Full-color stereoscopic imaging with a single-pixel photodetector

Eva Salvador-Balaguer, Pere Clemente, Enrique Tajahuerce, Filiberto Pla and Jesús Lancis

***Abstract*— We present an optical system for stereoscopic color imaging by using a single-pixel detector. The system works by illuminating the input scene with a sequence of microstructured light patterns generated by a color digital light projector (DLP). A single monochromatic photodiode, synchronized with the DLP, measures the light scattered by the object for each pattern. The image is recovered computationally by applying compressive sensing techniques. The RGB chromatic components of the image are discriminated by exploiting the time-multiplexed color codification of the DLP. The stereoscopic pair is obtained by splitting the light field generated by the DLP and projecting microstructured light patterns onto the sample from two different directions. The experimental setup is configured by simple optical components, a commercial photodiode and an off-the-shelf DLP projector. Color stereoscopic images of a 3D scene obtained with this system are shown.**

***Index Terms*—Optical imaging, color imaging, digital micromirror device (DMD), stereo image processing.**

I. INTRODUCTION

Computational imaging with single-pixel detectors is a remarkable alternative to conventional imaging techniques. It enables to obtain spatial information of an object, such as the reflectance distribution or other optical properties, by sampling the scene with a set of microstructured light patterns [1]. A simple bucked detector, for instance a photodiode, records the signal associated to each pattern and the image is reconstructed by mathematical algorithms. In this way, by avoiding sensor arrays, it is possible to add new degrees of freedom to the sensing process, allowing one to use very sensitive light sensors, to explore unusual spectral bands for imaging, or to use exotic photodetectors such as spectropolarimeters.

The technique is closely related to ghost imaging [2-4] and dual photography methods [5], which also use single-pixel detectors to reconstruct images. In the first case, imaging is based on the correlation between two signals. One signal is the intensity distribution of the light illuminating the object, as measured by using a detector array or evaluated by numerical simulation, while the second signal collects the total amount of light actually interacting with the object. In the second case the image is obtained by exploiting the Helmholtz reciprocity principle. This is mainly used in computer graphics research, and it is based on the idea that the flow of light can be reversed without altering the radiance transfer. Besides, some high resolution imaging techniques, such as fluorescence microscopy, also benefit from single-pixel detectors by using point scanning illumination. In fact, the introduction of microstructured light patterns for excitation in these techniques has shown improved performance [6].

The detection scheme based on single-pixel sensors has several advantages compared to conventional imaging techniques using sensor arrays. The simplicity of the sensing device allows them to work efficiently in conditions where light is scarce [7]. It also allows measuring the spatial distribution of multiple physical dimensions of the scene in a simple way. In this direction, single-pixel detection arquitectures have been designed for polarimetric imaging [8], color or multispectral imaging [9,10], time-of-flight imaging [11,12] or holography [13]. Moreover, single-pixel detectors provide a broader spectral range compared to conventional cameras, permitting to extend imaging techniques to different spectral regions [14,15]. Furthermore, it has been proved the ability of single-pixel cameras to perform non-invasive imaging through scattering media in biological tissues [16,17]. All these advantages could make single-pixel imaging a relevant technique in biomedical imaging, where fast, high-resolution, multispectral, and tolerant to scattering imaging is required.

One of the main characteristics of imaging techniques using single-pixel detectors is that they are very well adapted to apply the theory of compressive sampling (CS) [1,6,7,18,19]. This theory exploits the fact that natural images tend to be sparse, i.e. only a small set of the expansion coefficients is nonzero when a suitable basis of function to express the image is chosen. In this way, images can be retrieved with a number of measurements lower than that established by the Shannon-Nyquist limit.

Several approaches have been proposed for applying these techniques to three-dimensional (3D) scenes. In principle, one may think that by simply displacing the light detector in any 2D single-pixel camera configuration it would be possible to obtain different 2D perspectives of a 3D scene. However, it

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has been shown that this displacement only changes the apparent illumination direction of the scene [5]. Using shape from shading approaches, this effect has been used to get 3D spatial information of an object [20, 21]. To this end, several photodetectors located at different positions record signals associated to the collection of illumination patterns simultaneously. The 3D shape is then reconstructed from the surface gradients obtained by comparing the illumination information of different images.

