

Image Coding by Samples of Counts as an Imitation of the Light Detection by the Retina

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Abstract: The results of the study of a new method of image coding based on samples of counts are presented. The method is based on the concept of an ideal image, motivated by the mechanisms of light perception by the retina. In this regard, the article discusses general statistical issues of the interaction of radiation with matter and based on a semiclassical approach, formalizes the concepts of an ideal imaging device and an ideal image as a point Poisson 2D-process. At the centre of the discussion is the problem of reducing the dimension of an ideal image to a fixed (controlled) size representation by a sample of counts. The results of illustrative computational experiments on counting representation/coding of digital raster images are also presented.

1 INTRODUCTION

In the human visual system, the radiation (light) coming from the outside World is registered by the special cells called photoreceptors. These cells are the main components of the outer layer of the retina, see Figure 1, and are divided into rods, cylindrical cells, and cones having a conical shape. It is these two types of photoreceptors that allow the visual system to receive primary information in the form of light radiation from the outside. The usefulness of such data is due to most objects around us, even though they themselves are not sources of light radiation, reflect light from other sources quite well, depending on their characteristics, such as surface structure, shape, luminosity and others.

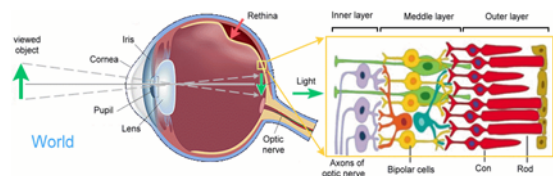



Figure 1: Scheme of the human eye with retina, based on which the data about objects of the external World are transformed into internal Visual system representations.

The methods of registration and primary processing of optical radiation in the visual system began to be actively used already since the XVIII century, after the discovery of photochemical reactions by Wilhelm Homberg in 1694. However, the first cameras appeared much earlier, it is known that back in the V century BC, the ancient Chinese philosopher Mo-Tzu described the action of a pinhole camera, the simplest device that allows you to obtain an optical image of objects. To date, image registration and transformation systems have been improved, and with them, the number of borrowed mechanisms of the visual system has grown. It is worth noting several common borrowings, such as the use of an optical focusing system presented in the visual system in the form of a lens, a diaphragm (pupil), as well as a variety of sensitive elements (photoreceptors) registering radiation, ranging from the simplest transparent and translucent films and plates with a photosensitive mixture applied to the surface, and ending with high-tech CCD/CMOS photodiodes. Some features of the eye, such as the presence of a vitreous body between the lens and photoreceptors, the shape of the retina (the photosensitive surface of the eye) in the form of a hollow ball, not a plane, etc. are not essential in this context.

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The use of visual perception mechanisms in artificial systems was best manifested in the registration of light radiation. It is worth remembering such discoveries as daguerreotype, a technology for the manifestation of a weak latent image using mercury vapor, developed by Daguerre in 1837, and his developments - silver-coated plates, which by the 20th century had been improved to celluloid photographic films with gelatin-silver emulsion, which was the beginning of analog photography. And by the beginning of the XXI century, with the development of technologies, the registration of light radiation moved to a new level, digital photography appeared, which was based on photodiode arrays registering radiation. To a large extent, these successes were provided by the invention of a charge-coupled device (CCD) in 1969 by Willard Boyle and George Smith and the further invention of photosensitive matrices on complementary metal-oxide-conductor (CMOS) structures. In 1993 the team of Eric Fossum developed the first CMOS sensor of active pixels. The transition from analog photography to digital one has made it possible to improve several parameters of photo and video cameras, of particular importance among which is an increase in spatial resolution, which resulted from a reduction in the size of photodetectors down to several microns. It is also worth mentioning other achievements related to the development of digital technologies, such as reducing power consumption, increasing frame rate, etc.

Let us note, that the technological achievements listed above are essentially related to the scientific developments of the XX century, in particular, such branches of science as quantum electrodynamics (the interaction of radiation with matter) (Fox, 2006) and solid-state theory (the development of semiconductor structures) (Holst, 2011).

Modern ideas indicate that along with the progressive decrease in the size of photodetectors of digital matrices, the nature of radiation registration also changes, acquiring a pronounced quantum character, allowing the sensors to work in the so-called mode of counting single photoelectrons. To date, the registration of individual photons has already been achieved by several modern technologies, such as photon-counting Image Sensors (Fossum, 2017). It is also worth mentioning the variety of such sensors represented by electron-multiplying matrices with charge capacity (EMCCD) (Robbins, 2011), single-photon avalanche diodes (SPAD) (Dutton, 2016), avalanche photodiodes in Geiger counter mode (GMAPD) (Aull, 2015), see Figure 2.

