# Environmental Effects on Measurement Uncertainties of Time-of-Flight Cameras

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***Abstract*— In this paper the effect the environment has on the SwissRanger SR3000 Time-Of-Flight camera is investigated. The accuracy of this camera is highly affected by the scene it is pointed at: Such as the reflective properties, color and gloss. Also the complexity of the scene has considerable effects on the accuracy. To mention a few: The angle of the objects to the emitted light and the scattering effects of near objects. In this paper a general overview of known such inaccuracy factors are described, followed by experiments illustrating the additional uncertainty factors. Specifically we give a better description of how a surface color intensity influences the depth measurement, *and* illustrate how multiple reflections influence the resulting depth measurement.**

## I. Introduction

The SwissRanger [1] camera is designed to be a cost-efficient and eye-safe range finder solution.

Fig. 1. The SwissRanger SR3000 Camera

Basically it has an amplitude modulated light source and a two dimensional sensor built in a miniaturized package (see Fig. 1). The light source is an array of 55 near-infrared diodes (wavelength $850\text{nm}$) that are modulated by a sinusoidal at $f_{\text{mod}} = 20\text{MHz}$. This light is invisible to the naked eye.

The sensor is a $176 \times 144$ pixel custom designed $0.6\mu\text{m}$ CMOS/CCD chip where each pixel in the sensor demodulates the reflected light by a lock-in pixel method, taking four measurement samples $90°$ apart for every period [2]. From these samples the returning signal is reconstructed and two images are generated: An intensity (gray scale) image derived from the amplitude of the signal and a range image (depth measurement per pixel) derived from the phase offset of the signal.

The accuracy of the depth measurements is subject to error due to many factors. On one hand internal effects such as noise of the sensor, diodes as well as the camera calibration. On the other hand the scene at which the camera is pointed has substantial effects as well, e.g. its complexity – causing multiple reflections – and reflective properties, etc. In the first part of this paper an overview of related work in describing this uncertainty is presented. This is followed by experimental data illustrating the issue further, specifically with the SwissRanger SR3000.

## II. What Affects the Accuracy of the SR3000 Depth Measurement?

Here uncertainty effects are categorized as either internal or environmental. This is depending on wether the can mainly be attributed to effects independent of the scene viewed or not. This simple taxonomy will be used to describe related work in the following.

### *A. "Internal" Effects*

Some errors originate from imperfections of the LED array – e.g. seen in Fig. 1 – where inhomogeneities in the emitted near-infrared field disturb the measurement accuracy. This error can be reduced by modelling it e.g. calibration, something which has been improved considerably in the SR3000 design over earlier camera models from the same manufacturer. Calibrating with respect to the spatial lens system and the depth measurement, also reduces errors effectively. Both of these issues have been issued thoroughly by Kahlman et al [8].

Typical sources of noise in solid state sensors are: Thermal, quantization noise, reset noise, electronic noise and photon shot noise. Most of these noise inputs can be greatly attenuated or eliminated. The largest remaining factors are in low light conditions electronic noise. In higher intensity acquisitions then the photon shot noise is the dominating noise factor. Photon shot noise is explained by quantum physical effects, when

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the number of photons hitting the sensor are small compared to natural fluctuations. This phenomen is theoretically Poisson distributed, with a standard deviation of, c.f. [2],

$$\sigma_R = \frac{R_{\max}}{\sqrt{8}} \frac{\sqrt{I}}{2A} \quad , \tag{1}$$

Here $R_{\max} = \frac{c}{2 f_{\text{mod}}}$ is $7.5\text{m}$, the maximum distance derived from the $c$, the speed of light and $f_{\text{mod}}$ the modulation frequency of the emitted light. $I$ is explained mainly by two factors; the intensity offset due to background light and the active RF-modulated illumination. $A$ is the amplitude of the reflected signal. This means that the physical dictated lower accuracy bound is strongly affected by the properties of the scene. To mention a few: the background light, which is suppressed by an optical filter as well as on-chip filtering, and the amplitude, $A$, which is affected by the distance to the object and its reflective properties. This lower accuracy bound of the sensor has been investigated and well documented by CSEM in [2], [9], [10]. Here it is shown that the measured values from the camera are close to this physical limitation in certain given scenarios. In conclusion: for maximum range accuracy the offset must be minimal and the amplitude as high as possible.

### B. *Environmental Effects*

The environmental measurement uncertainties are more difficult to categorize than the internal effects, due to the great variability of possible scenes. This is likely a reason for these effects not having been described in the same quantifying manner.

Some of these effects are explained, in part, by Equation (1), i.e. how the reflectance properties have direct influence on $A$. Other environmental errors are caused by false measurements due to scattering and multiple reflection, which are even harder to model well statistically. Some of these problems have been described in the literature by Gut and May et al [5], [7]. The scattering effect due to objects near to the camera is especially well documented here. May et al propose a method to limit this effect, by a procedure of selecting the integration time optimally and minimizing saturation problems. More work is, however, needed to satisfactorily understand and deal with these effects.

The multiple reflection problem has, to the best of our knowledge, only been dealt with very superficially. Thus this will be an issue of the next section.