Nowadays, for many imaging applications it is even more important to efficiently display 3D information than to reconstruct the 3D shape of objects in the scene. The principle of stereoscopic vision can then be applied for 3D information recording and visualization, as it is done in commercial 3D movies by using switching or polarized glasses. The 3D perception is created by the human brain through the fusion of the pair of different images acquired by the eyes. In this work we present an optical system for stereoscopic color imaging based on computational imaging with a single-pixel detector together with a CS strategy. Our system is able to produce full-color stereoscopic images of a scene by using a low number of optoelectronic components, just a simple monochrome photodetector and a digital light projector.

II. SINGLE-PIXEL IMAGING AND COMPRESSIVE SENSING

The operation of a single-pixel camera is shown schematically in Fig. 1. A sequence of M microstructured light patterns with irradiance distribution $\Psi_i(m,n)$, being m, and n discrete spatial coordinates and $i=1,\ldots,M$, is projected onto the input object. Light back scattered by the object is collected by the photodiode. If we denote with $T(m,n)$ the reflectance distribution of the object at the points sampled by the light patterns, then the photodiode measures sequentially the M inner products

$$I_i = \sum_{n=1}^{\sqrt{N}} \sum_{m=1}^{\sqrt{N}} \Psi_i(m,n) \cdot T(m,n). \qquad (1)$$

In Eq. (1), N is the number of pixels of the microstructured light patterns. The sampling operation in Eq. (1) implies that the spatial resolution of this imaging technique is determined by that of the projected light patterns.

Different approaches for single-pixel imaging use different sampling functions $\Psi_i(m,n)$, being random patterns, for example, very common for the subsequent application of CS algorithms. In our work the sampling patterns are 2D functions $H_i(m,n)$ pertaining to the Walsh-Hadamard basis [22]. The 2D patterns represented in Fig. 1 are examples of these functions. This choice provides several advantages. Firstly, these patterns are members of an orthonormal basis. In this way, the intensity measurements, I_i, directly provide the representation of the object in the basis. This also means that, in principle, by using all the functions of the basis the object could be exactly recovered for a given sampling frequency. Secondly, natural images tend to be sparse in the Hadamard basis, making these functions very useful also for compressive sensing purposes. And third, these patterns are binary function with values +1 and -1. Therefore it is very easy to codify them with fast binary amplitude modulators.

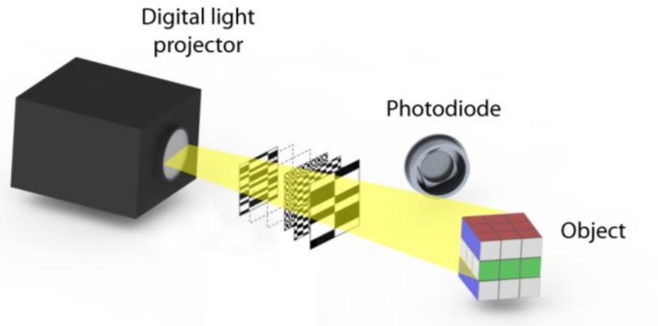


Fig. 1. Single-pixel scheme. A sequence of binary masks are projected onto an object and the light is collected by a photodiode.

Taking into account the definition of the Hadamard matrices, it is straightforward to show that, for any two patterns with index i and j,

$$\sum_{n=1}^{\sqrt{N}} \sum_{m=1}^{\sqrt{N}} H_i(m,n) \cdot H_j(m,n) = N \cdot \delta_{ij} \ , \qquad (2)$$

where δ_{ij} is the Kronecker delta. Therefore, by using a sequence of M Hadamard patterns, the irradiance distribution of the object in Eq. (1) can be estimated by applying a simple superposition principle in the following way:

$$T'(m,n) = \frac{1}{N} \sum_{i=1}^{M} I_i \cdot H_i(m,n) \ . \qquad (3)$$

It is important to note that in the absence of noise, by using a sequence of N different Hadamard patterns Eq. (3) provides an exact replica of the object with a sampling resolution of N pixels. Note also that this approach looks similar to ghost imaging techniques if we realize that the operation in Eq. (3) can be understood as a parallel correlation between the sequence of measured irradiances I_i and the sequence of light irradiance illuminating each pixel $H_i(m,n)$.

