Distance errors correction for the Time of Flight (ToF) Cameras.

Dragos Falie
Laboratorul de Analiza si Prelucrarea Imaginilor
Universitatea "Politehnica" Bucuresti
dfalie@alpha.imag.pub.ro

Vasile Buzuloiu
Laboratorul de Analiza si Prelucrarea Imaginilor
Universitatea "Politehnica" Bucuresti
buzuloiu@alpha.imag.pub.ro

Abstract

One of the most important distance measurement errors is produced by light reflections. These errors can't be avoided and black are more affected than white objects. The measured distance to an object in the scene by the ToF camera changes if surrounding objects are moved. The distance error can be greater than 50% and camera calibration is useless if objects are moved.
The calibration method we propose can be performed not only in laboratory condition but also in any conditions. The distance errors for all objects in the scene can be corrected if on the objects are attached white or black tags, labels.
The ToF cameras can be improved using an active illumination with structured light. The improvement will eliminate the distance errors produced by light reflections.

1. Introduction

The TOF cameras are a new type of 3D camera. This camera has its own illumination source, an array of infrared LEDs, so that it can work even when there is no other light source. Each pixel of the camera measures the incoming reflected light and the distance to the objects in the scene. This information is obtained by using amplitude modulated light. The amplitude and the phase of the modulating wave are detected by a phase detector. In this way only the modulated light is detected and the background light is rejected. The principia of the ToF camera are presented in fig. 1. The distance to the object is given by the relation (1) where the phase difference between the emitted and reflected wave is φ, c is the speed of light and f the modulation frequency.

$$d = \frac{\varphi}{4\cdot\pi}\cdot\frac{c}{f} \quad (1)$$

For each cameras pixel i the detected light signal $I(i)$ is given by the relation:

$$I(i) = a(i)\cdot e^{j\cdot\varphi(i)} \quad (2)$$

In the above relation $a(i)$ is the amplitude of the detected light and $\varphi(i)$ is the corresponding phase difference measured at the pixel i. The distance $d(i)$ (which is half of the distance traveled by emitted light from the camera to the object and back) is computed with the relation (1).

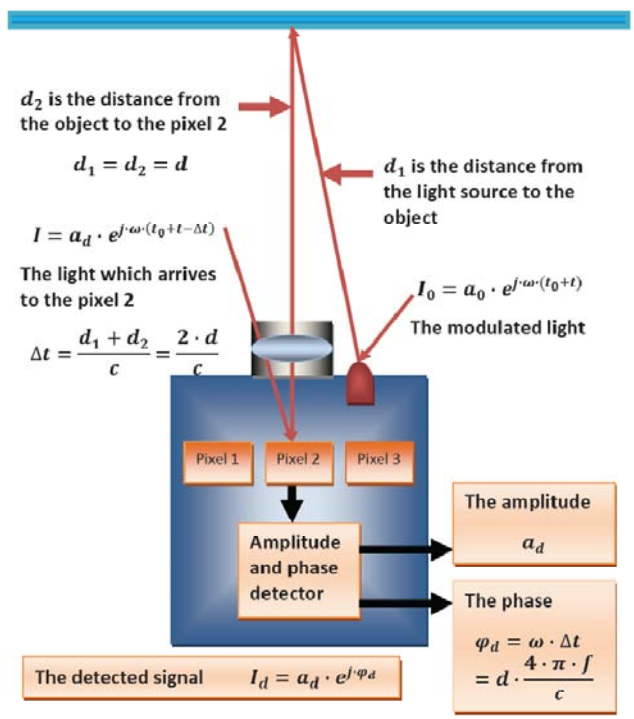

Figure 1: The principia of the Time of Flight camera.

Distance measurement errors to a dark object, characteristic to Time-of-Flight (ToF) cameras, have been noticed for a long time. Possible explanations for distance errors to very dark objects have been given [1], [2].