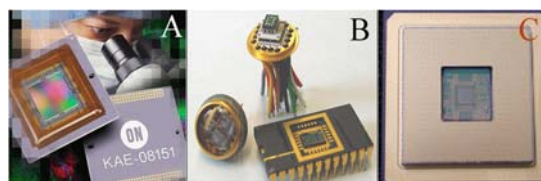


Figure 2: Modern photon-counting sensor technologies based on A) EMCCD, B) SPAD, C) GMAPD.

Since photons are transformed into the electric current from the digital video-matrix of photodiodes, the last can be easily included in various electronic circuits, which, in turn, may contain microprocessors necessary for digital signal processing (DSP).

Taking into account the high efficiency of modern microprocessors, it becomes possible to solve not only a standard set of video signal preprocessing tasks related to glare compensation, dark current, white balance, but also to perform significantly complex operations comparable to those that occur in the human brain - pattern recognition, event analysis, classification of images by features, etc. Such a possibility opens up new opportunities in the formation, processing, and analysis of images based on digital image signal processing (DISP) methods.

In turn, the modern DISP theory (Gonzalez, 2007) provides digital video data recording devices with a number of tools and methods for processing visual information, see Figure 3.

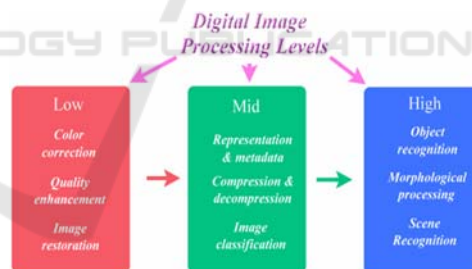


Figure 3: A rough diagram of modern digital image signal processing (DISP).

Conventionally, all methods aimed at processing digital images can be divided into three main types – computerized processes of the low, medium, and high level (Figure 3). The first level of processes usually includes operations related to the preprocessing of input data. These include noise reduction, quality correction, contrast improvement, etc. The second level consists of procedures for segmentation, classification of images by common features, recognition of individual elements, and bringing them into a form convenient for possible further computer processing. And finally, the third level of processing covers tasks such as semantic analysis of recognized

objects and scenes. In other words, high-level processing implies some "comprehension" of what was recorded in the image, which can be associated with human vision.

It should be noted that some mechanisms of the human visual system are also actively used at all levels of the DISP (Gabriel, 2015). At the same time, each of the three levels can be correlated with the corresponding elements of the visual system. The methods of the first level are characterized by the mechanisms of preprocessing registered data in the retina. The third level contains the methods that simulate some brain processing of input data mechanisms. The last are associated with serious work in the cerebral cortex (Rodieck, 1998), in this connection, it is worth highlighting machine learning methods (Barber, 2012), such as object and scene recognition, morphological analysis, etc. As for the methods of the second group, they occupy a median value between the first and third levels and are probably implemented by the visual system also in the area between the retina and the cerebral cortex itself.

It should be noted that, despite the current level of technological achievements, the use of visual perception mechanisms in artificial imaging systems is implemented within the DISP with a certain degree of approximation. Already at the level of representation of registered data, approximate modeling is used, since most traditional DISP methods are focused on raster (bitmap) images representing discrete pixels – the digitized result of the accumulated energy of the radiation recorded by the detectors during the exposure time. In other words, the pixel values are proportional to the total number of photons registered by the sensitive areas of the corresponding matrix detectors. In the case of the retina, photoreceptors react rather to individual photons of radiation, transmitting a count signal to the ganglion cells of the inner layer instantly, without the accumulation (Rodieck, 1998). This difference in the representation of input data in natural and artificial video systems is a consequence of the fact that until recently, the technological capabilities for implementing image registration methods similar to those occurring in the visual system were simply absent. Fortunately, significant progress has been made in recent decades in the development of photodiode matrices operating in the mode of counting single photons (see also (Morimoto, 2020)). It opens new opportunities for the DISP methods, modeling the processes of registering visual data in the retina. One of the possible approaches to developing this problem is presented below as a new

method of encoding (representing) images with samples of counts simulating the mechanism of registering radiation in the human visual system.

2 IMAGE CODING BY SAMPLES OF COUNTS

To substantiate the method of coding (representation) of visual data (images), first of all, it is worth considering the processes of light radiation registration by photosensitive elements of the human visual system. The following discussion is justified by widely known biophysical facts about the interaction of radiation with photoreceptor cells of the retina (Rodieck, 1998) and are also motivated by the provisions of quantum electrodynamics (Fox, 2006) at least in its semi-classical approximation (Goodman, 2015). All results will be further formalized in the form of a general model of an ideal image (Pal, 1991), which is recorded by an ideal imaging device, containing a huge array of point photodetectors (Antsiperov, 2021).

