Measurements with ToF Cameras and Their Necessary Corrections

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Abstract— **The most important characteristic of time-of-flight (ToF) cameras is the ability to measure the distance to each image pixel. Thus, for each pixel, information on both its amplitude and distance to the camera are available. However, technological problems inherent to the acquisition principle lead to inaccuracies in estimating both characteristics: on one hand, there are errors in estimating the distance, especially for far-distance pixels. On the other hand, the detected amplitude decreases with the distance. Part of these inaccuracies are corrected with special camera-calibration software. In this paper, we propose two methods that attempt to further correct each information based on the other one. First, the amplitude image is enhanced by using distance information: a pixel-wise, distance-based correction of the amplitude brings to light details otherwise unnoticeable. Secondly, an amplitude-based distance modification corrects some of the distance estimation errors for far-distance pixels.**

I. INTRODUCTION

The 3D Time-Of-Flight (ToF) camera [1], [2], [3] is a new type of imaging device that simultaneously delivers gray-level images and 3D information of the scene. The camera uses its own illumination source in form a matrix of LEDs that emit modulated infrared light. Based on the detection of the reflected waves, two images are formed: the distance image $D(i,j)$ is computed based on the phase shift between the emitted and reflected signals, whereas the amplitude image $A(i,j)$ is estimated based on the amplitude of the reflected signal at every pixel location.

The interest for ToF cameras is evident. Use of depth information in addition to amplitude may be a key factor for finding workable solutions to a number of applications of interest, e.g., face detection, video surveillance etc. However, given its special acquisition principle, both distance and amplitude images delivered by a ToF camera have a number of systematic defects that must be compensated.

The main amplitude-related problem comes from the fact that the power of a wave decreases with the square of the distance it covers [4]. Owing to this, the light reflected by imaged objects rapidly decreases with the distance between object and camera. In other words, objects with the same reflectance located at different distances from the camera will appear with different amplitudes in image A. In this paper, we develop a correction of the amplitude image, in order to compensate this effect. For this purpose we will use the distance information at each pixel (i,j). The fact that the distance image provided by the ToF camera has an appreciable level of noise (especially in the case of far objects, where the amplitude image correction is needed most) is taken into account by applying a spatial filtering to the distance image prior to using it for amplitude correction.

On the other hand, the distance information provided by a ToF camera is not always very accurate. The greatest errors in computing the distance occur for far-distance objects with a poor reflectivity. However, thorough testing on various setups showed that these errors appear to be systematic. Thus, they can be compensated for by using prior information on the ToF camera. In this paper, we present a method to correct distance information for far-distance dark objects.

The remainder of this paper is organized as follows: in Section II, the correction of the amplitude image based on distance information is presented. Section III deals with correcting the distance image based on amplitude information. Finally, in Section IV, conclusions and perspectives are presented.

II. DISTANCE-BASED AMPLITUDE IMAGE CORRECTION

As previously mentioned, the amplitude image given by a ToF camera has the drawback that objects located at far distance appear darker than those located near the camera. Figure 1 presents a typical amplitude image provided by a ToF camera, whereas Figure 2 presents the gray-level image of about the same scene (with a slight modification of the viewing angle) acquired with a common webcam. One can notice that the intensities of the two boxes and of the wall behind them (located approximately in the middle of the image), even though of similar reflectance (as shown in Figure 2), appear with decreasing values in the ToF amplitude image.

As stated before, the decrease of the intensity of an imaged object is proportional to the square of the distance to that object. But the distance information is available too in the ToF camera! Therefore, we could implement the perfect correction to the brightness picture by increasing the brightness of each pixel in the reverse way to the decreasing of the lighting, i.e., by multiplying the amplitude with the square of the distance:

$$A'(i,j) = A(i,j)D^2(i,j), \tag{1}$$

where A' represents the corrected amplitude value of a pixel. However, correction (1) cannot be applied as is, owing to the fact that the distance image is affected by noise, especially for

Figure 1. A typical amplitude image delivered by a ToF camera.

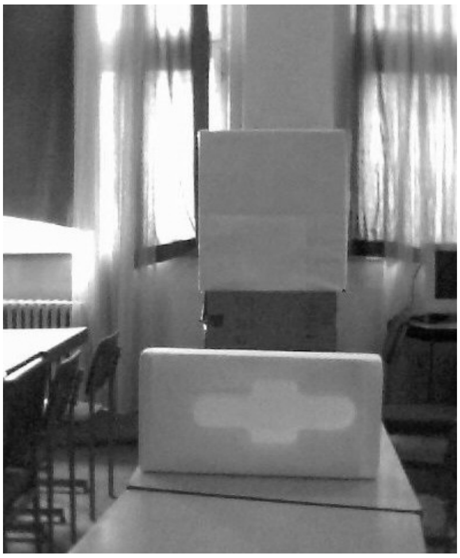

Figure 2. Approximately the same scene as in Figure 1 viewed with a common webcam.

objects located at far distance. Moreover, by taking the square value, the noise is amplified, the final result being a noisy corrected amplitude image. Figure 3 presents the amplitude image after correction given by Equation (1).

