements on the camera to produce sharp high-acutance and high-resolution images.

Finally, the results of an experimental test conducted on an OIS system have been presented proving the effectiveness of this application using the captured images where jitter-caused blur has been strongly reduced and the images' higher quality has been guaranteed by the adoption of this technology.

## 10. Acronyms

| Acronym | Definition |
|---|---|
| ADC | Analog-Digital Converter |
| CMOS | Complementary Metal-Oxide Semiconductor |
| DAC | Digital-Analog Converter |
| DIS | Digital Image Stabilization |
| dps | degree per second |
| DSC | Digital Still Camera |
| EIS | Electronic Image Stabilization |
| HS | Hall Sensor |
| IC | Integrated Circuit |
| IS | Image stabilization |
| LCD | Liquid Crystal Display |
| LL | Liquid Lens |
| LSb | Less Significant bit |
| MCU | MicroController Unit |
| MTF | Modulation Transfer Function |
| NFC | Near Field Communication |
| OIS | Optical Image Stabilization |
| PCB | Printed Circuit Board |
| PWM | Pulse Width Modulation |
| SFR | Spatial Frequency Response |
| SMA | Shape Memory Alloy |
| SPI | Serial Peripheral Interface |
| SR | Suppression Ratio |
| VCM | Voice Coil Motor |

**Table 1: Acronyms list**

## 11. Bibliography


[1] . "*IC Suppliers Shift Strategies to Counter Decline in Digital Still Cameras*", IC Insights, July 01, 2014, http://www.icinsights.com/news/bulletins/IC-Suppliers-Shift-Strategies-To-Counter-Decline-In-Digital-Still-Cameras/?_sm_au_=iVVjFrTNfDTFQ87M;

[2] . Paresh Rawat, Jyoti Singhai, "*Review of Motion Estimation and Video Stabilization techniques for hand held mobile video*", Signal & Image Processing : An International Journal (SIPIJ) Vol.2, No.2, June 2011;

[3] . Kazuki NISHI, Tsubasa ONDA, "*EVALUATION SYSTEM FOR CAMERA SHAKE AND IMAGE STABILIZERS*", The University of Electro-Communications, Tokyo 182-8585, Japan, IEEE, ICME 2010;

[4] . Wyne, Kevin T., ” *A comprehensive review of tremor*”, 2005;

[5] . Eric Simon, Bruno Berge, Franck Fillit, Hilario Gaton, Martin Guillet, Olivier Jacques-Sermet, Frédéric Laune, Julien Legrand, Mathieu Maillard, Nicolas Tallaron “*Optical design rules of a camera module with a liquid lens and principle of command for AF and OIS functions*”, Varioptic, 24B, rue Jean Baldassini, 69007 Lyon, France;

[6] . *Opto-mechatronic systems handbook*, Techniques and Applications, CRC Press LLC, 2003;

[7] . Chien-Sheng Liu and Psang-Dain Lin, “*High Position Repeatability of Miniature Actuator*”, Department of Mechanical Engineering, National Cheng Kung University, Tainan 70101, Taiwan, Sensors and Materials, Vol.20, No.7 (2008) 319-326, MY Tokyo;

[8] . L. K. Lai, T. S. Liu, “*DESIGN OF AUTO-FOCUSING MODULES IN CELL PHONE CAMERAS*“, Department of Mechanical Engineering, National Chiao Tung University, Hsinchu 30010, Taiwan, INTERNATIONAL JOURNAL ON SMART SENSING AND INTELLIGENT SYSTEMS VOL. 4, NO. 4, DECEMBER 2011;

[9] . Seung-Kwon Lee, Jin-Hyeung Kong, “*An Implementation of Closed-loop Optical Image Stabilization System for Mobile Camera*”, Dongwoon Anatech. Co. Ltd., Kwangwoon University, 2014 IEEE International Conference on Consumer Electronics (ICCE);

[10] . Koichi Sato, Shigeki Ishizuka, Akira Nikami, and Mitsuru Sato, “CONTROL TECHNIQUES FOR OPTICAL IMAGE STABILIZING SYSTEM”, Sony Corporation, Tokyo, Japan, IEEE 1993;

[11] . STM32 32-bit ARM Cortex MCUs: http://www.st.com/web/en/catalog/mmc/FM141/SC1169?s_searchtype=reco;

[12] . Motion MEMS Smart multi-axis solutions for enhanced user experience, http://www.st.com/web/en/resource/sales_and_marketing/promotional_material/brochure/brmems.pdf, BRMOTIONMEMS1213;

[13] . TA0343 Technical article, “*Everything about STMicroelectronics’ 3-axis digital MEMS gyroscopes*”, Doc ID 022032 Rev 1, http://www.st.com/web/en/resource/technical/document/technical_article/DM00034730.pdf;

[14] . “*L3G4IS MEMS motion sensor: three-axis digital output gyroscope for gaming and OIS*”, Datasheet, Doc ID 022612 Rev 1, http://www.st.com/web/en/catalog/sense_power/FM89/SC1288/PF253096?s_searchtype=keyword;

[15] . Zhang Yong-xiang, “*A Method of Resolving Gyro Zero Drift in Electronic Stabilization System*”, College of Information Engineering, Capital Normal University Beijing, China, International Conference on Computer and Automation Engineering;

[16] . Tzuu-Hseng S. Li, Ching-Chang Chen, “*Extended Kalman Filter based Hand-shake Detector for Optical image Stabilization Using a Low Cost Gyroscope*”, IEEE;

[17] . Chin-Teng Lin, Fellow, IEEE, Chao-Ting Hong, Member, IEEE, and Chien-Ting Yang, “*Real-Time Digital Image Stabilization System Using Modified Proportional Integrated Controller*”, IEEE TRANSACTIONS ON CIRCUITS AND SYSTEMS FOR VIDEO TECHNOLOGY, VOL. 19, NO. 3, MARCH 2009;

[18] . Zhang Yong-xiang, Zhang Wei-gong, Zhao Xiao-xu, and Yuan Hui-mei, “*Study on Electronic Image Stabilization System Based on MEMS Gyro*”, College of Information Engineering Capital Normal University Beijing, China;

[19] . SPIE: “*Modulation Transfer Function*” Society of Photo-Optical Instrumentation Engineers, Redondo Beach, California, 1968, Proceedings, Seminar-in-Depth;

[20] . Bengt Nielsen, “*Resolution, unsharpness and MTF*”, Institutionen för medicin och vård Avdelningen för radiofysik Hälsouniversitetet, Department of Medicine and Care Radio Physics Faculty of Health Sciences;

[21] . Erlend Rønnekleiv, “*SFR test chart”*, http://www.eronn.net/camera/test-chart/resolutionChart.jpg ;

[22] . SLRgear Image Stabilization Testing, Version 2, http://www.slrgear.com/articles/ISWP2/ismethods_v2.html.