As mentioned above, the primary device in the human imaging pipeline is the retina. To substantiate the adequacy of retina model used below, it is worth mentioning several key facts concerning it. It is well known that the retina of the human eye includes about 100 million rods and 10 million cones capable of registering individual photons of the visible spectrum of light radiation. The density of these photoreceptors varies from 100 to 160 thousand receptors per mm^2 (in some living creatures, this parameter may be significantly higher, for example, in birds of prey, there are about a million photoreceptors per square millimetre of the retina). At the same time, it is worth noting that the signals coming to the cerebral cortex via the optic nerve are (see Figure 1) not the same data that were received by photoreceptors. These signals are formed from receptors by the upper layer of cells of the retina of the eye, undergoing processing in a complex system of cells of the middle and inner layers. At the final stage, visual information entering the cerebral cortex is transmitted along the optic nerve – axons of ganglion cells. Their number is about a million, which is about two orders of magnitude less than the number of photoreceptors.

The prototype of the imaging device for forming an ideal image, which can also be perceived as a technical implementation of the latter, can be selected in the form of a matrix of single-photon avalanche diodes (SPAD) (Morimoto, 2020), or any of its analogues (Fossum, 2017). The production of such

matrices currently allows to get amazing results – about a million micro-detectors of light radiation are placed on a surface of 120 mm² in pitch of 9.4 microns. Each detector has a dynamic binary memory for storing registered data and has a memory refresh rate of 24 thousand frames per second (Morimoto, 2020). From where the flow of information from the SPAD matrix of photodiodes is easily estimated. If the information flow in the human visual system is approximately 50 Mbit/sec, then the information flow of the matrix of single-photon avalanche diodes reaches 25 Gbit/sec (Koch, 2006).

Despite the difference between artificial and natural mechanisms of forming an image, they all have common features. Both have a finite 2D-dimensional photosensitive region containing a huge number of receptors / photodetectors. Each detector can register single photon of radiation incident on it. The prototypes have a certain amount of memory that allows storing for a short period all the events associated with the registration of photons by detectors. The above-mentioned characteristics can be used to formalize the concept of the imaging device, which will be some formal generalization not only of the above models but also of several other imaging systems, including photographic films with an emulsion applied to them, photographic plates, etc.

Summing up above discussion, it is worth formulating the following definition. An imaging device is the two-dimensional surface Ω of finite size with coordinates $\vec{x} = (x_1, x_2)$, in which small (point) photodetectors are located (Antsiperov, 2021). The sensitive surface area ds of these detectors is so small, that allows them to be placed close to each other. It follows from the definition that the total number of photodetectors can be represented as the ratio of the area S of a two-dimensional region Ω to the surface area ds of a single photodetector $N = S/ds$. In the case when the area of such receivers tends to zero $ds \rightarrow 0$, it is assumed that their number N will tend to an infinity $N \rightarrow \infty$. Formally, it can be assumed that the imaging device has a continuous surface of light-sensitive detectors, indexed by coordinates \vec{x} .

When light radiation with the intensity $I(\vec{x})$, $\vec{x} \in \Omega$ hits the photosensitive region Ω , individual photons are registered by individual photodetectors. The event of photon registration during the exposure time T by some detector is defined as a photocount with the specified coordinates \vec{x} of that detector. In the case of an infinitely small sensitive area of the photodetector $ds \rightarrow 0$, the probability of photocount is determined in the semiclassical theory of radiation/matter interaction as $P(\vec{x}) = \alpha TI(\vec{x})ds$,

where $\alpha = \eta(h\bar{\nu})^{-1}$, $h\bar{\nu}$ is the average photon energy, $\eta < 1$ is the dimensionless coefficient determining the quantum efficiency of the photodetector material, h is Planck's constant, $\bar{\nu}$ is the characteristic frequency of radiation. According to the above, each point photodetector with coordinates $\vec{x} \in \Omega$, registering incoming radiation with the intensity $I(\vec{x})$, can be represented by a random binary value $\sigma \in \{0, 1\}$, which, depending on whether the detection has occurred or not, takes the values $\sigma = 1$ and $\sigma = 0$, respectively. The probability distribution for this binary value σ is the Bernoulli one:

$$P(\sigma|\vec{x}) = \begin{cases} \alpha TI(\vec{x})ds, & \sigma = 1 \\ 1 - \alpha TI(\vec{x})ds, & \sigma = 0 \end{cases} \quad (1)$$

It follows from the distribution (1) that the average number of counts $\bar{\sigma}$ at the point \vec{x} is given by the formula $\alpha TI(\vec{x})ds$, from where we get the value for the integral that determines the average number of all counts generated on the surface Ω during time T : $\bar{n} = \alpha T \iint_{\Omega} I(\vec{x})ds$.