As mentioned the objects' reflection properties have an impact on the measurement results. Highly glossy objects such as glasses can cause saturation and color differences can result in different depth estimates. Guðmundsson [4] showed the effect of how black regions in a white plane were measured as holes in the plane. This problem will also be further investigated in the following section.

## III. Experiments

In this section two experiment are reported, both illustrating 'new'[1] environmental effects on the accuracy. The experiments are performed by using the optimal camera integration time procedure described in [2], [7], to minimize saturation effects and achieve the highest accuracy. Averaging over multiple frames was also done to obtain higher accuracy.

### A. *Multiple Reflection Experiment*

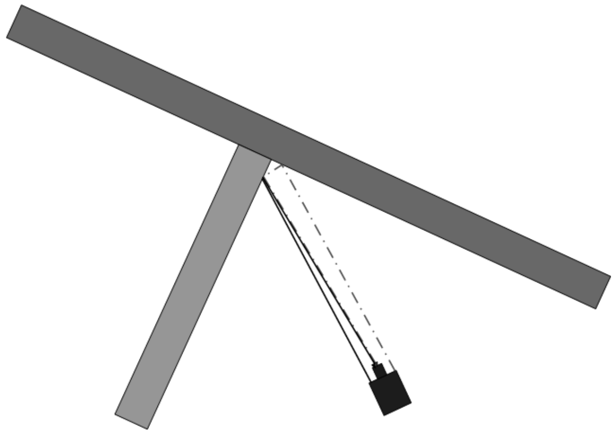

Fig. 2. The multiple reflection experiment setup. One image is taken with the lighter gray wall present and one without. The multiple reflection problem is also illustrated; the correct path is denoted by the black line, an erroneous double reflection by the dashed gray line. The results are illustrated in Fig. 3 and Fig. 4.

In the SR3000 manual [3] the multiple reflection or multi-path artifact is mentioned, but no attempt is made to quantify it. A simple experimental setup is illustrated in Fig. 2. Here two measurements are made from the same camera position: First of two walls forming a corner then removing one of the walls leaving a single long wall. The point-clouds of the two measurements are shown in Fig. 3. It is clear that the corner setup is very distorted, i.e. the wall that is measured in both conditions is shifted between the two measurements, the corner is very rounded and the angle between the walls is not $90°$.

Better visualization is made by fitting planes with RANSAC [6] to the points in Fig 4. The dihedral angle between the corner planes (light and medium gray) is hereby estimated as $122°$.

This effect has been explained by the sensor measuring multiple reflections i.e. the emitted light that has bounced off both walls before reaching the sensor. This is in turn unable to discriminate between photons reflected along a shorter path and the longer path. This problem is hard to quantify rigorously, again due to the great variability of possible scenes. Our experiment however gives an intuitive idea of the impact of this effect.

### B. *The Influence of Intensity on Depth*

Simply considering Equation (1) could lead one to think that the error accompanying varying intensity is random. This is

[1]To our knowledge, never reported before.

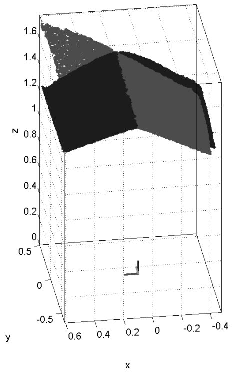


Fig. 3. Results of the multiple reflection experiment, c.f. Fig. 2, illustrating the estimated 3D positions. Dark points are the results of the experiment in the presence of the both walls, gray are the one wall measurements.

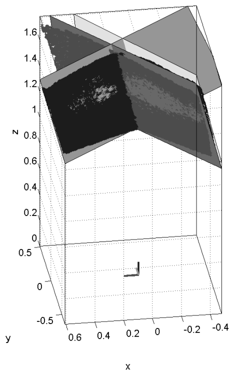


Fig. 4. The same data as in Fig. 3, but two planes fitted to the data via RANSAC. **Dark gray:** Plane fitted to the dark wall in Fig. 2 in solitude. **Light gray:** Plane fitted to the same wall, but in the presence of both walls. **Medium Gray:** Plane fitted to the lighter gray wall in Fig. 2.

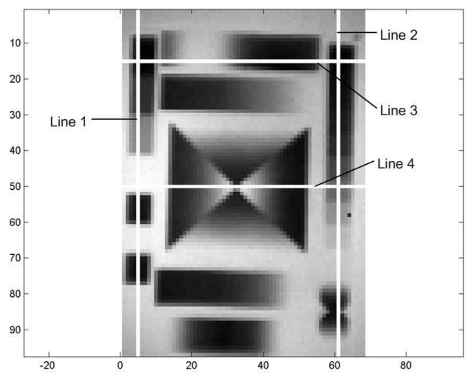


Fig. 5. The measurement pattern. The example lines from Fig. 6 are marked. This measurement target has different gray scale patterns; different levels of gray, linear and sinusoidal changes in levels of gray etc.

not the case, as this experiment demonstrates. The uncertainty in fact also has a bias factor that is also proportional to the inverse intensity amplitude. This systematic error in turn implies that depth measurements can be improved given the object's intensity. An intensity already supplied by the camera.

