DEPTH CAMERA TECHNOLOGY COMPARISON AND PERFORMANCE EVALUATION

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Abstract: How good are cheap depth cameras, namely the Microsoft Kinect, compared to state of the art Time-of-Flight depth cameras? In this paper several depth cameras of different types were put to the test on a variety of tasks in order to judge their respective performance and to find out their weaknesses. We will concentrate on the common area of applications for which both types are specified, i.e. near field indoor scenes. The characteristics and limitations of the different technologies as well as the concrete hardware implementations are discussed and evaluated with a set of experimental setups. Especially, the noise level and the axial and angular resolutions are compared. Additionally, refined formulas to generate depth values based on the raw measurements of the Kinect are presented.

1 INTRODUCTION

Depth or range cameras have been developed for several years and are available to researchers as well as on the market for certain applications for about a decade. PMDTec, Mesa Imaging, 3DV Systems and Canesta were the companies driving the development of Time-of-Flight (ToF) depth cameras. In recent years additional competitors like Panasonic, Softkinetic or Fotonic announced or released new models.

The cameras of all these manufactures have in common that they illuminate the scene with infrared light and measure the Time-of-Flight. There are two operation principles: pulsed light and continuous wave amplitude modulation. The earlier comes with the problem of measuring very short time intervals in order to achieve a resolution which corresponds to a few centimeters in depth (e.g. ZCam of 3DV Systems). The continuous wave modulation approach avoids this by measuring the phase shift between emitted and received modulated light which directly corresponds to the Time-of-Flight and in turn to the depth, where ambiguities in form of multiples of the modulation wavelength may occur.

For a long time the ToF imaging sensors suffered two major problems: a low resolution and a low sensitivity resulting in high noise levels. Additionally, background light caused problems, when used outdoors. Currently, ToF imaging chips reaching resolutions up to *200x200* pixels are on the market and chips with *352x288* pixels are in development and for a few years some ToF chips feature methods to suppress ambient light (e.g. Suppression of Background Illumination - SBI).

Other depth cameras or measuring devices, such as laser scanners or structured light approaches, were not able to provide (affordably) high frame rates for full images with a reasonable resolution and not e.g. lines. This was true until in 2010 Microsoft (PrimeSense) released the Kinect. Instead of using a time varying pattern as was widely applied previously, it uses a fixed irregular pattern consisting of a great number of dots produced by an infrared laser led and a diffractive optical element. The Kinect determines the disparities between the emitted light beam and the observed position of the light dot with a two megapixel grayscale imaging chip. The identity of a dot is determined by utilizing the irregular pattern. Here it seems that the depth of a local group of dots is calculated simultaneously, but the actual method remains a secret up until today. Once the identity of a dot is known the distance to the reflecting object can be easily triangulated. In addition to the depth measurements, the Kinect includes a color imaging chip as well as microphones.

The accuracy and the reliability of such a low cost consumer product, which is to our knowledge

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also the first of its kind, is in question and will be evaluated in the course of this paper. Instead of an investigation of a specific application, the approach taken to judge the performance of the Kinect is to devise a set of experimental setups and to compare the results of the Kinect to state of the art ToF depth cameras.

This paper is structured as follows: In section 2 the related literature is reviewed and in section 3 an overview of the depth cameras used in the comparison is given. In section 4 the experimental setups are detailed and the results are discussed. This paper ends with a conclusion in section 5.

2 RELATED WORK

The performance of ToF cameras using the Photonic Mixer Divece (PMD) was widely studied in the past. Noteworthy are for example (Rapp et al., 2008) and (Chiabrando et al., 2009). The measurement quality at different distances and using different exposure times is evaluated. Lottner et al. discuss the influence and the operation of unusual lighting geometries in (Lottner et. al., 2008), i.e. lighting devices not positioned symmetrically around the camera in close distance.

In (Wiedemann et al., 2008) depth cameras from several manufactures are compared, which are PMDTec, Mesa Imaging and Canesta. The application considered is 3D reconstruction for mobile robots. And in (Beder et al., 2007) PMD cameras are compared to a stereo setup. They use the task of scene reconstruction to judge the performance of both alternatives.

The most closely related paper is (Stoyanov et al., 2011), in which two ToF cameras are compared to the Kinect and to a laser scanner. The application in mind is navigation for mobile robots and the methodology is the reconstruction of a 3D scene with known ground truth.