Using (1), it is possible to determine the joint distribution of random variables \vec{x} and σ . To do this, let us randomly select any point detector from the array of N imaging device detectors (with probability $Q(\vec{x}) = N^{-1}$). Let it has coordinates \vec{x} . Then, bearing in mind (1), we get

$$P(\sigma, \vec{x}) = P(\sigma|\vec{x})Q(\vec{x}) = \begin{cases} \frac{\alpha TI(\vec{x})ds}{N}, & \sigma = 1 \\ \frac{1 - \alpha TI(\vec{x})ds}{N}, & \sigma = 0 \end{cases} \quad (2)$$

To obtain the marginal distribution of σ , which determines the frequency of the appearance or absence of a count in any place, we sum up the distribution (2) over the entire number of N point detectors:

$$P(\sigma) = \begin{cases} \frac{\alpha T}{N} \iint_{\Omega} I(\vec{x})ds = \frac{\bar{n}}{N}, & \sigma = 1 \\ 1 - \frac{\alpha T}{N} \iint_{\Omega} I(\vec{x})ds, & \sigma = 0 \end{cases}, \quad (3)$$

Now, to obtain a conditional probability of finding a photocount with the coordinates \vec{x} in Ω , it is enough to divide the probabilities $P(\sigma, \vec{x})$ (2) by the corresponding probabilities $P(\sigma)$ (3), for the case $\sigma = 1$:

$$P(\vec{x}|\sigma = 1) = \frac{P(\sigma=1, \vec{x})}{P(\sigma=1)} = \frac{I(\vec{x})ds}{\iint_{\Omega} I(\vec{x})ds}. \quad (4)$$

Note that the conditional probabilities obtained (4) differ in meaning from the conditional probabilities for the count with the given coordinates $P(\sigma|\vec{x})$ (1).

Moreover, instead of conditional probability (4), it would be convenient to use the corresponding probability distribution density $\rho(\vec{x}|I(\vec{x})) = P(\vec{x}|\sigma = 1)/ds$, indicating explicitly the condition for the registration of photo count for a given radiation intensity $I(\vec{x})$. In this case distribution (4) takes the form:

$$\rho(\vec{x}|I(\vec{x})) = \frac{I(\vec{x})}{\iint_{\Omega} I(\vec{x}) ds}, \quad (5)$$

from where it follows, that when the light radiation is recorded by the imaging device, the probability density of the count corresponds to the normalized intensity $I(\vec{x})$, incident on the photosensitive area Ω . Note that expression (5) has a universal character since the conditional probability distribution density is not dependent either on the radiation period T , either on the quantum efficiency of the detector material η , either on the characteristic frequency $\bar{\nu}$ (radiation spectrum). Moreover, the density does not depend on the value of intensity norm, given by the total radiation power $W = \iint_{\Omega} I(\vec{x}) ds$, since it is determined only by the intensity form $I(\vec{x})/W$. It is worth to mention, that the above parameters significantly affect other statistical characteristics of a counts set, such, for example, as their average number $\bar{n} = \alpha TW$. Therefore, we once again point out that the normalized intensity $I(\vec{x})/W$ is the only sufficient statistic for the probability density distribution $\rho(\vec{x}|I(\vec{x}))$ (5).

Understanding the concept of an imaging device allows us to form a model of an ideal image, for which we define an ideal imaging device. The ordered set $X = (\vec{x}_1, \dots, \vec{x}_n)$, $\vec{x}_i \in \Omega$ of all n random photo counts recorded by the photosensitive region Ω of the ideal imaging device during a given time T will be considered an ideal image. An ideal image is essentially random object that should be distinguished among its possible realizations. It is worth noting that such an image is characterized by a random number of counts n in the set X , as well as random coordinates \vec{x}_i with density distributions (5).

Given the conditional independence of the counts $\{\vec{x}_i\}$, we can present a complete statistical description of the ideal image in the form of distribution densities $\{\rho(\vec{x}_1, \dots, \vec{x}_n, n|I(\vec{x}))\}$, $\vec{x}_i \in \Omega$, $n = 0, 1, \dots$ (note that the conditional independence is understood here in the sense of the independence of all counting events at a given fixed form of the recorded intensity $I(\vec{x})$):

$$\begin{aligned} \rho(\vec{x}_1, \dots, \vec{x}_n, n|I(\vec{x})) &= \\ &= \prod_{i=1}^n \rho(\vec{x}_i|I(\vec{x})) \times P_n(I(\vec{x})), \\ P_n(I(\vec{x})) &= \frac{\bar{n}^n}{n!} \exp(-\bar{n}), \\ \bar{n} &= \alpha T \iint_{\Omega} I(\vec{x}) ds. \end{aligned} \quad (6)$$

where, according to (5), the probability density $\rho(\vec{x}_i|I(\vec{x}))$ is determined as the normalized intensity $I(\vec{x})/W$, $P_n(I(\vec{x}))$ is the Poisson probability distribution with parameter \bar{n} .

