Acurate distance measurements with the Time of Flight (ToF) Cameras.

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I. Extended abstract

One of the most important distance measurement errors with ToF cameras are produced by indirect light reflections and these errors can't be avoided. The measured distance to an object in the scene changes if surrounding objects are moved. The distance error can be greater than 50% and camera calibration is useless.

The calibration method we propose can be performed in any conditions not only in the laboratory. The distance errors for all objects in the scene can be corrected if white or black tags/labels are attached on the objects.

The ToF cameras can be improved using an active illumination with structured light. The improvement will eliminate the distance errors produced by light reflections.

II. Introduction

The TOF cameras are a new type of 3D camera [1]. These cameras have their own illumination source, an array of infrared LEDs; so that they 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 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 [1].

$$d = \frac{\varphi}{4\cdot\pi}\cdot\frac{c}{f} \tag{1}$$

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

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

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 [2], [3].

These quantities $a(i)$ and $\varphi(i)$ are only affected by the amplitude modulated light emitted by the camera source. The light reflected by an object in the scene and detected by pixel i is composed by the direct reflected (camera modulated) light, the indirect light and the background light. The indirect light is the camera emitted light reflected by other objects in the scene which illuminate also the object.

We shall split the detected light signal $I_m(i)$ by the pixel i in a few 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:

$$I_m(i) = I_d(i) + I_{r1}(i) + I_{r2}(i) = I_d(i) + I_p(i) \tag{3}$$

$$I_{r1}(i) = a_{r1}(i)\cdot e^{j\cdot\varphi_{r1}(i)}, \tag{4}$$

$$I_{r2}(i) = a_{r2}(i)\cdot e^{j\cdot\varphi_{r2}(i)} \tag{5}$$

$$I_d(i) = a_d(i)\cdot e^{j\cdot\varphi_d(i)}, \tag{6}$$

$$I_p(i) = a_p(i)\cdot e^{j\cdot\varphi_p(i)} \tag{7}$$

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

III. 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 using the following setup: in the center of a scene a (80%) black square was put 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. We analyze and plot the amplitude and distance along a horizontal line which cross the central black square. Shifting back the white screen, the amplitude of the reflected signal from the white pixels will be smaller (it decreases by the square of the distance). This shift also influences the amplitude of the signal from the black pixels of the central square but for the distance measurement it is unimportant.

When the white screen is moved from the initial position to 150 cm behind the black square, the measured 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). This behavior leads to difficult problems for the development of the “action recognition” software.

IV. THE CORRECTION OF THE DISTANCE MEASUREMENTS ERRORS.

A way of eliminating perturbation component $I_p(i)$ is to get a second relation for a neighbor white pixel i' for which we have $I_m(i') \neq I_m(i)$ and $I_p(i') = I_p(i)$:

$$I_m(i') = I_d(i') + I_p(i) \quad (8)$$

In this case we shall have:

$$I_m(i') - I_m(i) = (a(i') - a(i)) \cdot e^{j\cdot\varphi(i)} \quad (9)$$

and the corrected distance is obtained from the same proportionality $d(i) = k \cdot \varphi(i)$ because φ is the correct phase of I_d.

Another way to obtain the correction is to use a structured light [4]. If we take a 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.

IV. 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).

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. 1 the measured and the corrected distance are plotted. The corrected distances to the black square are all grouped and the differences between them are only a few millimeters (due mainly to the thermal drift).

V. 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. In the case of industrial applications the use of a structured light could be the practical solution.

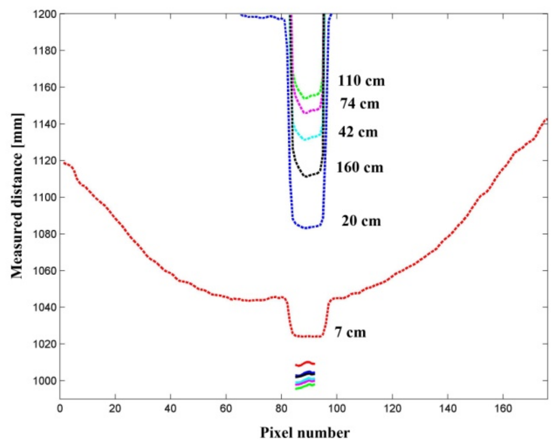

Figure 1. The measured distances are plotted with dash lines and the corrected distances to the black square with continuous lines.

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