Thus, additional processing must be done in order to obtain a reliable correction of amplitude images. The most straightforward processing is to remove the noise present in the distance image through a spatial filtering operation. Among the plethora of existing non-linear filters, we chose to use the adaptive-neighborhood filters (ANF) [5], [6] for this task. The basic principle of ANF is to derive, for each image pixel, a variable-sized, variable-shaped neighborhood that, ideally, contains only pixels belonging to the same statistical population as the central pixel (called “seed” when being processed). The neighborhood determination is performed in two steps. The first step is a classical region growing algorithm [7] with threshold equal to the noise standard deviation (prior information about noise statistics must be known). The second step involves reinspecting all of the non-aggregated pixels that were inspected in step one. The pixels whose values lie closer to the seed value than twice the noise standard deviation are also aggregated. Finally, the filtered value for the seed pixel is computed by averaging the values of pixels aggregated in the seed’s adaptive neighborhood. As shown in [5], [6] adaptive-neighborhood filters generally outperform classical filters in terms of both noise power reduction and detail preservation.

Figure 3. Image in Figure 1 after distance-based correction without prior filtering.

Given the specificity of the distance image, we performed some (slight) modifications to the classical ANF by changing the preprocessing step (we used a modified median filter to compute a more reliable initial value for the seed pixel). Also, estimation of noise standard deviation (which is central to the success of ANF) has been carried out on numerous distance images.

In Figure 4 we show the distance image corresponding to the scene in Figure 1 before and after filtering with ANF. We can observe that the background noise is almost completely eliminated, while edges are very well preserved.

Finally, the proposed final amplitude correction can be expressed as:

$$A'(i,j) = A(i,j)D^2_{\mathrm{ANF}}(i,j), \tag{2}$$

where D_{ANF} is the distance image filtered by the ANF. The result in shown in Figure 5. One can notice that the noise induced by the distance information (visible in Figure 3) has been reduced. At the same time, reflectivity of objects has been restored by removing the dependance on the distance, e.g., the central boxes and the wall behind them have similar

Figure 4. Distance image before (top) and after (down) adaptive-neighborhood filtering.

reflectivity after correction (which is normal, as pictured in Figure 2).

III. AMPLITUDE-BASED DISTANCE IMAGE CORRECTION

The distance image delivered by a ToF camera is not very accurate, in that there are sometimes significant differences between true and measured distances. Intensive testing showed that the errors in distance measuring increase with the distance, but this effect is more pronounced for dark objects, whereas for highly reflective objects, distance estimation errors are practically negligible. However, the errors seem to be deterministic: objects with similar intensity, located at the same distance will produce the same error in the distance image. Therefore, errors can be compensated for based on a pre-analysis of the data delivered by the camera. Figure 6 shows a plot of the observed distance estimation error as a function of distance for a dark object (all measurements have been made using an integration time of 40ms). As we can notice, the magnitude of the error can be as high as 20 cm, and is most important for distances between 3 and 6 meters.

Figure 5. Amplitude image after correction based on distance image filtered with ANF.

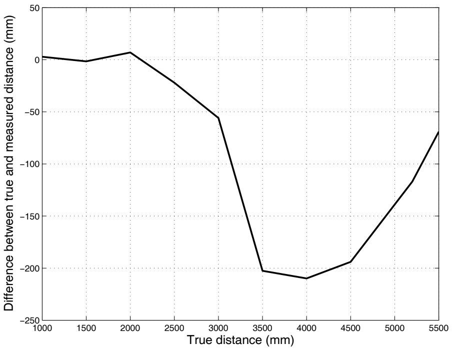

Figure 6. Plot of the distance estimating error versus true distance for dark pixels.

Distance correction based on the curve in Figure 6 must first identify dark pixels. This procedure must be carried out in the amplitude image. However, as discussed in Section II, amplitude itself is distance dependent. Therefore, thresholds used to segment dark pixels in the amplitude image must be computed with respect to distances. The curve in Figure 7 presents the experimentally determined thresholding function that will be used to determine which pixels in amplitude image are dark based on the distance those pixels are located at.