The main limitation in imaging by single-pixel techniques is that they may require long acquisition times. This time depends on the number M of projected masks, the projection rate R_{SLM} and the integration time t_{int} of the light detector through the equation

$$t_a = M\left(\frac{1}{R_{SLM}} + t_{\text{int}}\right) \ . \qquad (4)$$

Ideally the integration time should be as short as possible and the frequency rate as high as allowed by the digital light projector. A way to further decrease the acquisition time is by reducing the number of measurements. This can be done very efficiently by using CS algorithms because natural images tend to be sparse in the frequency space. The CS theory establishes that by using a number $M < N$ of randomly chosen patterns, it is possible to reconstruct the original image

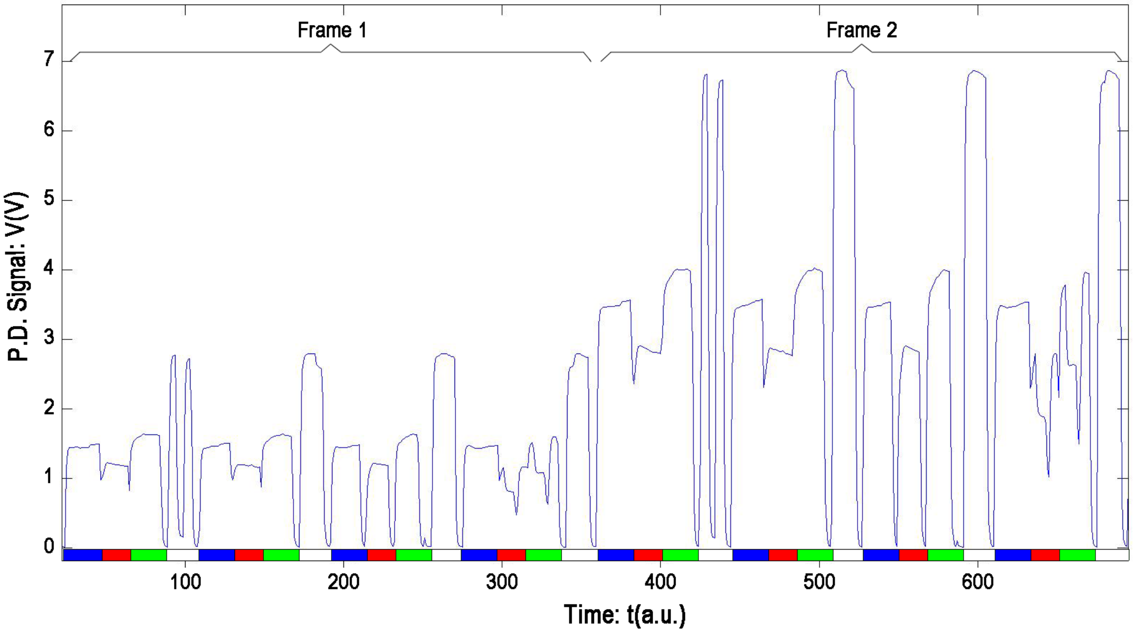


Fig. 2. Signal captured by the photodiode for two consecutive frames in which an arbitrary pair of Hadamard patterns have been sent. In the horizontal axis of this graph, arbitrary units are used to express time. In the vertical axis the signal voltage is given by Volts.

