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ARTIFICIAL ENHANCEMENT OF FILL FACTOR AND RESOLUTION FOR MONOCHROME CMOS SENSOR ARRAY

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Abstract. In this paper we present a piezoelectric method to increase simultaneously both resolution and fill factor of a conventional CMOS sensor array. For this improvement we scan a photo lens image plane with the surface of a commercial CMOS sensor, placed perpendicular on the system optical axis at 45 degrees to the horizontal. The method takes advantage of the image sensor inter-photosite distance and its higher diagonal resolution. For our experiment we use two images of the same scene, distanced from each other, on the horizontal axis of the image plane, with half of a diagonal length of an effective sensor photosite area. The images are combined, using a pixel interlacing method, into one new image with higher resolution and fill factor.

Key words: CMOS sensor, fill factor, resolution, pixel.

1. INTRODUCTION

Since its infancy, almost 50 years ago, CMOS sensors have come a long way toward becoming a proven technology. Nowadays, its high degree of versatility, not found in other sensor arrays, makes them suitable for complex imaging applications in various fields of activities like: space, security, scientific, medical, biometrics etc. [1–3].

A CMOS sensor consists of a light-sensitive area divided into a grid of photosensitive diodes, called *photosites*. Each photosite is capable of generating an electrical charge proportional to the intensity of the light that reaches its surface. Straight from the manufacturing process a CMOS sensor is color blind and its light sensing performance can still be improved. Covering the sensor with a mosaic pattern color filter (Bayer or CMYG) and a microlens array will offer its color sensitivity and enhance its light-gathering ability. The necessity for using a microlens array is intimately related to an essential parameter of image sensors, namely fill factor. Since always a part of the sensor area is assigned to electrodes, transistors and registers to form the photosite structure, fill factor can be described as the ratio of the remaining photosensitive area *versus* total area of the sensor. Knowing that only the photosites contribute to light conversion, the spaces between them remain blind to incident radiation and a potential part of image information is lost [5–9].

An important factor that limits the resolution of imaging systems, in addition to diffraction and optical aberrations, is the size of the photosite [4]. Although the pixels of an image have no physical shape or size the information contained in them correspond to the sensor photosites whose dimensions can be measured [10]. Often fine image details are smaller than what a pixel can represent and in order to observe them we need to increase the optical resolution. Traditionally this can be achieved by replacing the sensor with a more expensive one, with higher photosite density for the same photosensitive area.

For this paper our main objectives are to increase the resolution of a monochrome CMOS sensor and compensate its fill factor without any physically modifying its structure. To demonstrate our method we use two images of the same scene, distanced from each other with the equivalent of half a photosite diagonal. Overlapping the sensor photosites area over its blind area, by diagonal translation, we collect new image samples, relevant for our final image. Further, through a process of 2 × 2 pixels binning, we redefine the photosite size and compensate the sensor fill factor.

2. MATERIALS AND METHODS

Continuous exposure to a visually rectangular world shaped human vision to manifest higher visual acuity on horizontal and vertical axis than in other orientations [3, 4]. Yet, current and future commercial imaging systems tend to provide a higher optical resolution on their diagonal axis.

Figure 1 shows at point “a” the geometrical orientation of the sensor surface and its physical positions F_1 and F_2 in the image plane, and at point “b” Aptina MT9M001 CMOS sensor surface, under a microscope magnification.

Rotating the sensor 45° on the system optical axis serves as a geometric trick to change the vertical/horizontal resolution with diagonal resolution. Further, by collecting the information from the blind spaces between diagonal adjacent photosites we gain additional image information.

