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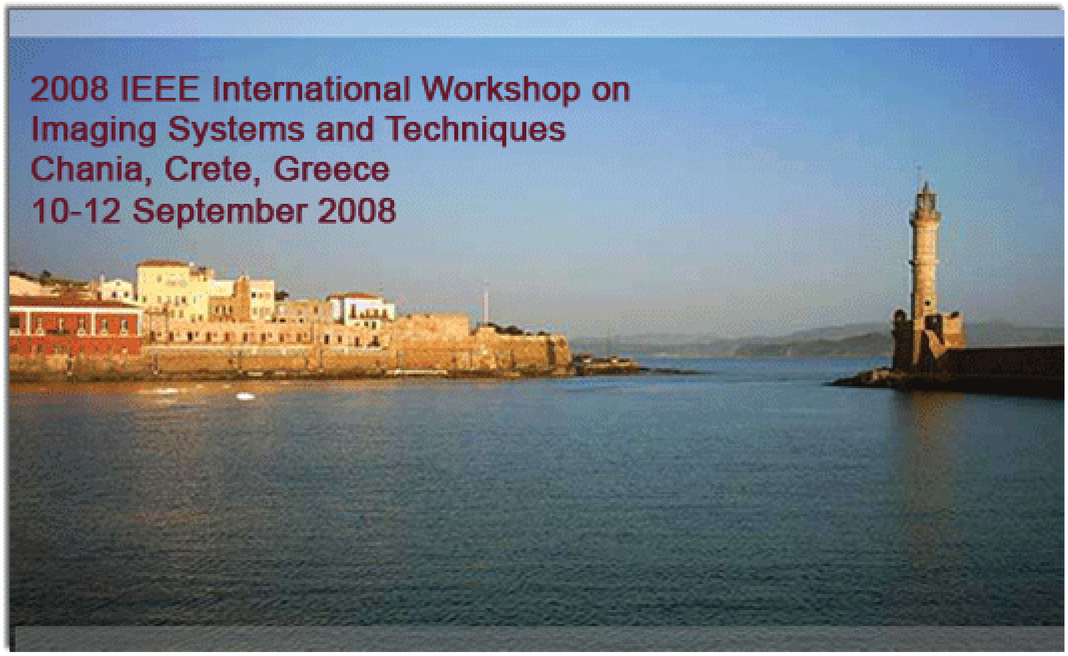

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Distance Errors Correction for the Time of Flight (ToF) Cameras.

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Abstract—**The Time of Flight (ToF) cameras, using their own light source, deliver two images simultaneously: brightness image and distance image and so they become 3D camera. At present, in spite of a theoretical very good resolution in distance, the distance errors are unacceptable big and not under control due to the multiple reflexions of the active light outside and inside the camera. To our best knowledge, till now there is no method to correct these errors. We propose a model for describing these errors and methods for correcting them. One is simple enough for building it inside camera for real time correction.**

Keywords- image processing; ToF cameras; error correction; distance measurement

I. INTRODUCTION.

ToF cameras – a new type of 3D cameras, see e.g. [1] – uses its own light source (e.g. infrared one) and acquires, at the same time, two images: one is the classical amplitude (brightness) image and the second is a “distance image”; this last one is still affected by important errors (till 50%) due to multiple reflections of the light, which depend on the scene, or moving scene, as well as on the camera geometry. In this paper we continue to develop the framework for their correction (started in [2]). We stress that the model we build is able to correct adaptively the image – i.e. depending on the scene – and by far is not limited to this kind of applications – i.e. on ToF cameras.

We resume the work principle of the ToF cameras which is described in [1]: an own light source illuminates the scene and the camera only records this reflected light but not the other light coming from the objects in the scene; this is so because the light source generates a monochromatic (infrared) modulated (with e.g. 20 MHz) light (see Fig. 1). Due to propagation, the light intensity of the far objects is smaller than that of the near ones and so, a far “white” object could be darker than a near to the camera “grey” one. In [2] an algorithm is given for pixel-wise correction of this error using the distance image. On the other hand this distance image itself must be corrected. Indeed, the ToF camera measures, pixel-wise, the amplitude, a, and the phase shift, φ, of the incoming light; the distance to a point in the scene is given by (1) where c stands for the speed of light, f for modulation frequency, φ for the phase shift between the emitted wave and the received