with high quality. The idea is better stated by rewriting the measurement process in Eq. (1) in matrix form as

$$\vec{I} = \Phi \cdot \vec{t} = \Phi(\Gamma \cdot \vec{s}) = \Theta \cdot \vec{s}, \tag{5}$$

where $\vec{I}$ is a $M \times 1$ vector containing the measured coefficients, and $\vec{t}$ and $\vec{s}$ are $N \times 1$ vectors representing the input object in the sampling space and in the Hadamard frequency space, respectively. Matrix Φ is an $M \times N$ matrix containing a random subset of M Hadamard patters codified in the different rows, and matrix Γ is the transformation matrix between the sampling space and the Hadamard space. The product of matrix Φ and Γ gives the matrix Θ acting directly on $\vec{s}$. In CS, the undetermined matrix relation in Eq. (5) is solved by off-line reconstruction algorithms such as those based on convex optimization or greedy algorithms. In our approach we use a convex optimization algorithm based on the minimization of the ℓ_1 norm of $\vec{s}$ subjected to the restriction given by Eq. (5). In particular, the object estimation, $\vec{t}'$, is obtained by solving

$$\min_{t'} \left\| \Gamma^{-1} \vec{t}' \right\|_{l_1} \text{ subject to } \Phi \vec{t}' = \vec{I} \tag{6}$$

Note that by using CS algorithms, acquisition time in Eq. (4) is reduced but certain amount of post-processing time is added to reconstruct the final image. Furthermore, CS algorithms are known to be time consuming. For that reason some recent approaches aiming to get high resolution imaging at high frame rates focus on reducing this post-processing time by using different alternatives to CS based on adaptive sensing [23,24].

III. SINGLE-PIXEL COLOR IMAGING

The key elements to implement a single-pixel camera, according to the approach shown in Fig. 1, are a spatial light modulator, to sample the input object with microstructured light patterns, and a light detector. In our setup we use an off-the-shelf digital light projector (DLP) based on a digital micromirror device (DMD) to generate the light patterns. This is a low-cost alternative to scientific-grade DMD devices that, additionally, incorporates the light source, allows color codification of the output light patterns, and is controlled by very simple standard video signals. In particular, the DLP used in our experiments is a Dell M110 Ultra-Mobile Projector with a 0.45’’ WXGA S450 DMD. The light detector, measuring the light scattered by the object for each projected pattern, is a photodiode Thorlabs DET36A EC. The photodiode output signal is digitized by a DAQ card, NI USB-6003 connected to a computer.

To get color information from the scene, we take advantage of the codification procedure used by the DLP for color video projection. In the standard video projection mode, white light from the projector lamp passes through a spinning color wheel. The color wheel filters the light so that it changes sequentially to red, green, blue and white colors. In particular, for the video projector used in our experiment, each RGB chromatic component, and the white component, are encoded onto 4 time slots within a frame. This sequence is represented by color horizontal bars in the lower part of Fig. 2. Depending on how much color is required, mirrors of the DMD are tilted on or off a shorter or a longer time within the corresponding time slot. The white slot is used to control the brightness of the image. Therefore, the DLP technology relies on the viewer's eyes to fusion the light into the final color by time multiplexing.

In this way, we can obtain color information with a single monochromatic photodiode by projecting black and white Hadamard patterns with the video projector and measuring the photodiode signal at the proper time. In particular, we send a single Hadamard pattern per frame and measure the amount of light scattered by the object for each RGB chromatic channel, I_{iR}, I_{iG} and I_{iB}, integrating the photodiode signal during the time slot associated to each channel. The color irradiance distribution of the input object is estimated by using the superposition approach in Eq. (3), or the CS approach in Eqs. (5) and (6) for each chromatic component. Fig. 2 shows the experimental signal provided by the monochromatic photodiode when two consecutive arbitrary Hadamard patterns are projected onto a scene following the setup in Fig. 1. It can be seen that four different colors are detected for each frame, the three chromatic components R, G, and B, plus a white component. And four different time slots are used to codify each color, thus providing 16 different time slots. The total amount of light scattered by the object for each chromatic component is measured by integrating the signal along the corresponding RGB time slots. The white slot is used in our application for synchronization purposes. In Fig. 3 we show the color image of an object reconstructed with our experimental setup. For this particular example we used Hadamard patterns of 256x256 pixels. Moreover using CS the total number of measurements to recover the scene was 10% of the 256^2 measurements established by the Nyquist criterion.

Fig. 3. Color image, with 256x256 pixels, of an object obtained by using the single-pixel scheme shown in Fig. 1 and CS algorithms.