It is worth noting the correspondence of the statistical description (6) with some two-dimensional point inhomogeneous Poisson process (Streit, 2010) with intensity $\lambda(\vec{x}) = \alpha T I(\vec{x})$. It is known that the two-dimensional Bernoulli process $\{(\vec{x}, \sigma)\}$ is successfully approximated by the Poisson point process (Gallagher, 2013), which is stated in the above result.

Densities $\rho(\vec{x}_1, \dots, \vec{x}_n, n|I(\vec{x}))$ (6), including P_n and $\bar{n} = \alpha TW$, partially lose the universality property, since they depend now on the parameters α, T, W . Despite this, conditional densities $\rho(\vec{x}_1, \dots, \vec{x}_n, n, I(\vec{x}))$ will be independent of these parameters if n is fixed (Streit, 2010). This fact makes sometimes the analysis of ideal images simpler, allowing to separate the associated with n "energy" estimates, and "geometric", structural estimates associated exclusively with the configuration of the set $X = (\vec{x}_1, \dots, \vec{x}_n)$, $\vec{x}_i \in \Omega$ (Antsiperov, 2019).

For theoretical research, it is useful to use an ideal image model and its statistical description (6), for example, when searching for optimal methods of image processing, in particular, in the problems of objects identification in the images and artefacts recognition (Antsiperov, 2019). Moreover, the statistical description (6) can be used quite effectively at low intensities of the recorded radiation with not large values of $\bar{n} = \alpha TW$, such as in positron emission tomography (PET), fluorescence microscopy, single-photon emission computed tomography (SPECT), optical and infrared astronomy, etc. (Bertero, 2009).

Unfortunately, the use of the ideal image model becomes problematic in cases of normal radiation intensity, typical, for example, of daylight. The reason for this is the need of enormous resources for solving applied problems. As it is known, the light flux of the photons from the sun is quite huge under normal conditions: on a clear day it is $\sim 10^{15} - 10^{16}$ photons per section $S \sim 1 \text{ mm}^2$ in 1 s (Rodiek, 1998). For devices operating in the photon counting mode, the number of counts per second will be $\bar{n} \sim 10^{15}$

(1000000 Gbit/sec = 1 Pbit/sec), provided that they will form one count per ~ 10 photons (with quantum efficiency $\eta = 0.1$). Processing such an information flow is an unrealistic task, so in this case, it is recommended to develop other methods for encoding/presenting images.

Earlier in our work, the following solution was proposed to the above-mentioned problem of reducing the dimensionality of the ideal image representation (Antsiperov, 2021). To begin with, it was proposed to fix the size of the working representation to an acceptable level $k \ll \bar{n}$. In other words, considering the ideal representation $X = \{\vec{x}_i\}$ of the image as some general population of counts, it proposed to select from it a sample in k random elements $X_k = \{\vec{x}_j\}$. According to the approach of classical statistical theory, a similar "sampling" representation at dimensions $k \ll \bar{n}$ will also represent in a sense an ideal image. We call such a fixed size sample X_k the sampling representation (representation by sample of random counts). Integrating $\rho(\vec{x}_1, \dots, \vec{x}_n, n | I(\vec{x}))$ (6) over the coordinates of unselected counts in X_k and summing the result over the number $l = 0, 1, \dots$ of unselected counts, we obtain a statistical description of the sampling representation in the form:

$$\rho(X_k | I(\vec{x})) = \prod_{j=1}^k \rho(\vec{x}_j | I(\vec{x})) \times P_{n \geq k}(I(\vec{x})) \quad (7)$$

where $P_{n \geq k}(I(\vec{x}))$ indicates the probability of existing of more than k counts in an ideal image. Taking into account the asymptotic (for $\bar{n} \rightarrow \infty$) tendency of Poisson distribution P_n to a Gaussian one with the mean \bar{n} , it can be easily found that in the case $\bar{n} \gg 1$, the probability $P_{n < k}(I(\vec{x}))$ will be less than ε , as soon as the number of selected counts $k \leq 2\varepsilon\bar{n}$ ($k/\bar{n} \leq \varepsilon/0.5$), i.e. the probability $P_{n \geq k}(I(\vec{x}))$ in (7) will differ from the unity less than by ε .

