EMVA1288 compliant Interpolation Algorithm

Author: Jörg Kunze

Description of the innovation:
Basler invented an interpolation that is designed to create values of virtual pixels at given positions and with a common given size, which fulfill all EMVA 1288 requirements for real pixels. This allows an easy replacement of old CCD cameras with new CMOS cameras without changing the optical setup or software of the application.

Let us assume, we want to emulate a CCD sensor image with big 5.6 µm pixels and we have a new CMOS sensor image with smaller pixels, e.g. with a size of e.g. 3.6 µm. This situation is depicted in Fig. 1a. The newer sensor with the array of smaller pixels is drawn in blue and the older sensor with the array of bigger pixels is drawn in orange. The pixel center positions are depicted as a grid of small circles in the respective color. It is clearly visible that both grids do not match. We basically need to create an image with a lower resolution.

Two previously known methods to lower the image sensor resolution are subsampling and binning. Both methods work only for integer factors in horizontal and vertical resolution, i.e. 2×2, 3×3, 4×4 and so on. But usually the ratio between CCD and CMOS pixel size does not form a pair of integer numbers. In the given example, the ratio is approximately 1.56 × 1.56. Therefore, subsampling and binning do not provide a viable solution. The first key problem is to create a pixel value at the correct position. In Fig. 1a it can be seen, that the correct positions for the orange grid are mostly off the blue grid. For such cases, interpolation is frequently used. The most common interpolation methods are Nearest-Neighbor, (Bi-) Linear and (Bi-) Cubic Interpolation.

Fig. 2a shows a plot of the one-dimensional synthesis function of the Nearest-Neighbor Interpolation. The application of Nearest-Neighbor Interpolation often creates artefacts to straight lines or edges in the image, because it takes a brightness value from somewhere else and thereby violates the correct
interpolated pixel position. Fig. 2b plots the one-dimensional synthesis function for Linear Interpolation and Fig. 2c for Cubic Interpolation.

The following mathematical conditions have been identified as mandatory for a proper solution:

1. All interpolated pixels must be at the correct position.
2. All interpolated pixels must have the same gain.
3. All interpolated pixels must have the given size.

These conditions are completed by additional mathematical conditions, e.g. for symmetry, steadiness and locality. The latter help to create a natural image impression and to remove visible artefacts. All these conditions pile up to a multi-dimensional non-linear functional equation system. This equation system turned out to be unexpectedly demanding.

After one year of research, Basler identified an efficiently computable solution. This algorithm runs well even on a small 8-Bit controller and enables real-time application. The interpolation has been named Virtual-Pixel Interpolation, because in contrast to all other interpolations it is designed to create values of virtual pixels at given positions and with a common given size, which fulfil all EMVA 1288 requirements for real pixels. The interpolation math is visualized in Fig. 2d. For ease of understanding, only one-dimensional solutions are shown as synthesis functions. The blue curve represents the interpolation for a 1 × 1 unity size pixel, while the orange curve is adapted in shape to a relative size of 1.56 × 1.56. This two-dimensional Virtual-Pixel Interpolation has been tested on the ICX618 raw image series for different resolutions. An EMVA 1288 report has been created for each resolution. All of the EMVA 1288 reports contained plausible results that were exactly as expected for a CCD image sensor with the respective pixel size. As an example, the resulting QE values are plotted over pixel area in Fig. 3b. All QE values are exactly as expected within a small error bar and equal the original ICX618 QE value for the used wavelength.

The Virtual-Pixel Interpolation has been implemented in the Basler acA640-121gm camera. This camera is intended as a 1:1 replacement for ICX618 CCD cameras. It has been directly compared to two conventional Basler ace cameras, one containing an original ICX618 and the other containing an IMX287. The latter has been proposed by Sony as successor for the ICX618. All three cameras have been tested in an optical lab using identical lenses and target scenes at different lighting conditions and different wavelengths.

Fig. 4 shows three resulting images taken under identical conditions. As the sensors vary in pixel count, all images have been cropped to VGA size for better comparison. It can be seen, that the new camera image in Fig. 4c matches the ICX618 image in Fig. 4b well, whereas the IMX287 image in Fig. 4a clearly differs in field of view. The same finding holds true when zooming into the details. The ICX618 Replacement Sensor image in Fig. 4f can hardly be distinguished from the original ICX618 image in Fig. 4e, whereas the IMX287 image in Fig. 4d clearly does not match. And finally the histogram of IMX287 in Fig. 4g is clearly different from the original ICX618 histogram in Fig. 4h, whereas the ICX618 Replacement Sensor
shows a perfect match in Fig. 4i.