The background light or the natural light reflected by objects does not affect the amplitude $a(i)$ or the phase $\varphi(i)$ in relation (2). These quantities $a(i)$ and $\varphi(i)$ are affected only by the amplitude modulated light emitted by the camera. The light reflected by an object in the scene and detected by pixel i is composed by the direct cameras modulated light, the indirect light and the background light. The indirect light is the cameras emitted light reflected by other objects in the scene which illuminate the object. This indirect light resultant is the integration of all the reflected lights which illuminate an object. The phase information of his light is not related to the distance of the object to the camera with relation (1).

We shall split the detected light signal $I_m(i)$ by the pixel i in more components. The main component is the signal $I_d(i)$ produced by the detection of the direct light reflected by the object. Another component is $I_{r1}(i)$, the signal produced by the integrated indirect light reflected by various objects. Inside the camera body the incoming light also suffers reflections and a fraction of it $I_{r2}(i)$ is detected by the pixel i. Finally the detected light by pixel i is:

$$I_m(i) = I_d(i) + I_{r1}(i) + I_{r2}(i) = I_d(i) + I_p(i)$$

$$I_{r1}(i) = a_{r1}(i) \cdot e^{j \cdot \varphi_{r1}(i)}, \quad I_{r2}(i) = a_{r2}(i) \cdot e^{j \cdot \varphi_{r2}(i)}$$
$$I_d(i) = a_d(i) \cdot e^{j \cdot \varphi_d(i)}, \quad I_p(i) = a_p(i) \cdot e^{j \cdot \varphi_p(i)}$$

In the above relation $I_p(i)$, the sum of all the signals resulting from multiple reflections of the light inside and outside the camera body, is the perturbative component.

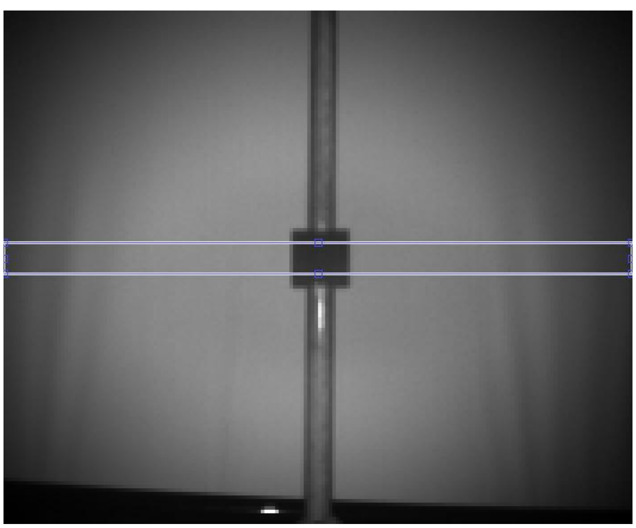

Figure 1: Experimental setup: a black square is placed at a constant distance from the camera. Behind it a white screen is moved at different distances.

2. Experimental setup

The theoretical point of view developed above has to be evidenced and refined experimentally, to evaluate the distance errors due to the reflections. We analyzed the effect of reflections inside the camera body using the following setup (see fig. 1): In the center of a scene a (80%) – black square filling approximately 5% in length (0.25% in area) of the image was put (a 6 by 6 cm at a distance of approx 1.3 m). Back to the black square a white screen was placed at various distances: 20, 40, 80, 150 and 250 cm. The two horizontal lines in fig. 1 which cross the central black square determine a band with many lines; in view of noise reduction we averaged all the lines of the band in just one single 1D line to get the signal profile (all these lines have to have the same signal profile in principle). We plotted the amplitude signal of this average line in fig. 2 and its distance signal in fig. 3.

Let us analyze the plots of fig. 2: it is clear that, shifting back the white screen, the amplitude of the reflected signal from the white pixels will be smaller (it decreases faster than by the square of the distance). But, as one can obviously remark, this shift also influences the amplitude of the signal of the black pixels of the central square: in fact, in our relative units, the amplitude value drops from about 6000 to 2000. Nevertheless this effect will disturb nobody unless the (not completely -) black square becomes whiter than the white wall (which reflects a very low signal because at the end it is far back). The situation is completely different in the case of distance errors.