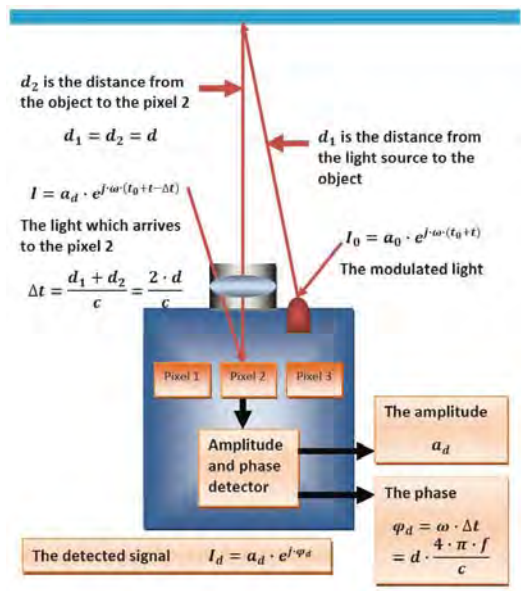

Figure 1. The principles of the Time of Flight camera

wave (the modulating wave of the IR light):

$$d = \frac{1}{2} \cdot \frac{\varphi}{2\pi} \cdot \frac{c}{f} \tag{1}$$

The measured signal at the pixel *i* is

$$I_m(i) = a_m(i) \cdot e^{j\varphi_d(i)} \tag{2}$$

In spite of the fact that the ambient light doesn’t affect the “measured signal” this one has an important parasitic component due to the perturbing factors: namely the reflections outside and inside the camera have a big weight in it. That is why one is led to write the measured signal $I_m(i)$ as a sum of the signal coming from the region in the scene corresponding to the pixel *i* i.e. the direct signal $I_d(i)$, and a parasitic component $I_p(i)$.

$$I_m(i) = I_d(i) + I_p(i) \tag{3}$$

We stress that this is a decomposition of complex numbers and, in general, $\varphi_d(i) \neq \varphi_p(i)$ so that $\varphi_d(i) \neq \varphi_m(i)$ too; and so we have $d_p(i) \neq d_m(i)$.

In the previous papers on this subject [3], [4] we have shown that, even in the laboratory conditions (using special scenes) $I_p(I)$ is not zero and it varies with the scene and so the calibration of the camera becomes a tricky business. In what follows we shall develop a way to correct the measured distance for the objects of any scene, using as the main tool the decomposition (3).

II. Parasitic Component.

Obviously (3) is not enough to get $I_d(i)$ from $I_m(i)$ if we don't know $I_p(i)$. Nevertheless we can imagine the same scene illuminated differently only on the small region corresponding to the pixel *i* in the image so that

$$a_{d1}(i) = k \cdot a_{d2}(i) \qquad (4)$$

but $I_p(i)$ remains the same. In this case we get

$$I_{m1}(i) - I_{m2}(i) = I_{d1}(i) - I_{d2}(i) \qquad (5)$$

and because $\varphi_d(i)$ only depends on the distance and this doesn't change, we also have

$$I_{d1}(i) = k \cdot I_{d2}(i)$$

and

$$I_{m1}(i) - I_{m2}(i) = [a_{d1}(i) - a_{d2}(i)] \cdot e^{j\varphi_d(i)} \qquad (6)$$

For a known k one gets

$$I_{d1}(i) = k \cdot I_{d2}(i) = k \cdot \frac{I_{m1}(i) - I_{m2}(i)}{k-1}$$

$$I_p(i) = \frac{I_{m1}(i) - k \cdot I_{m2}(i)}{1-k}$$

and

$$\varphi_d = \arg(I_{m1}(i) - I_{m2}(i))$$

from which *d* comes out with (1).

Two ways of accomplishing the above conditions are described in the following section together with the measurements done on particular scenes, which prove the truth of our assumptions and the degree of correction obtained. We shall also comment on the power of our approach in various fields of applications.

III. Correction with Black-White Labels.

We have in Fig.2 and 3 the distance images of a scene with a porcelain vase (which appears in Fig. 4 as a normal-intensity image). We worked with a SR-3000 camera [5].

In Fig. 2 the distances are coded by color while in Fig. 3 we put a 3-d image just to show how big the errors on distance in some images like ours, are. Two (black and respectively white) labels (squares) are put on the superior part of the vase (they look as being at different distances as one can see by the different colors). The labels are obviously much greater than a pixel. In spite of that, the hypothesis that I_p is enough constant in the two regions of labels (and even on a broad area), seems to be effective for correction.