3 EVALUATED DEPTH CAMERAS

The comparison involves three different depth cameras which are shown in figure 1. The Microsoft Kinect as a recent consumer depth camera in addition to two Time-of-Flight cameras based on the Photonic-Mixer-Device (PMD), all of which will be briefly discussed in the following.

Figure 1: Depth cameras used in the evaluation. Left PMDTec 3k-S, middle Microsoft Kinect and on the right PMDTec CamCube 41k.

3.1 Microsoft Kinect

The Microsoft Kinect camera uses a diffractive optical element and an infrared laser diode to generate an irregular pattern of dots (actually, the same pattern is repeated *3x3* times). It incorporates a color and a two megapixel grayscale chip with an IR filter, which is used to determine the disparities between the emitted light dots and their observed position. In order to triangulate the depth of an object in the scene the identity of an observed dot on the object must be known. With the irregular pattern this can be performed with much more certainty than with a uniform pattern. The camera uses a *6mm* lens and produces a *640x480* pixel sized raw depth map which consists of an *11*-bit integer value per pixel. The depth values describe the distance to the imaginary image plane and not to the focal point. There are currently two formulas to calculate the depth in meters publicly known, cf. (OpenKinect Wiki). An integer raw depth value d is mapped to a depth value in meters with a simple formula by

$$\delta_{simple}(d) = \frac{1}{-0.00307d + 3.33}. \quad (1)$$

A more precise method is said to be given by

$$\delta_{tan}(\mathrm{d}) = 0.1236 \cdot tan\left(\frac{\mathrm{d}}{2842.5} + 1.186\right). \quad (2)$$

Since the depth map has about *300k* pixels, calculating the later formula *30* times per second can be challenging or even impossible especially for embedded systems.

Using the translation unit described in section 4.3 refined formulas have been determined:

$$\delta_{simple}^{refined}(d) = \frac{1}{-0.8965 \cdot d + 3.123} \quad (3)$$

$$\delta_{tan}^{refined}(\mathrm{d}) = 0.181\ tan(0.161\ \mathrm{d} + 4.15). \quad (4)$$

See section 4.3 for a comparison of these formulas.

3.2 PMDTec CamCube 41k

The CamCube 41k by PMDTec[Vision], cf. (PMDTechnologies GmbH), contains a *200x200* pixel PMD chip and includes two lighting units. Modulated infrared light with frequencies up to *21MHz* is emitted and the phase shift between the emitted and received light is calculated. The phase corresponds to the distance of the reflecting object and it is determined using the so-called four phase algorithm. It operates by recording four images A_1 to A_4 at different phase offsets and then using the arc tangent relationship to retrieve the phase difference by

$$\varphi = \arctan\left(\frac{A_1 - A_3}{A_2 - A_4}\right). \qquad (5)$$

With this phase difference the distance can be determined with

$$\delta = \frac{c \cdot \varphi}{2\pi \cdot f}, \qquad (6)$$

where *c* ist the speed of light and *f* is the modulation frequency.

The CamCube uses a method to suppress background illumination called SBI to allow for outdoor imaging. It provides the possibility to synchronize the acquisition of images with the means of a hardware trigger. A wide variety of different lenses can be used due to the standard CS-mount adapter. The camera is connected to a computer via USB.

3.3 PMDTec 3k-S

The 3k-S PMD camera is a development and research version of PMDTec and it uses an older PMD chip with only *64x48* pixels. It features a SBI system and contains a C-mount lens adapter and uses firewire (IEEE-1394) to communicate with the computer. This PMD camera is known to be significantly less sensitive than cameras with newer PMD chips even though the pixel pitch is *100nm* compared to *45nm* of the 41k PMD chip.

4 EXPERIMENTAL SETUPS

In this section the evaluation methods and the most notable results of the comparison will be discussed. For the first experiments only the CamCube will be used as a reference for the Kinect, due to space restrictions. To make the results comparable an

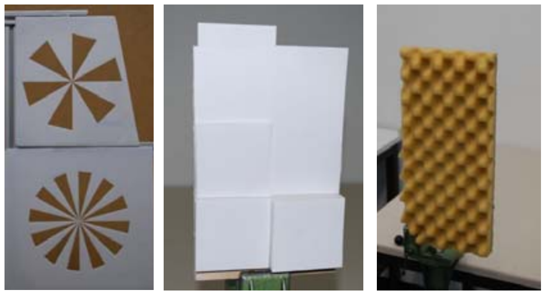


Figure 2: Resolution test objects. Left: two Böhler Stars with 20cm diameter each. Middle and right: two objects to evaluate and visualize the angular and axial resolution of depth cameras.