Based on the aforementioned observations, the distance correction procedure we developed consists of the following steps:

1) Detect all pixels located between 3 and 6 meters (this operation involves a mere thresholding of the distance

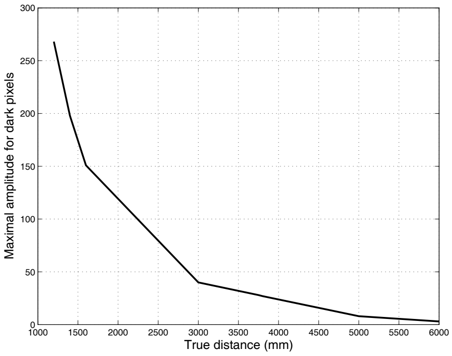

Figure 7. Plot of the thresholds used for selecting dark pixels in the amplitude image.

image $D(i,j))$.

2) From all pixels determined in step 1, retain only those that are dark, namely, provided that $A(i,j) \leq f(D(i,j))$, with function $f(\cdot)$ being pictured in Figure 7.
3) For each pixel retained after step 2, apply distance correction: $D'(i,j) = D(i,j) + E(D(i,j))$ with $E(\cdot)$ being the error function presented in Figure 6.

Results obtained by the proposed correction technique are shown below. Figure 8 presents the amplitude image of the test scene. One can notice in the image center a sheet of paper half-white/half-black, located at 3.8 meters from the camera.

Figure 8. Amplitude image of the test scene.

In Figure 9 we present a mesh of the distance image on the area of the half-white/half-black sheet of paper before and after correction. Even though distance correction is not perfect (the distances of the two halves of the sheet are not level even after correction) one may notice that the proposed technique significantly improved the distance information on the dark half of the paper.

IV. CONCLUSION

In this paper we have presented two correction techniques of the data (amplitude and distance) provided by a Time-of-Flight camera. The amplitude correction involves multiplication with the square of the distance, after spatially filtering the latter with an adaptive-neighborhood filter in order to remove noise. The proposed distance correction involves detecting dark pixels in the amplitude images and then adjusting their distance value based on pre-determined error values. Both proposed techniques act towards improving the reliability of the data delivered by the ToF camera.

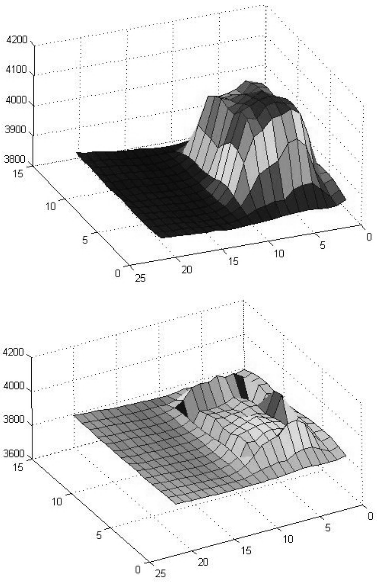

Figure 9. Mesh of the distance information for the half-white/half-black sheet of paper before (top) and after correction.

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REFERENCES

[1] T. Oggier, M. Lehmann, R. Kaufmann, M. Schweizer, M. Richter, P. Metzler, G. Lang, F. Lustenberger, and N. Blanc, "An all–solid–state optical range camera for 3d real-time imaging with subcentimeter depth resolution (swissranger)," in *Optical Design and Engineering*, ser. Proc. SPIE, L. Mazuray, P. J. Rogers, and R. Wartmann, Eds. SPIE, February 2004, vol. 5249, pp. 534–545.

[2] R. Kaufmann, M. Lehmann, M. Schweizer, M. Richter, P. Metzler, G. Lang, T. Oggier, N. Blanc, P. Seitz, G. Gruener, and U. Zbinden, "A time–of–flight line sensor: development and application," in *Optical Sensing*, ser. Proc. SPIE, B. Culshaw, A. Mignani, and R. Riesenberg, Eds. SPIE, September 2004, vol. 5459, pp. 192–199.

[3] R. Lange, "3D time–of–flight distance measurement with custom solid–state image sensor in cmos/ccd technology," Ph.D. dissertation, University of Siegen, 2000.

[4] R. P. Feynman, R. B. Leighton, and M. Sands, *The Feynman Lectures on Physics*, 2nd ed. Addison–Wesley, 2005.

[5] R. M. Rangayyan, M. Ciuc, and F. Faghih, "Adaptive–neighborhood filtering of images corrupted by signal–dependent noise," *Applied Optics*, vol. 37, no. 20, pp. 4477–4487, July 1998.

[6] M. Ciuc, P. Bolon, E. Trouvé, V. Buzuloiu, and J. P. Rudant, "Adaptive–neighborhood speckle removal in multitemporal synthetic aperture radar images," *Applied Optics*, vol. 40, no. 32, pp. 5954–5966, November 2001.

[7] F. M. Wahl, *Digital Image Signal Processing*. Boston: Artech House, 1987.