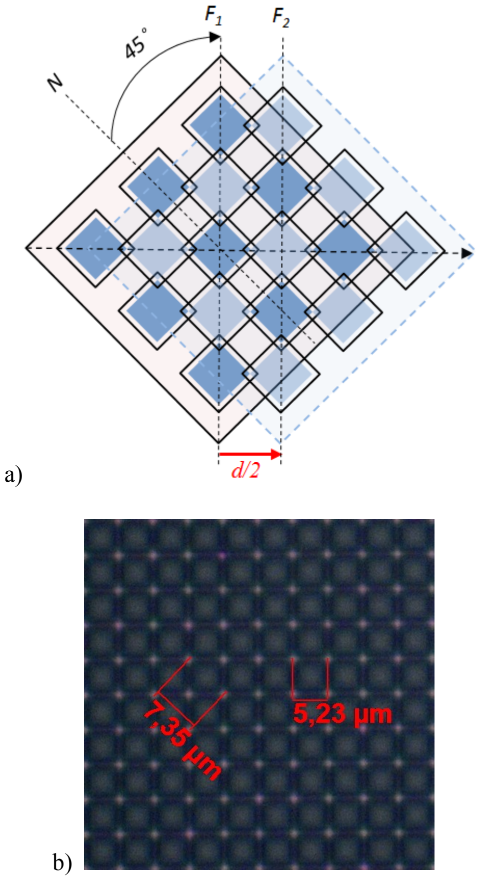


Fig. 1 – a) Geometrical orientation of the sensor surface and its physical positions F_1 and F_2 in the image plane; b) Aptina MT9M001 CMOS surface, under the magnification of Zeiss AxioImager.

We use a two-step method to acquire two images of the same scene at two predefined positions in the image plane. After the first image is taken, we reposition the sensor at precisely half the diagonal length of two adjacent photosites ($d/2$), to acquire the second image.

For the accurate determination of $d/2$ value, we measure the physical dimensions of a photosite with Zeiss AxioImager optical microscope and compare the measurement values with the sensor specification sheet. The measurement information, illustrate a square-shaped photosite of ~ 5.23 µm sides and ~7.35 µm diagonals, values which are consistent with the manufacturer specifications, and from which we geometrically estimate the value of $d/2 \approx 3.677$µm.

To put our method to the test we use a CMOS sensor with 1280/1024 resolution, mounted on a high precision piezoelectric actuator. The integer part value of *d*/2 is at micrometer scale, while the fractional part is at nanometer scale. In order to precisely position the sensor on the horizontal axis of the system, for the second image acquisition, we need a length measurement tool capable of measuring long range excursions with nanometer precision. After the image of an object is formed on the sensor surface, with a fixed focal length photo objective, the image frames acquisition starts. For each image acquisition we maintain a constant aperture, focal length, object distance and irradiance. Also the electronic settings of the sensor are kept constant at a fix value.

Figure 2 offers an elaborate visual representation of the optical system and its components.

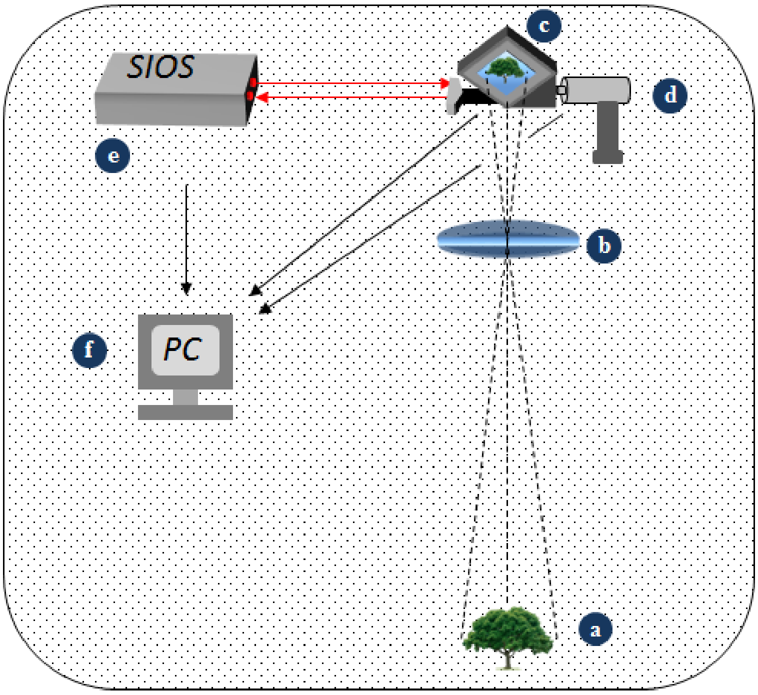


Fig. 2 – Experimental improvement of CMOS sensor resolution and fill factor. System physical components: a) object scene; b) photo-objective lens; c) CMOS sensor; d) piezoelectric actuator; e) SIOS interferometric length measurement system; f) computational and control unit.