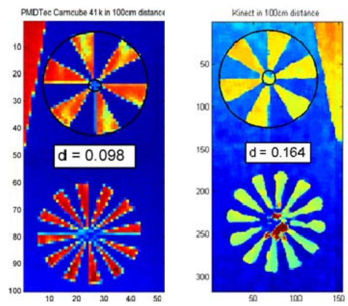
appropriate lens has to be chosen for the CamCube. Since the Kinect uses a fixed *6mm* lens and the grayscale chip has a resolution of *1280x1024* (only *640x480* depth pixels are transmitted) with a pixel pitch of *5.2µm* this results in a chip size of *6.66x5.33mm*. The CamCube has a resolution of *200x200* pixels with a pixel pitch of *45µm* resulting in a chip size of *9x9mm*. Therefore, the corresponding lens for the Cambube would have focal length of *8.11mm* for the width and about *10.13mm* for the height. Due to obvious limitations a lens with a focal length of *8.5mm* was chosen as a compromise.

4.1 Böhler-Star

A Böhler Star, see figure 2, is a tool to determine the angular or lateral resolution of depth measurement devices. It can be understood as a three dimensional Siemens-Star. In (Böhler et al., 2003) it was used to compare laser scanners. But especially for the Kinect, for which the effective resolution is not known, it promises insights. The axial resolution *r* of an imaging device can be calculated as

$$r = \frac{\pi \cdot d \cdot M}{n} \qquad (7)$$

with *n* being the number of fields of the star (here *12* and *24* respectively), *d* being the ratio of the diameter of the incorrectly measured circle in the middle of the star to the diameter *M* of the star.



(a) CamCube (b) Kinect

Figure 3: Results for the Böhler Stars at *1* meter distance.

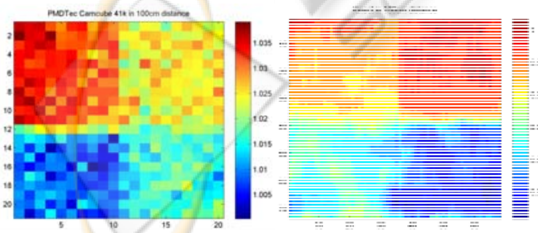
For the Böhler Stars frames were taken at different distances and in figure 3 the respective parts of one set of the resulting images are shown. In theory the CamCube with a *8.5mm* lens has an opening angle of *55.8* degrees which leads to an angular resolution of *0.28* degrees. Using the Böhler stars in one meter distance the angular resolution of the CamCube can be specified with *0.51cm*, which corresponds to *0.29* degrees. Therefore, the theoretical value can be considered to be confirmed.

The Kinect has an opening angle of *58.1* degrees and with *640* pixels in width it has a theoretical angular resolution of *0.09* degrees (*0.12°* in height). In practice an angular resolution of *0.85cm* and *0.49* degrees was determined. This corresponds to a resolution of *118* pixels in width. The significant difference is due to the fact, that multiple pixels are needed to generate one depth value (by locating the infrared dot). Although the Kinect contains a two megapixel chip and delivers only a VGA depth map, this still does not to compensate the need for multiple pixels. Additionally, the Kinect performs to our knowledge either a post-processing or it utilizes regions in the identification process, which may lead to errors at boundaries of objects.

This observation agrees with estimates that the dot pattern consists of about *220x170* dots which can be understood as the theoretical limit of the lateral resolution.

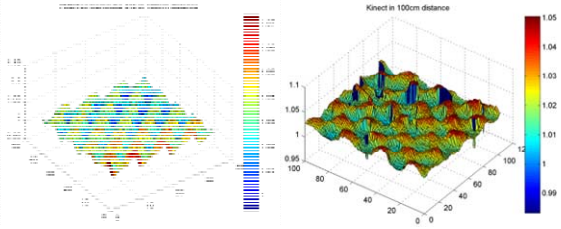
4.2 Depth Resolution Test Objects

Figure 2 additionally shows two objects to visualize the angular and axial resolution the depth cameras shown. The first object consists of a ground plane and three *6cm x 6cm* cuboids of different heights which are *3*, *9* and *1mm*. The second object has a surface close to a sinusoidal formed plane with an amplitude of *1.75cm* and a wave length of *3.5cm*.