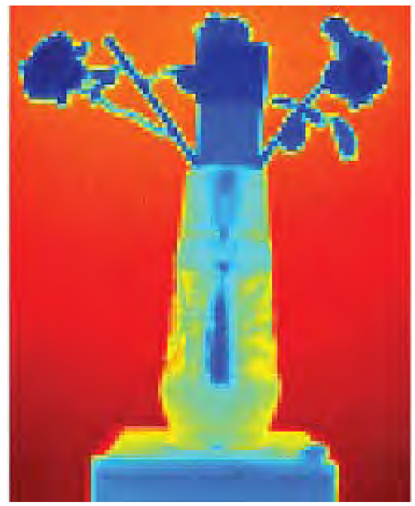

Figure 2. The distance image of the vase, without correction, with distance coded in color.

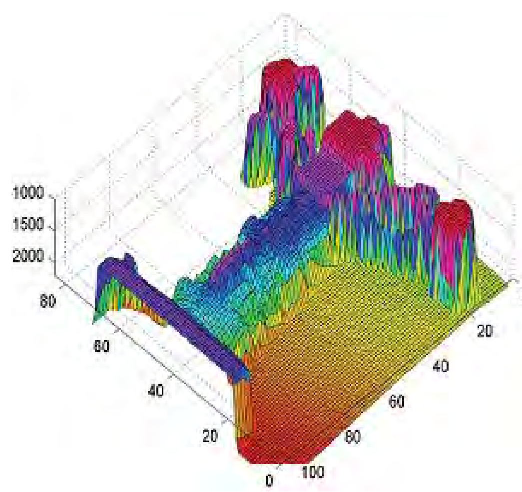

Figure 3. A 3-d plot of the distance image where one can see the big difference (cca. 0,5m) in distance for the two labels (white, black) in the upper part of the vase.

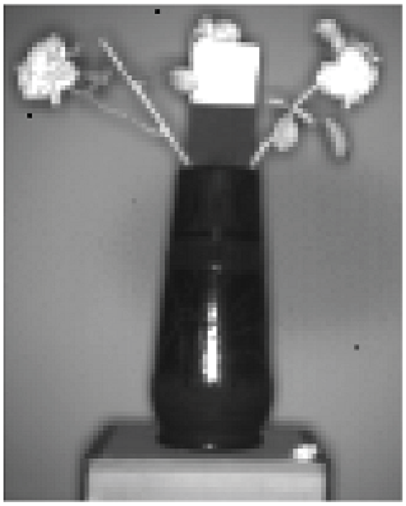

Figure 4. An intensity image of the vase with two labels –white and black- on the top, at the same distance to the camera.

Using the formulae of §2 one is able to correct surprisingly well the distance image as can be seen in Fig. 5 and Fig. 6 respectively.

Of course, this proves that I_p as an image looks like only having very low spatial frequency components which is a theme per se for other study; nevertheless one can be aware of the fact that the correction doesn't mean just subtraction of a quantity from the previous value: we have to eliminate a (more or less constant) complex quantity I_p from the measured quantities $I_m(I)$ themselves complex too.

Fig. 7 shows the diagram of distances along a vertical line passing in the middle of the vase from which one can read exactly the improvements obtain by this correction, obviously not perfect ones, due to the mentioned approximation of the

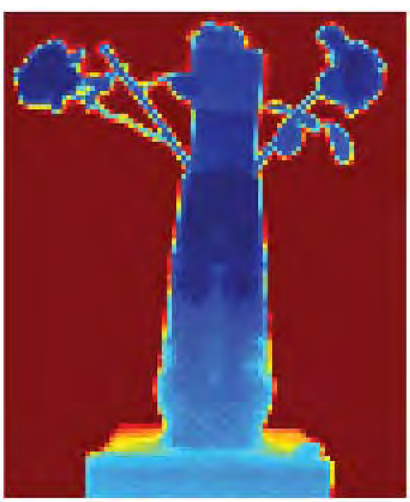

Figure 5. The distance image of the vase, with correction, with distance coded in colour.