For the image sensing part we use a Thorlabs DCC1545M camera with an Aptina MT9M001 CMOS monochrome sensor (Fig. 3c) [11, 12]. The displacement from one image frame to the next is performed with a *Piezosystem Jena* P-152-00 piezoelectric actuator (Fig. 3d) [13]. To control the actuator, we determine and correct its movement in a feedback loop with SIOS MI 5000 high accuracy retro-reflector interferometer (Fig. 3e) [14].

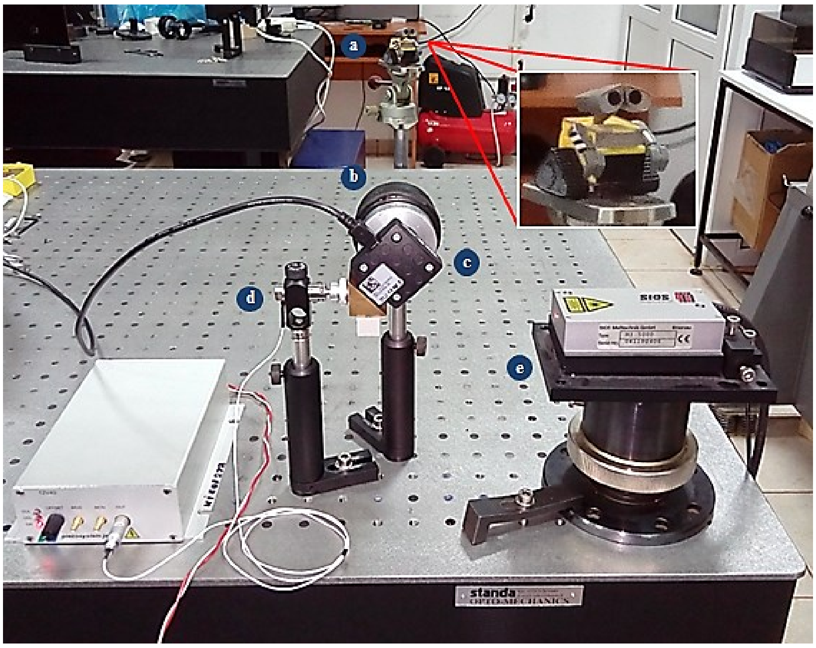


Fig. 3 – Laboratory setup for monochrome CMOS sensor resolution and fill factor improvement: a) image object; b) photo lens; c) Aptina CMOS sensor; d) PiezoJena actuator; e) SIOS MI-5000 interferometric length measurement system.

3. THEORY AND COMPUTATION

The sensor Aptina MT9M001 can produce images with maximum resolution of 1280(H) × 1024(V) pixels. A very important feature of digital imaging sensors, called windowing, allows the reading of a specific region of sensor photosite. To present our method in a more intuitive manner we chose to work with a square image resolution of 1023(H) × 1023(V) pixels, corresponding to a sensor photosite window of the same size.

Our method implementation is based on the sensor higher diagonal resolution and its non-photosensitive inter-photosite spaces. Therefore, we use two image frames, each for a different position of the sensor in the image plane, and a pixel interlacing method that merge their contribution into a final image. Each one of the image frames, digitally rotate at 45º, creates a new image grid with missing pixels. The two images are complementary and their pixels fill the grid of the final image.

To obtain the final image we extract the diagonals of each frame, interlace the pixels and rearrange them into a rhombic image grid shape. The diagonals extraction reshapes the resolution (Fig. 4), of our two image frames, to a size of 1023(V) × 2045(H) pixels. The interlacing stage, merge the horizontal pixels of our two image frames and rearrange them into the final image grid of 2046(H) × 2045(V) pixels.

