Wide Range Time of Flight Camera for outdoor surveillance.

D. Falie #1, V. Buzuloiu #2

#1,2 The Image Processing and Analysis Laboratory, University Polytechnica of Bucharest, Romania

dfalie@alpha.imag.pub.ro
buzuloiu@alpha.imag.pub.ro

Abstract— This paper presents the application of the Time of Flight (ToF) cameras to outdoor surveillance. The applications of ToF camera were limited to its non ambiguity distance range, less than 10 meters. We present the problems and the solution for extending the distance use of ToF cameras beyond the non ambiguity range. The distance ambiguity can be solved by measuring the distance with two different frequencies. The needed contrast range of the amplitude image increases with the square of the distance. The efficient use of ToF cameras for outdoor surveillances imposes not only the increase of the illuminating power but also to increase the accuracy of the distance and amplitude images. The ambiguity of the measured distance can be effectively solved if the multiple reflections inside the camera body are reduced.

I. INTRODUCTION

TOF (Time of Flight) camera is a relatively new type of 3D cameras which deliver concurrently two images of the same scene: - a usual amplitude image and a second one - the distance image which, for each pixel gives the distance to the camera of the corresponding point in the scene. The camera has its own illumination source (the active light): an infrared amplitude modulated light. The distance \( d \) is measured by \( \Phi \), the phase shift of the envelope of the received light with regard to the envelope of the emitted light [1]:

\[
d = \frac{\Phi \cdot c}{4\pi f}
\]

In (1) is the speed of light and \( f \) is the modulation frequency.

The amplitude image is only produced by the reflected active light (the background light is rejected by the in phase detection). So, the amplitude image values depend not only on object points reflectivity but on the distance too (the light intensity decreases with the square of the distance to the object); if e.g. the distance ranges between .7m to 7 m. The amplitude image of an object will vary (decrease) 100 times.

This feature has to be corrected and can be corrected pixelwise just by using distance image [2]. Such a correction does not exist in the SwissRanger3000, [3] which has been the camera we have worked so far, but will exist in the future models.

The next problem with these TOF camera was that the errors on distance measurements (i.e. on phase shift) could be much higher than expected, due to multiple reflections outside and inside the camera and for their estimation as well as correction we developed a very efficient model ([4], [5]) which has proved able to reduce the (huge) errors of say 0.5m to a few mm.

Finally we address here another problem of these TOF camera: the fact that their distance range is quite limited...
because the phase shift measured by a phase detector will only give us a value between 0 and $2\pi$ i.e. the true value of the phase shift modulo $2\pi$. Thus, the non-ambiguity distance for the situation at hand, with 20 MHz for the envelope of modulated infrared, is about 7.5m. The closer objects in the distance image are grey; with the distance increase, they become whiter; as soon as the distance is slightly greater than 7.5m, the objects in distance image become black (and so the “measured distance” is zero). Increasing the distance, we can observe this periodic alternance from black to white and again sudden drop to black and so on.

We have such an image in Fig. 1. Fig. 2 shows the same scene but using the logarithm of the amplitude image (some details are lost). The distance image in Fig. 1 was obtained as a superposition of the many (1000) images taken during the night and it is remarkably well pointed out the phenomenon of mod $2\pi$ distance image. More surprisingly on both images, one can see buildings at higher distance.

II. OUTDOOR SCENE

In the images above the objects are placed between 2.5m and 50m while the non-ambiguity distance range for the (amplitude) modulated light with 20 MHz is 7.5m. The amplitude image decreases 1000 times from 2.5 to 50m.

We put in Fig. 3 the amplitude image of the same scene after histogram segmentation. It is clear that for the true correction of the distance one has to resolve the ambiguity as soon as we are out of the first interval of non-ambiguity.

![Fig. 3 The amplitude image of the scene obtained by histogram segmentation.](image)

III. RESOLVING THE MEASURED DISTANCE AMBIGUITY

The distance ambiguity can be resolved by measuring the distance with two different modulation frequencies: in one frame with $f_1$ and in a second frame with $f_2$. In the non-ambiguity range the measured distances are equal; outside this region they are different. Namely we have the relations:

$$d_1 = d_{m1} + n_1 \frac{c}{f_1} = d_{m1} + n_1 \lambda_1$$ (2)

$$d_2 = d_{m2} + n_2 \frac{c}{f_2} = d_{m2} + n_2 \lambda_2$$ (3)

where obviously $d_1 = d_2$ (the true distance to the object) $d_{m1}$ and $d_{m2}$ are the “measured” values (in the interval $(0, \lambda_1)$ respectively $(0, \lambda_2)$) and $\lambda_1$, $\lambda_2$ and $f_1$, $f_2$ are the corresponding wave lengths and frequencies and $c$ is the speed of light; $n_1$ and $n_2$ are integers and namely small integers.