Here a planar target with and without the texture of Fig. 5 is taken, Fig. 8 shows these two measurements. In Fig. 6 four lines in the depth and inverse intensity, $1/A$ are compared. By standardizing the data, i.e. subtracting the mean and dividing by the standard deviation, it is seen that the graphs are highly correlated. Fig. 7 illustrates further how the two images are correlated.

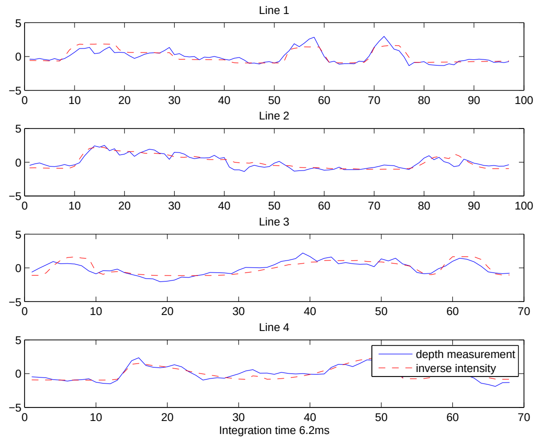


Fig. 6. Examples of how well the depth measurements and the inverse intensity correlate. Both have been standardized to compare the two on the same scale. The four lines refer to the marked lines in Fig. 5

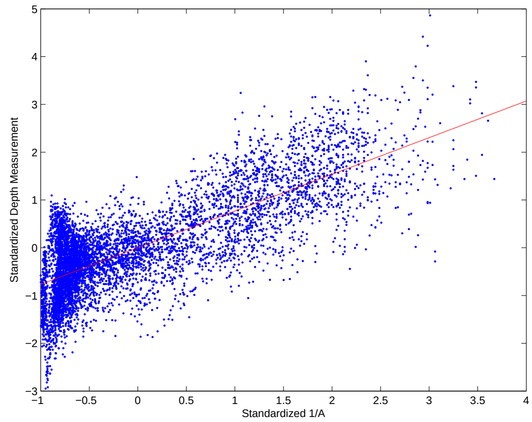


Fig. 7. Scatterplot of the standardized data of the inverse intensity image of Fig. 5 versus the depth measurements. A fitted regression-line shows how the the two images are highly correlated. Thus the measurement accuracy is biased and not purely random as could come to think by just considering Equation 1.

This high correlation can be used to correct or improve the depth measurement by removing the bias. This is illustrated in Fig. 9 where the standardized inverse intensity has simply been subtracted from the depth measurement which is afterwards shifted and scaled back to the nonstandardized state resulting in a much lower noise level. Comparing the minimum-maximum range divided by the mean distance gives the white plane's accuracy resolution of: $1.27\%$, the patterned plane: $3.16\%$ and the corrected plane: $1.36\%$. Using the mean of the white plane as a reference the RMS noise reduction is $57\%$.

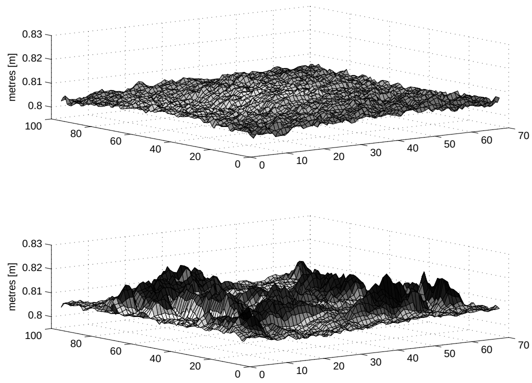


Fig. 8. Depth measurement of a white plane, without (above) and with (below) the target-pattern of Fig. 5 attached. The scale is in meters with the minimum-maximum range of $0.0107\mathrm{m}$ in the white image and $0.0255\mathrm{m}$ in the patterned image. Here it is clearly seen that the intensity influences the depth estimate, and that this estimate is biased by the intensity.

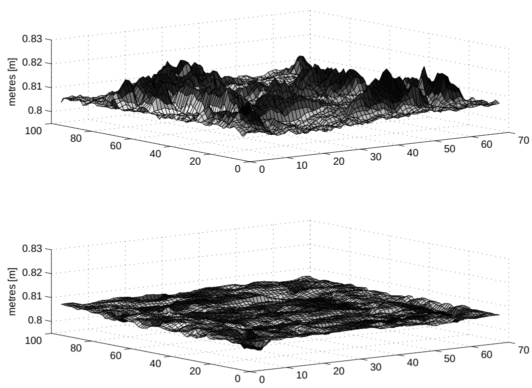


Fig. 9. **Above:** Same as below of Fig. 8. **Below:** Same data, but corrected by removing the bias explained by the intensity.This gives the min-max range of $0.0109\mathrm{m}$ The RMS noise reduction is $57\%$.

## IV. Results and Summary

Here a survey regarding the uncertainty of the SwissRanger SR3000 has been presented. In addition two new experiments illustrating the matter are reported. One giving an intuitive feel for the impact of the multiple reflection problem, the other demonstrating that an object's intensity gives a systematic error on the depth measurements.

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