Indeed, let us analyze the plots of fig. 3. When the white screen is moved from the initial position (20 cm behind the black square) to 150 cm behind the black square, the distance of the black square increases steadily from 1.3 m to 1.8 m (in spite of the fact that this black square is kept in a fixe position relative to the ToF camera) seemingly following the shift of the white screen. Of course, this behavior (and the big values of the errors) leads to difficult problems for the development of the “action recognition” software. Also from fig. 3 one can see that this effect is not a monotonic one: further increasing the distance between the black square and the white screen from 150 cm to 250 cm – that is where the amplitude signal for the white screen becomes smaller than that from the black square – the measured distance to the black square decreases again.

It is clear that the errors in distance measurements are very important (0.5 m!) and they must be corrected or reduced. On the other hand it is obvious from our experiment that they are produced by (multiple) reflected light. To avoid reflections some simple measurements could be prescribed:

- The room in which the images are taken must be with dark walls for the 850 nm infrared light
- All unimportant objects or persons must also reflects as small as possible light

- All important objects or persons must wear white clothes

Apart of these desirable measures it is important to correct the distance errors.

3. The correction of the distance measurements errors.

In what follows an algorithm for partial correction of these errors is presented. We shall use the under index m for the measured quantities: so $a_m(i)$ is the amplitude and $d_m(i)$ the distance of the pixel i and the phase $\varphi_m(i)$ is proportional $d_m(i)$ and the complex signal

$$I_m(i) = a_m(i) \cdot e^{j \cdot \varphi_m(i)} = I_d(i) + I_p(i) \qquad (7)$$

where $I_p(i)$ is the perturbation which depends of the objects in the scene and when they move, $I_p(i)$ will vary. A way of eliminating $I_p(i)$ is to get (or to fabricate) a second relation in which $I_p(i)$ apeears:

$$I'_m(i) = I_d'(i) + I_p(i) \qquad (8)$$

There are various ways of obtaining such a relation. One which is simple / at hand is to chose a neighbor pixel, close to i, for which $I'_m(i) \neq I_m(i)$ but for which very likely $I_p(i') = I_p(i)$. This is easily obtaind for an object having a texture with contrasts and the neighboring pixels at the same distance. In this case we shall have (see also [art2])

$$I_m(i) - I'_m(i) = a"(i) \cdot e^{j \cdot \varphi"(i)} \qquad (9)$$

and the corrected distance is obtained from the same proportionality:

$$d(i) = k \cdot \varphi"(i)$$

Because $\varphi"$ is the correct phase of I_d.

Another way to obtain the correction is to use a structured light. If we take s second picture of the same scene for which $I'_d(i) \neq I_d(i)$ but $I'_p(i) = I_p(i)$ we can use the above trick. To obtain these conditions it is enough that the lighting of the pixel i is different in the second picture. This situation can be easily obtained using a structured light [poza].

4 Testing the corrections.

The method described above for the distance corrections was tested with the same experimental setup with the addition of o little white square nearby the black square (both at 1 m from the ToF camera).

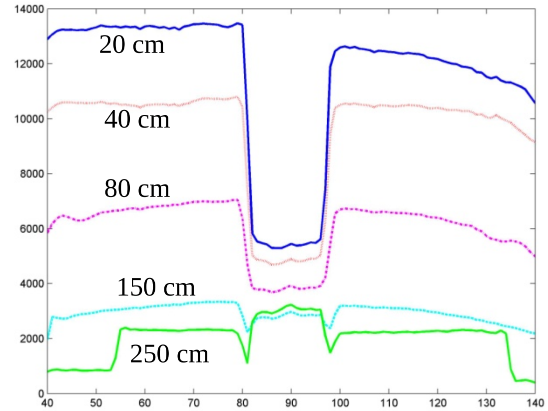

Figure 2: The detected light amplitude by the pixels in the marked rectangle in fig. 1. The distance between the black rectangle and the white screen is marked for each curve in the figure.