From the above one gets

$$d_{m1} - d_{m2} = n_2 \lambda_2 - n_1 \lambda_1$$ (4)

which is a quasi-diophantic equation with an infinity of solutions – pairs of $(n_1, n_2)$ – from which, imposing limitations on $n_1$, $n_2$, one can get the true unique solution of our problem.

Nevertheless there are points/distances for which the ambiguity cannot be resolved.

In Fig. 4 we plotted the measured distances with two frequencies in an ideal case pointing out the points of ambiguity.

![Fig. 4 The points where the ambiguity can’t be solved are marked with circles. On the abscline axis is represented the distance and on the ordinate the measured distances.](image)

The real lines of true measurements obviously don’t have the perfect sawtooth shape but one can see in Fig. 5 that, at the border between the non-ambiguous zone and the first ambiguous one there are points for which the ambiguity wasn’t solved.

To solve the distance measurement ambiguity we have selected the frequencies $f_1 = 19$ MHz and $f_2 = 21$ MHz and record two consecutive images one taken with $f_1 = 19$ MHz and the next with $f_2 = 21$ MHz. The ambiguity is resolved
only in the first interval when \( n_1 = n_2 = 1 \) further we shall 
explain why in the next intervals the ambiguity wasn’t solved.

We observe in Fig. 5 that at the border between the non 
ambiguous and the first ambiguous zones remain points where 
the ambiguity wasn’t solved. These points correspond to thous 
marked on Fig. 4 and these points remain “ambiguous” because the signal of the real ToF camera is 
different of the signal generated by an mathematical 
(analytical) expression.

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![](image1.png)

**Fig. 5** The distance image where the measured distance is corrected in the 
first ambiguous zone.

Fig. 6 are plotted the measured distances with the 
frequency of 19 MHz with continues blue line and the 
corresponding measured distance when the frequency of 21 
MHz was used , with red dashed line.

The selected vertical line is represented in Fig. 1. In bottom 
region of the distance image, i.e. when the measured distance 
is less than 10m the ToF camera performs like the theory. The 
plot of the measured distance with and \( f_1 = 21 \) MHz made the 
first transition to the ambiguity zone, the transition is a perfect 
vertical line, the second transition of the measured plot for the 
frequency \( f_1 = 19 \) MHz it is a little bit smoother. The 
transition value L1 is very close to the value of \( \lambda_1 = 7.89 \) 
but is lower; this is the first symptom of a nonlinear phase 
detector. When the signal decreases the maximum and 
minimum values of the phase detector decreases and the 
output i.e. the measured distance also decreases. The value of 
transition to the next ambiguity zone (nr. 2) is less than 5 m

![Image](image2.png)

**Fig. 6** The measured distance along a vertical line of the distance image (Fig. 
1) for the two modulation frequencies used.

The measured distance errors to dark object have been 
noticed for a long time [3], [7] and but now is clear that when 
the incoming signal to the phase detector decreases the output 
signal decreases. One phenomenon is the decrease of the 
phase range; normally output of the phase detector is from 0 
to \( 2\pi \). When the input signal decreases the phase detector 
can’t reach neither of these limits (0 and \( 2\pi \)). We observed 
that in many cases a black object seems to be further than a 
white one, but in other cases the measured distance to a black 
object is shorter. If we look to the Fig. 6 we see that both 
cases can be explained. The second transition to the ambiguity 
zone nr.2 is centered to the 3.5 m distance. In this case of low 
input signal the lower part of the plot does not reach the zero 
phase (0 m), it is not enough signal to drive the phase detector 
to zero phase. If we look to the right end of the plot we 
observe that the measured distance varies around the 3.5m 
value. With zero input signals the output signal of the phase 
detector is pi or 3.5 m. In the case of o black object if this is 
paced at a distance lower than 3.5m for example at 2m and if 
the light reflected by this object decreases than the measured 
distance to this object increase toward 3.5 m. The error is 
greater if the object is closer to the camera. The situation is 
reversed for an object situated at a distance greater than 3.5m.

Grace to this new application of the ToF camera to outdoor 
surveillance we succeeded to explain many problems.
The output value of the phase detector without any input signal (the value of the input signal is zero) is which correspond to a distance equals half of the non ambiguity range, in the case when the modulation frequency is 20 MHz this value is 3.75 m.

The distance jump at the border to the first ambiguous region was only 7.23 m in the case when \( f_1 = 19 \text{ MHz} \) and 6.48 in the case \( f_2 = 21 \text{ MHz} \), these values are with 8.4\% and 9.3\% less than the correct values. The amplitude of the input signal in these cases, i.e. the picture brightens, is about 400 units from 65 000 which represent the maximum value. This means that when the amplitude image value is about 400 units we expect to have systematic distance errors.

Increasing the illuminating power impose also the redesign of the system. In Fig. 8 we observe white zones at the border of the image, this means that light enter somehow in the CCD chip compartment.

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