Further, assuming for representations X_k that their dimensions satisfy the condition $k < 2\varepsilon\bar{n}$ for small enough ε , so putting $P_{n > k}(I(\vec{x})) \cong 1$ we will get finally:

$$\rho(X_k | I(\vec{x})) = \prod_{j=1}^k \rho(\vec{x}_j | I(\vec{x})) \quad (8)$$

Putting for example $\varepsilon = 0.001$ and $\bar{n} \sim 10^{15}$, we obtain that (8) holds up to $k \sim 2 \times 10^{12}$, however, and this estimate is, most likely, strongly underestimated.

Due to the fixed size of sampling representation $k \ll \bar{n}$, as well as several other circumstances, the statistical description (8) for $X_k = \{\vec{x}_1, \dots, \vec{x}_k\}$ seems more convenient than a complete statistical description of an ideal image. First of all, this is due to the fact that it fixes the same conditional

distribution of all k counts $\{\vec{x}_j\}$ and their conditional independence. Further, it is worth noting that the densities of distributions of individual counts $\rho(\vec{x}_j | I(\vec{x}))$ in the region Ω depend only on normalized intensity $I(\vec{x})$, which means that the universality property for (8) also holds. In other words, there is no dependence on the exposure time T , the quantum efficiency of the detector material η , or the characteristic frequency $\bar{\nu}$. The above-mentioned properties of sampling representation distribution (8) make it possible to provide the necessary type of input data for many machine learning methods, as well as statistical approaches, including the naive Bayesian one (Barber, 2012).

The final note of this section is devoted to the following important fact. Since $\rho(\vec{x}_j | I(\vec{x}))$ in (8) is determined exclusively by the normalized version of the intensity $I(\vec{x}) / \iint_{\Omega} I(\vec{x}) ds$ (see (5)), statistical description of the representation (8) also does not depend on the physical values of intensity $I(\vec{x})$. For example, in the case where the detected radiation intensity $I(\vec{x})$ was recorded by the pixels $\{n_i\}$ of some raster image, the sampling representation does not directly depend on the digital quantization parameter $Q = \Delta I$. It will only depend on the pixel bit depth parameter $v = \log_2(I_{max}/\Delta I)$, which is a standard characteristic of a digital images. In the next section some examples of sampling representations will be given.

3 EXPERIMENTS ON DIGITAL IMAGE CODING BY SAMPLES OF COUNTS

The made above remark implies the fact that the procedure for sampling the given raster image can be ultimately reduced to normalizing $\pi_i = n_i / \sum n_i$ pixel values (since $I_i \sim n_i$, $I(\vec{x})/W \sim n_i / \sum n_i$) followed by sampling of k random counts from the related probability distribution $\rho(\vec{x}_j | I(\vec{x})) \approx \pi_j$. It is also worth noting that machine learning provides a great number of algorithms and approaches for organizing the sampling procedures, which are united by a common name Monte Carlo method (Robert, 2004). Among these methods, we can recall the well-known Gibbs, Metropolis-Hastings algorithms, sampling by significance, acceptance/rejection and others. Such a set of methods makes it possible to optimize the sampling procedure by evaluating it from different angles, for example, from the perspective of the specifics of the task, evaluating the

effectiveness of its implementation, etc. At the same time, it should be understood that some sampling methods do not require some preliminary processing, and it will be sufficient to provide a condition under which all pixels will be bounded from above by the value 2^v , where v is the pixel bit depth parameter of the image.

Let us illustrate the forming of sampling representation for the standard test image “Sailboat on the lake”, shown in Figure 4. This image was taken from the USC-SIPI Image Database, which is often used in image processing publications. The figure shows several representations of a random counts of an image having the following initial parameters: image format - TIFF, dimensions - 512×512 pixels, a color depth of $v = 24$ bits. First of all, the image was converted to GIF format with the same dimensions 512×512 , but in a gray palette with a color depth $v = 8$ bits (see Figure 4 (A)), which allowed to reduce the overall amount of calculations. Figures 4 B-F show samples of sizes $k = 100\,000, 500\,000, 1\,000\,000, 2\,000\,000$ and $5\,000\,000$, the procedure itself was performed using the simplest method of rejection sampling (Robert, 2004) with a uniform auxiliary distribution $g(\vec{x}) = (s \times s)^{-1} = 512^{-2}$ and a constant upper bound of pixel values $c = 2^v = 256$. The choice of $g(\vec{x})$ and boundary c was due to the constraints $n_j < 2^v$, which in the case of the mean $\bar{m} = \sum n_j / s^2 > 1$ lead to the following majorization of the distribution density of the count:

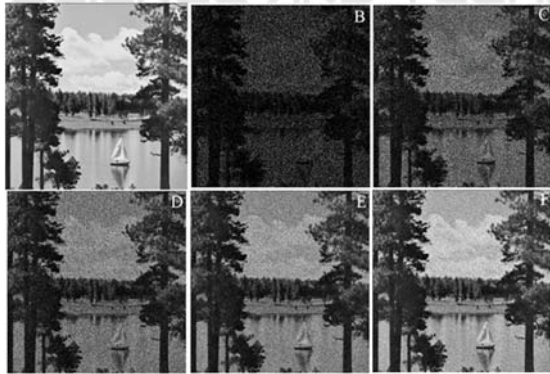


Figure 4: “Sailboat on lake” (USC-SIPI Image DB, 2021) image representation by samples of random counts: A original image in TIFF format, B – F representations with the sample sizes respectively $k = 100\,000, 500\,000, 1\,000\,000, 2\,000\,000$, and $5\,000\,000$ counts.

$$\begin{aligned} \rho(\vec{x}_j | I(\vec{x})) &\approx \pi_j = \frac{n_j}{\sum n_j} < \bar{m} \frac{n_j}{\sum n_j} = \\ &= \frac{n_j}{s \times s} < \frac{2^v}{s \times s} = c g(\vec{x}_j). \end{aligned} \quad (9)$$

As you can see, the algorithmic implementation of the sampling method reduces to a random selection of vectors \vec{x}_j , uniformly distributed in the area $s \times s$ (area Ω) with coordinates - floating-point numbers and the inclusion of these vectors in the sample of counts X_k when performing the test (9) $u_j < n_j$, where j is the index containing the pixel \vec{x}_j , and u_j is the realization of a uniformly distributed over $(0, c)$ random variable (see (Robert, 2004)). Normalization of pixels n_j is not required for this implementation.

The simplicity of forming fixed size samples of random counts $X_k = \{\vec{x}_1, \dots, \vec{x}_k\}$ and the universality of the statistical description (8) of the corresponding representation will be useful in many image processing tasks related to classification, identification and analysis of visual data, see (Antsiperov, 2021). However, this approach has a number of problems in applications related to visual perception. This fact can be observed in the fragments of Figure 4 - selective representations have a grainier texture than conventional images, as a result of which problems with the interpretation of images in the image are possible.

At the same time, it is worth remembering that traditional digital images are the result of rather complex algorithms for processing original images. TIFF image “The sailboat on the lake” in Figure 4A is one of such images obtained by scanning a photographic plate/film, the quality of which is increased due to the use of post-processing methods of the JPEG technology. Such images quality can be obtained also with the help of digital cameras. The above facts put us in front of solving another, important task of improving the quality of sampling representations for the possibility of visual perception of graphical data. Despite the fact that this topic goes beyond the scope of this work, leaving its solution for future research, we will limit ourselves to the results of the implementation of the simplest method for smoothing noisy images, which is based on the Parzen-Rosenblatt window method.

The smoothing method using the Parzen-Rosenblatt window is directly related to the nonparametric reconstruction of the probability density function based on the kernel density estimation (KDE) approach (Silverman, 1986). Since in the sampling representation $X_k = \{\vec{x}_1, \dots, \vec{x}_k\}$ the density of the distribution of independent counts $\rho(\vec{x} | I(\vec{x}))$ for our case is a multiple of the intensity parameter $I(\vec{x})$ (5), then the kernel estimate:

$$\hat{\rho}(\vec{x} | X_k) = \frac{1}{k\Delta} \sum_{j=1}^k K\left(\frac{\vec{x} - \vec{x}_j}{k\Delta}\right) \quad (10)$$

reconstructs both the density of distribution of counts and, to the accuracy of normalization, the intensity $I(\vec{x})$ (intensity form).

In (10) the kernel $K(\vec{x})$ is assumed to be a non-negative, normalized, symmetric function with a unit second momentum on a two-dimensional plane with coordinates $\vec{x} = (x_1, x_2)$. In other words, the kernel is the simplest smoothing window of unit width. The parameter $\Delta > 0$ is the smoothing parameter, it is often also called the window width (Silverman, 1986). In our experiments, a Gaussian distribution was used as the kernel $K(\vec{x}) = N(\vec{x} | \vec{0}, E)$, the window width parameter was not used – by default it was assumed $\Delta = 1$. The image dimensions were chosen of the same size $\times s$, $s = 512$ as those of the original image, i.e. it was assumed that the parameter Δ of the pixel size was chosen as the scale.