IV. STEREOSCOPIC COLOR IMAGING

When the goal of an imaging technique is not to reconstruct a complete 3D model but to visualize a realistic 3D scene, the best option consists in imitating the stereoscopic process followed by humans to get depth perception. Actually, our intention is to adapt the setup in Fig. 1 to be able to obtain stereoscopic information with single-pixel detection. In principle, one may think that by displacing the photodetector in the setup in Fig. 1 it would be possible to obtain different 2D perspectives of the 3D scene. However in single-pixel imaging is not the position of the photodiode but the orientation of the light projector what provides the different 2D perspectives.

In order to clarify the difference between capturing the scene with several photodiodes and our final approach we perform first the experiment depicted in Fig. 4. The input scene is sampled with a sequence of micro structured light patterns while two photodiodes located at different positions record light intensity signals. In our approach the 3D object is placed at 32 cm from the DLP. The pattern size and the pixel pitch at that distance are 3.2x3.2 cm and 250 µm respectively. A different 2D color image is obtained from each signal by using the approach described in Section III. The results are shown in Fig. 5. Fig. 5(a) is an image of the scene captured by a CCD camera, Fig. 5(b) is the image reconstructed with the signal provided by the left photodiode, and Fig.5(c) is the one obtained by using the right photodiode. It can be seen, comparing Figs 5(b) and (c), that they correspond to the same perspective of the input scene and thus they do not provide disparity to be applied in stereoscopy. However, the images appear to be illuminated from different directions. This fact can be checked by comparing the images of the dice in the foreground of both figures. Note that number 4 of the dice is only seen by using information from the left photodiode while number 5 is only shown from that of the right one. Each image is the same as that obtained by substituting the DLP with a conventional camera and the photodiode by a white-light point source located at the same position, as can be shown by the Helmholtz reciprocity principle.

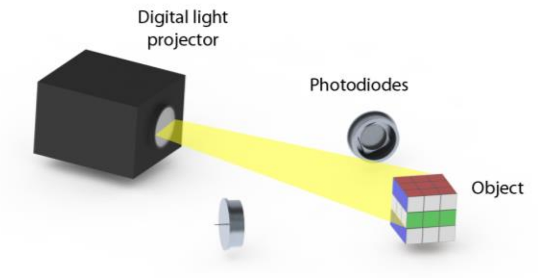


Fig. 4. Experimental setup for single-pixel imaging with two photodetectors. The signal provided by each photodiode is used to generate a different image of the scene.

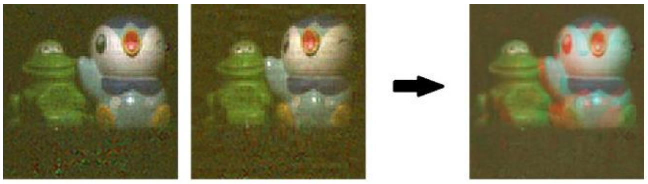
(a) (b) (c)

Fig. 5. (a) Image of the input scene captured by a CCD camera, (b) 128x128 image obtained by the left photodiode in Fig. 4 and (c) 128x128 image obtained by the right photodiode in Fig. 4 . Images in (b) and (c) provide the same perspective of the scene but with different illumination.

For obtaining two different 2D perspectives of a scene to be represented on a 3D display, or to be used for analyzing disparity, we developed the experimental setup shown in Fig. 6. In this configuration each pattern is projected towards the 3D scene from two different directions by displaying the same pattern in two different positions of the DLP. A 90º beam splitter and two mirrors, separated a distance equal to the interocular distance, are configured in such a way that both patterns overlap at the same plane in the 3D scene. In this second setup the 3D object is placed at 30 cm from the DLP. The pattern size and the pixel pitch at that distance are 6x6 cm and 234 µm respectively. The photodiode is placed at 6 cm from the 3D object. The light scattered by the object for each pattern is captured by a single monochromatic photodiode placed in front of the object. Again the photodetector signal is synchronized with the sequence of patterns, following the method in Section III. In this way, each set of patterns provides each one of the images of the stereoscopic pair.