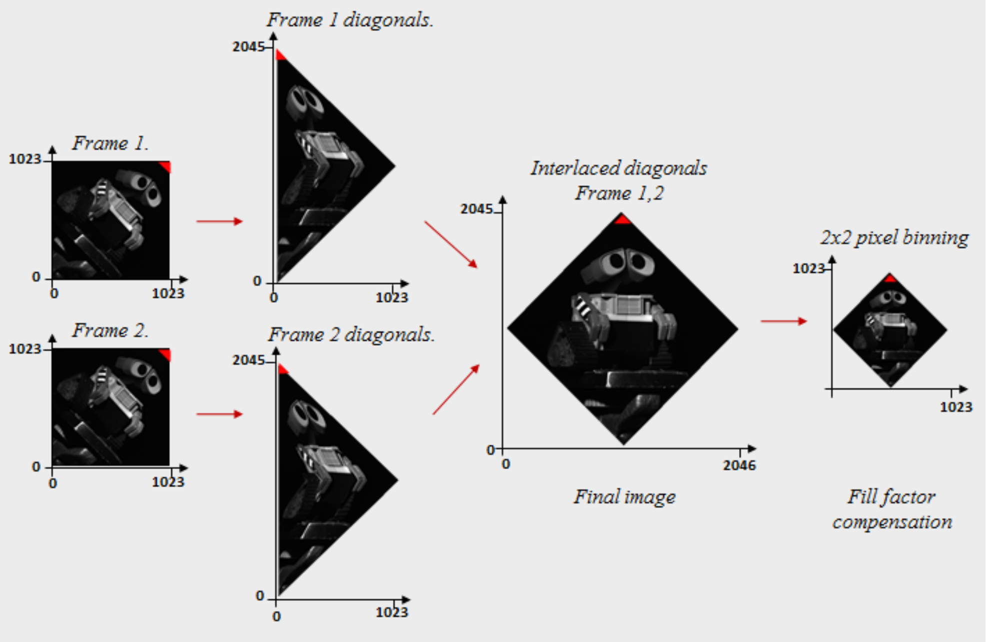


Fig. 4 – Different image processing stages for resolution improvement and fill factor compensation.

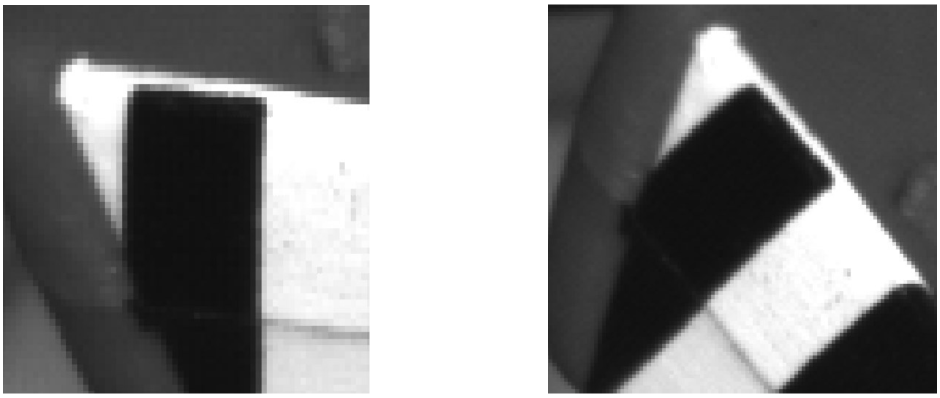
4. RESULTS

4.1. RESOLUTION IMPROVEMENT

If we define the resolution as the total number of pixels, then our sensor is capable of registering 1 MP (megapixel) images. Interlacing our two images *Frame* 1 and *Frame* 2, creates a higher resolution image of 2 MP which extend the level of details in our *Final image*.

Figure 5 offers a visual comparison of two enlarged areas corresponding to the image *Frame* 1 and to the *Final image* frame.