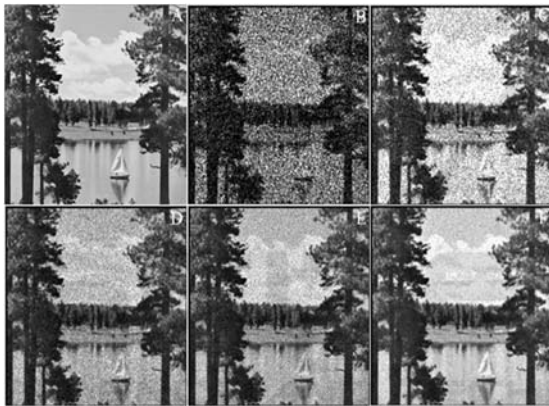


Figure 5: “Sailboat on lake” (USC-SIPI Image DB, 2021) image reconstruction using random sampling: A) original image in TIFF format, B) – F) reconstructed images by sample sizes, respectively $k = 100.000$, 500.000 , $1.000.000$, $2.000.000$, and $5.000.000$ counts.

Figure 5 shows the processed images obtained from samples of the corresponding sizes size $k = 100.000$, 500.000 , $1.000.000$, $2.000.000$, and $5.000.000$ counts (Figure 4). Separately, it is worth noting that relatively small samples ($k = 1.000.000$) generally satisfy the possibility of visual perception of objects in the image, regardless of the presence of blurriness and noise elements. A further increase in the sample up to $k = 5.000.000$ counts allow to get even more useful information, such as the clarity of the boundaries of individual objects, their relief, and even give an assessment of other characteristics. However, along with the increase in the sample size, there is an increase in the time spent on its preprocessing and recovery itself.

4 CONCLUSIONS

The paper presented a method for coding (representing) an image by fixed size samples of random counts. The formation of such a sampling representation allows not only to reduce the amount of input information but also to obtain other, not less obvious characteristics. Particular attention is paid to the performance of the sampling algorithm. Since most often one must work not with the only image, but with batches of similar images, an important parameter is the time required to fulfil the sampling procedure.

In the current work, attention was also paid to estimating the time for generating samples of counts of different sizes, which directly depends on the number of counts specified for the formation of a representation. With small numbers of counts, the sampling rate for the “Sailboat on lake” image was also small, for $k = 100.000$, the time was $t = 0.71$ seconds, with an increase in the sample size to $k = 1.000.000$ (10 times), the time was $t = 2.68$ seconds. This difference is extremely important if we are going to process, say, a group of 100 images, which will take us in the best case from one minute to 4 minutes if large sample size is selected. However, to determine how many counts to use when coding an image, it is necessary to operate with information about how the image can be used for further processing, as well as whether we can obtain a sufficient set of properties that allow us to identify objects and events rather accurately in the image. For example, the representation of the image with a sample of $k = 1.000.000$ counts allow us to visually compare the figures in the resulting coded image with similar figures in the original one, which seems almost impossible for a smaller sample. This allows us to conclude that the time spent on forming a sampling representation for images that have similar characteristics to the “Sailboat on lake” image (size 512×512 pixels, color, with a color depth of 24 bits) will not exceed 4 seconds, but it will take more than 1-2 seconds to form a visually interpreted image.

What about the samples of other sizes $k = 2.000.000$ and $k = 5.000.000$, the sampling time was $t = 10.04$ seconds and $t = 20.26$ seconds, respectively. Note that such representations have minor differences from the sample $k = 1.000.000$ if we consider the ability to visually perceive objects. However, such samples best eliminate noise and allow you to see smaller objects.

In general, reducing the original image with the help of samples of counts allows not only to switch to a new, simplified representation of the image but also

allows to effectively perform further operations on its processing. For the samples to be visually interpreted even with a small number of counts, the resulting image was restored with some degree of accuracy to the original one by smoothing methods. The sample size, of course, has a significant impact on the formation time of the smoothed image, as well as on the degree of its smoothness. This method of image restoration allows not only to process images with poor visual perception more accurately, but also simplifies the task of improving the perceptual characteristics of images with low quality and brightness parameters. Thus, we note that the average brightness level of the image has increased, which is mainly due to the elimination of dark areas in the image that remained between the recorded counts.

The time parameter spent on the implementation of the algorithm for smoothing samples of different sizes was also analyzed. Similarly, with the formation of the samples themselves, the smoothing algorithm showed the best results when working with small samples. With the number of counts $k = 100,000$, $500,000$ and $1,000,000$, the time was $t = 0.52$, 1.57 and 2.88 seconds, respectively. For large samples $k = 2,000,000$ and $5,000,000$ it took on average $t = 5.46$ and 13.24 seconds. When working with small samples, there was an improvement in image quality and the ability to interpret images on it. This indicates the possibility of using small samples of counts for image processing in the future, regardless of the visual perception of the operator.

All the processes outlined above, aimed at forming an ideal image, open a whole range of possibilities in the development, improvement, and use of various kinds of imaging devices, such as single-photon avalanche diodes (SPAD) operating in the mode of single photons counting.

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