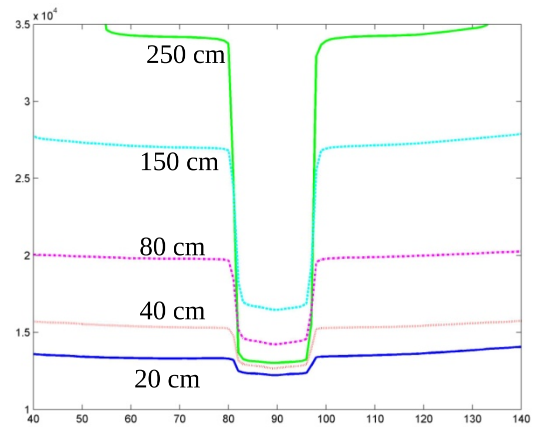

Figure 3: The measured distance to the objects included in the white rectangle presented in fig.1**.** For each curves the white screen is placed behind the black square at the distance marked in figure.

The black square was placed at 100 cm in front of the camera. We moved the white screen from 7 cm to 160 cm behind the black square. For each pixel on the horizontal axis (abscissa) we selected two closed pixels one in the region of the black square and the other in the region of the white one. Using the amplitude and distance data for these pixels we computed the corrected distance with relation (9). In fig. 4 the corrected distance is plotted with the same colors but with a continuous line. For example the measured distance to the black square when the white screen is placed at 42 cm behind it is plotted with cyan dash line and the corrected distance to the black square is plotted with continue cyan line.

The plots of the corrected distances to the black square are all grouped and the differences between them are only a few millimeters.

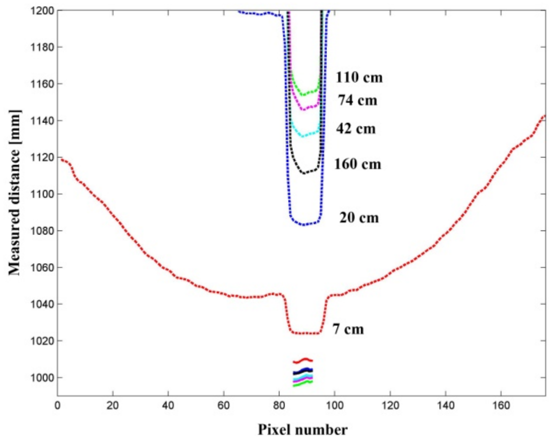

Figure 4: The measured distances in the selected region is plotted with dash lines and the corrected distances to the black square with continuous line.

3 CONCLUSIONS

We have set up a precise method to correct the distance errors produced by multiple reflections of the light in the ToF cameras. The algorithm is very simple and decreases the measurement errors with a factor of about 50.

In the future design of ToF cameras a hardware implementation of this algorithm will be benefic. A structured light is also useful in 3D stereo cameras. In the case of industrial applications the use of a structured light could be the practical solution.

Our algorithm can’t be applied in the case when the texture contrast of the objects in the scene is very low. In these cases a tag or a label must be attached to the objects. We remark that this is not a drawback of the ToF camera: it is also the case of the stereo 3D cameras. With these cameras we can’t measure the distance to uniform surfaces (without any detail).

The measurement errors caused by multiple reflections inside the camera body can be corrected by applying anti reflex coating to the chip window lenses, by painting the box with a black paint, etc. All these will be benefic but multiple reflections produced outside the camera body can’t be corrected in the same fashion and our method for the moment remains the single solution.

4 ACKNOWLEDGMENT

The ARTTS project is funded by the European Commission (contract no. IST-34107) within the Information Society Technologies (IST) priority of the 6th Framework Programme.
This publication reflects the views only of the authors, and the Commission cannot be held responsible for any use which may be made of the information contained therein.

References

[1] D. Falie, V. Buzuloiu. Noise characteristics of 3D time-of-flight cameras, ISSCS, 2007, Iasi.

[2] S. Oprisescu, D. Falie, Mihai Ciuc, Vasile Buzuloiu, Measurements with ToF Cameras and their necessary corrections,ISSCS, 2007, Iasi.