CMOS sensor Aptina MT9M001 has an optical format of ½ inch and an aspect ratio of 5:4. Knowing its total resolution and photosite size we determined its photosites density value to 3.7 Mp/cm^2. Appling our method, we increased the photosites density for the same area of the sensor to 7.4 Mp/cm^2 (Fig. 6).



a) b)

Fig. 5 – Enlarged area of: a) frame 1;
b) final image.

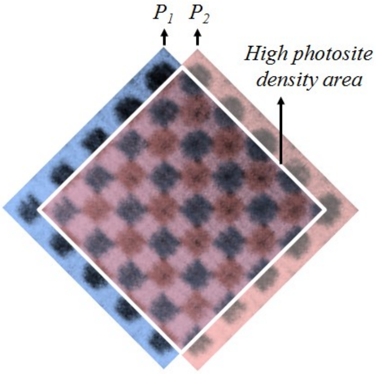
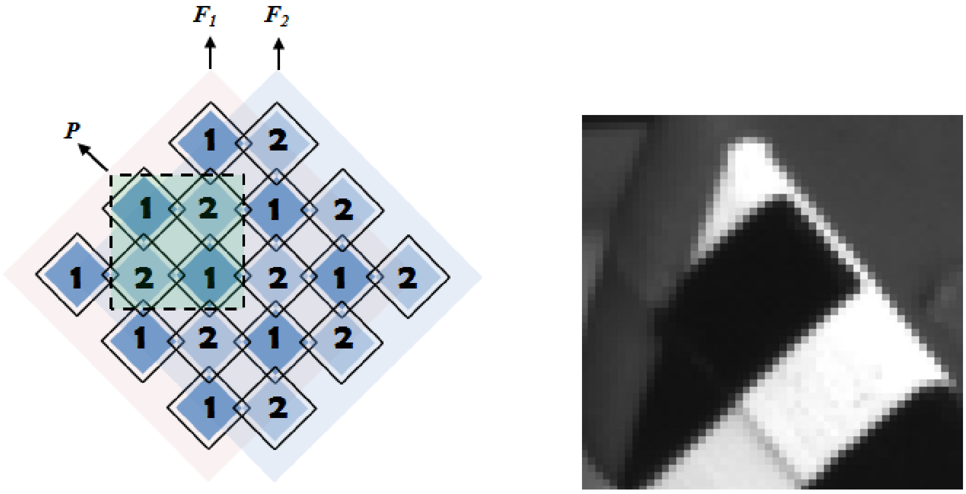


Fig. 6 – The picture P of Aptina MT9M001 CMOS surface on the microscope, virtually overlapped with itself at *d*/2 distance. The white square marks the area with high photosite density.

4.2. FILL FACTOR IMPROVEMENT

The Fill factor is a characteristic of CMOS technology and the only known effective way to improve it is with microlenses. Our method for resolution improvement has already achieved fill factor compensation, in the final image, by collecting the information between diagonal photosites without overlapping. Further, using a pixel binning method, we group four pixels to act like a single pixel. At sensor level, this method merges the corresponding photosites in order to act like one large artificial photosite, *P* (Fig. 7a). This new photosite *P* does not take physical shape; it is the result of pixel binning method applied on the final image (Fig. 7a,b).



a) b)

Fig. 7 – a) Pixel binning representation, two pixels from each image;
b) enlarged image area, after applying binning.

This process will resize the resolution of our final image to a new resolution of 1023 × 1023 pixels and will redefine the physical size of the photosite to 7.352 × × 7.352 µm as well as its electrical characteristics, like: sensitivity, dynamic range, SNR etc.

5. CONCLUSIONS

This paper address an inherent problem of CMOS image sensors related to fill factor and resolution.

Our method achieves a resolution increase, from 1 megapixel to 2 megapixels, which positively impacts the sensor fill factor. Collecting the image information between sensor photosites creates an artificial increase of photosite density from 3.7 Mp/cm^2 to 7.4 Mp/cm^2 and also redefines the fill factor percentage.

The knowledge produced through this work helps to establish the foundation for the development of higher performance imaging devices.

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