Technical details and advantages of the innovation:
Interpolation is a well-known technique to change the resolution of camera images. Especially Nearest-Neighbor, (Bi-)Linear, and (Bi-Cubic) interpolation are frequently used. However interpolated images frequently raise concerns in the machine vision community. In order to understand the source of these concerns, experiments on interpolated images have been carried out. Raw images have been recorded following the EMVA 1288 procedures using a monochrome Basler ace camera containing an ICX618 CCD image sensor. These raw images have been interpolated for different target resolutions using the state-of-the-art interpolation techniques. The respective image metadata has been converted to the new pixel size, corrected especially for the resulting pixel area and the calculated incident light. The resulting image piles have been characterized with well-established EMVA 1288 Version 3.0 scripts. The results contained a lot of surprise. As one example, the Quantum Efficiency (QE) measure is discussed here. The correct QE value for this particular sensor and wavelength is known to be slightly above 50%. It can be expected that interpolation does not affect the QE. But in the resulting QE values for green light, bi-cubic interpolation in Fig. 3a, this correct value has only been met for relative pixel areas of 1 × 1 and 2 × 2. For all other relative pixel sizes, the measured QE ranges somewhere above 80%. These values are not plausible. The raised QE values clearly indicate that something has gone wrong. The simplified example of Fig. 1b serves to explain the underlying effect. In this example, the pixel size is changed to 3/2 × 3/2 of the original. There, the center of the resulting pixel either matches the center of the previous pixel or is exactly placed in the middle between two horizontally, two vertically or four diagonally neighboring original pixels. This creates four possible situations. The mathematical implication of this example is explained in Fig. 1c for linear interpolation and for two horizontally neighboring pixels a and b. We want to know the brightness value of the pixel c in the middle between a and b. In this situation, linear interpolation calculates the mathematical average with the depicted formula c = 1/2 (a + b). This formula tells exactly, what this operation does to pixel physics. It creates the red superpixel d that covers all area of a + b. Then it multiplies the value of this superpixel with a half gain factor 1/2. The resulting pixel has basically double size and half gain. The four possible situations for the simple example lead to single size, double size or quad size superpixels with respective gain factors of 1, 1/2, or 1/4. They are depicted in Fig. 1d in red color. It becomes clearly visible that state-of-the-art interpolations create pixels of different sizes and gain factors. Generally speaking the pixel size is usually bigger than the original pixel and the gain factor is usually smaller or equal to one. It can be understood, that state-of-the-art image interpolation generally violates the EMVA 1288 assumption, that all pixels have the same size and gain. It may be also understood that those different pixel sizes account for visible artefacts. Bigger pixels attenuate high frequencies and thereby destroy information according to James R. Janesick’s MTF sampling response
formula. So the differences in pixel size and gain are identified as one important root cause for the common concerns on interpolation. Basler’s new algorithm avoids these negative effects of previous interpolation methods. It is also so efficiently computable on e.g. a small 8-Bit controller and enables real-time application. This is mandatory for machine vision applications. So basically with this algorithm in a new CMOS camera a CCD replacement is becoming easy and straightforward.

Relevance and application possibilities of the described innovation for the machine vision industry:
CCD image sensors have been integrated into a large number of machine vision camera models. These CCD cameras are still used in a widespread range of applications. But the availability of many CCD image sensors is limited in time and volume. Hence the question has to be posed: What happens in those applications after the CCD age? One approach is to replace the CCD cameras with newer CMOS cameras. This approach is e.g. recommended by Sony. The latest CMOS image sensors offer high pixel count and great image quality, so this solution should be theoretically viable. But the CMOS image sensors are generally no one-to-one replacements for the CCDs. The CMOS image sensors usually come with a different pixel size compared to the CCDs. In most cases the CMOS pixels are smaller. This may raise a severe problem for the application, because optics and software are usually well adapted to the pixel size. Thus, a CCD camera replacement by CMOS may require costly changes in application optics and software. Therefore it would be desirable to provide a new technology that can emulate an older CCD image sensor pixel array on top of a newer CMOS image sensor pixel array with even better image quality. The Virtual Pixel Interpolation serves as a technological base for a one-to-one replacement of a CCD camera by a CMOS camera sensor. It creates images consisting of virtual pixels of the same size as the replaced CCD image sensor. The replacement camera fully complies to EMVA 1288. The Basler acA640-121gm is the first CCD replacement camera incorporating this technology. Further 1:1 CCD replacement camera models are expected in the near future. A CCD replacement camera like this can directly replace an older CCD camera. The replacement is cost-efficient and easy. No further changes in application optics, mechanics, or software are expected. This saves cost in development, production and logistics for re-designs of vision machines.

Images:
39201_fig1.jpg
39201_fig2.jpg
39201_fig3.jpg
39201_fig4.jpg
39201_fig5.jpg
Fig. 1: Comparing pixel arrays before and after interpolation.

(a) Pixel size change creates grid mismatch.

(b) Pixel size change to \( \frac{3}{2} \times \frac{3}{2} \) of the original.

(c) Implications of a linear interpolation.

\[ \text{linear interpolation} = \frac{1}{2} \cdot \frac{d}{(a + b)} \]

- half gain
- double size

(d) Resulting pixels of different sizes and gains.
Fig. 2: Synthesis functions of different interpolations.
Fig. 3: Quantum Efficiency results for interpolated image sensors.
Fig. 4: Image comparison.