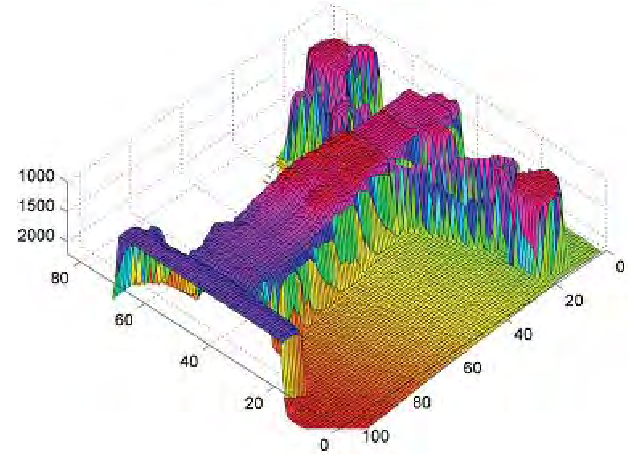

Figure 6. The 3-d plot of the distance image with correction; the two labels now appear at the same distance.

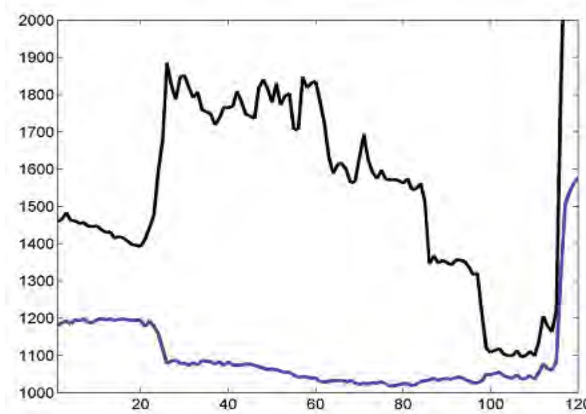

Figure 7. The plots of the distances along a vertical line passing in the middle of the vase; the upper one – before correction; the bottom one – after correction.

$I_p(i)$ by a constant on the whole central part of the scene, but obviously almost two orders of magnitude which already means a lot!

IV. Correction with Structured Light.

Details about "structured light" technique can be found in various papers e.g. [6]. To our best knowledge it was not yet used in connection with the TOF cameras; in connection with the model developed above, it is very effective and also simple to use. For a whole image it is enough to have three vertical and three horizontal lines like in Fig. 8 and either take two consecutive shots – one without and one with the lighted lines – or only consider the image with this simple structured light added to the standard light and compute the I_p in the 9 points/pixel of the lattice obtained at the intersections of the 6 lines (using the values in some neighbour pixels).

Each I_p will be used as the value of the parasitic component in the whole square centered in the pixel for which it was measured. This could produce a blocking effect on the image if the different corrections will be used each on its square. Using a fuzzy approach like in [7] and [8] we shall get a smooth passage from one square to the neighbour one and the correction obtained will meet the same quality on the whole distance image.

We stress that the correction is simple from the computational point of view and can be done in real time in the camera; in our opinion this way will become the standard way to correct the distance images in the TOF cameras.

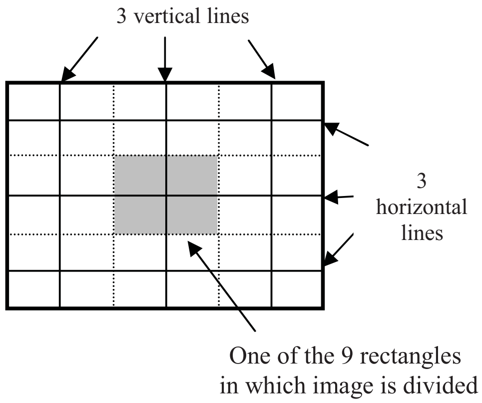

Figure 8. An image divided in 9 rectangles for using 9 I_p values and fuzzy support for correction

V. Conclusions and Acknowledgements

In our opinion ToF camera will evolve towards a cheap and efficient device for many useful real time applications of image processing/analysis; one of the necessary developments on this way is just the elimination of a few sources of important errors or their automatic correction. Our model proved to be effective in the drastical reduction of the errors of the category reflexions and we believe it is also effective in the reduction of other errors too.

The principle of ToF cameras, namely measuring the amplitude and phase of a wave modulating a monochromatic carrier, is quite general in many devices. In any such case our approach for extracting the useful signal from the measured one will be effective as soon as the parasitic one can be estimated indirectly.

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