In principle, each element of the pair of black and white patterns used to generate the two different perspectives should be projected independently onto the object in order to measure the photodiode signal associated to that perspective. However a faster alternative is to send a pair of patterns with chromatically opposite colors (red and cyan), as is shown in Fig. 6. This will provide us directly with an anaglyph, that is, a picture consisting of the overlapping of two stereoscopic images of the object, in two complementary colors. The method is similar to that described in Section III to reconstruct a color image. It is based in the time multiplexing nature of the light projected by the DLP, which codifies color information sequentially, as is shown in Fig. 2. This fact allows us to discriminate each RGB chromatic component from the signal captured by a single monochromatic photodiode. Therefore, after codifying each perspective with different colors, as is proposed in Fig. 6, we are able to discriminate not only the color but also the stereo pair. Despite anaglyph is not the best method to display stereoscopic images, it will allow us to analyze the results obtained in preliminary experiments so that they can be viewed with the appropriate color glasses.

Experimental results showing different 2D color perspectives of an input object are shown in Fig. 7. Fig. 7(a) shows a color image obtained by using the signal provided by the photodiode in Fig. 6 when the set of binary masks is projected from the left mirror and is the same as Fig. 3. Fig. 7(b) is the equivalent one obtained by using the light patterns coming from the right mirror. Finally, Fig. 7(c) is the anaglyph obtained from the previous images, similar to the one that it is obtained by sending red and cyan patterns simultaneously as described above. To get Fig. 7(c), only the red channel in Fig. 7(a) is used for the left image, while the green and blue channels in Fig. 7(b) are used for the right image. In this experiment we use Hadamard patterns of 256x256 pixels. The maximum frequency of our light projector is 60Hz, and this is the maximum rate to project the patterns. Nevertheless, as explained above in Fig. 3, we only used 10% of the 256^2 needed patterns, allowing us to obtain the anaglyph image in 109 seconds.



(a) (b) (c)

Fig. 7. Pair of 256x256 stereoscopic images, in (a) and (b), and the resulting anaglyph (c) is the anaglyph obtained from the previous images (a) and (b). For a better visualization of image (c), we have enhanced its brightness and reduced the noise.

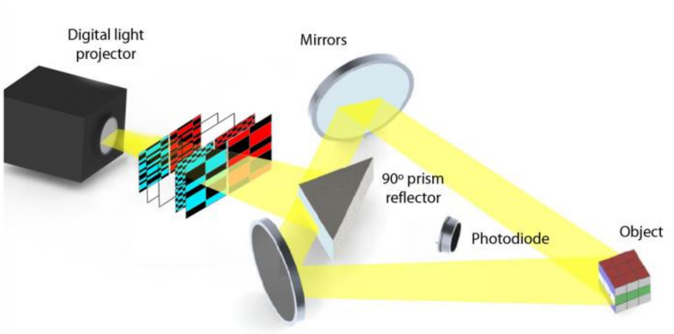


Fig. 6. Experimental setup to record stereoscopic images with a single photodetector. Pairs of Hadamard patterns with chromatically opposite colors overlap at a plane in the 3D scene. The signal from a single monochromatic photodiode allows us to obtain an anaglyph image of the object.

In contrast to imaging systems based on multiple cameras we do not need any calibration or rectification algorithm to get the stereoscopic pair. The calibration is accomplished by the preliminary overlapping of two patterns in a plane of the 3D scene. Then, once the prism and mirrors are properly placed the experimental setup can be used for several scenes.

V. CONCLUSION

In this paper we have shown that it is possible to produce full-color stereoscopic images with a single photodiode and an off-the-shelf projector. In this way, we have proposed a low-cost setup to produce a pair of images that can be used as an input in a 3D display. We have also clarified the difference between using several photodiodes and several projection viewpoints. In the proposed approach, the 3D information of the scene is provided by the disparity and not by light shading.

In principle, time required to project light patterns implies a low frame rate. However, to partially solve this problem we have used a CS algorithm and we plan to use more efficient adaptive compressive strategies in the near future. We expect that these methods will allow us to capture and visualize 3D scenes at practicable frame rates.

Single-pixel cameras are a promising alternative to conventional imaging techniques in applications such as polarimetric and multispectral imaging, or to deal with exotic spectral bands. Additionally, they have been applied with success in imaging through scattering media. This new approach can be the first step to extend all these applications to stereoscopic imaging.

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