(a) CamCube 100 cm (b) Kinect 100 cm

Figure 4: Cuboids of different heights recorded using the Kinect and the Camcube. *10* frames were averaged for each distance.



(a) CamCube 100 cm (b) Kinect 100 cm

Figure 5: Sinusoidal structure measured with both cameras in *1* meter distance.

Additionally, a *2x2cm* white plane mounted with a *0.5mm* steel wire was placed in some distance to a wall. Then the depth cameras were positioned at different distances to the plane and it was checked, whether they were able to distinguish between the plane and the wall.

In figure 4 some results for the cuboids are shown. Here *10* images were averaged. Both cameras are able to measure the different distances with high accuracy in one meter distance. At *1.5* meters distance the precision decreases and at *2* meters both cameras cannot resolve the pattern reliably. And in figure 5 a rendering of the sinusoidal structure is given. Again both cameras are able to capture the pattern correctly, but the detail preservation of the Kinect is higher.

For the small plane we get surprising results. Using the CamCube the *2x2cm* plane stays visible with correct depth value even in *4.5m* distance. The projection of the plane has then only a size of *0.7* pixels, which is enough to make a measurement. The pixel will observe a mixture of signals with different phases, but the one coming from the small plane is the strongest and therefore the measurement will function correctly. The Kinect displays a completely different behavior. Here a second camera with an optical IR filter was used to observe the infrared dots on the plane. In *1.75* meters distance the small plane is invisible to the Kinect. The number of dots on the plane is less than five. In 1.5 meter distance the plane is visible at about *50%* of the time depending on the lateral position. In one meter distance the plane is visible and correctly measure all the time with about *10-20* dots on the plane. The explanation for this behavior is the same as for the Böhler stars.

4.3 Translation Unit

All cameras were mounted on a translation unit which is able to position the cameras at distances between *50cm* and *5* meters to a wall with a positioning accuracy better than *1mm*. The cameras

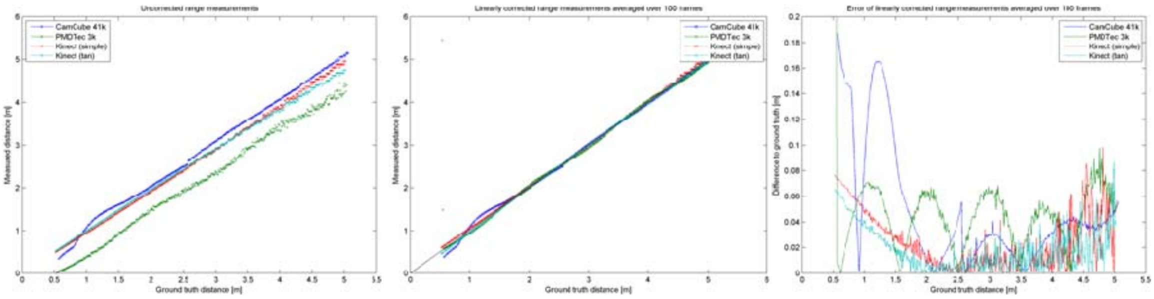


Figure 6: Depth measurements performed with the different cameras. From left to right: raw depth values, linearly corrected measurements averaged over *100* frames and absolute error to the ground truth distance.

were leveled and were looking orthogonally at the wall. *100* images were taken per position with a step size of *1cm* which results in *45000* images per camera. For all ToF cameras the same lens, the same modulation frequency of *20MHz* as well as the same exposure times (*5ms* for distances lower that *2.5* meters and *10ms* for higher distances) were used.

In figure 6 for the three evaluated cameras the raw depth measurements, depth values compensated for constant and linear errors and the absolute error to the ground truth are shown. Here the CamCube shows measurement errors for small distances due to overexposure and both PMD based ToF cameras show the well known wobbling behavior, cf (Kahlmann et al., 2006). The distance error of all cameras is comparable in the optimal region of application (*2-4m*) with a slight advantage for the Kinect. For PMD based cameras more complex calibration methods exist, see (Lindner and Kolb, 2006) or (Schiller et al., 2008), which are able to reduce the distance error further. The variance of the distance measurements based on *100* frames is plotted in figure 7. Here the Kinect shows surprisingly higher noise levels than the CamCube for distances larger than two meters. The variance of the PMDTec 3k camera is higher due to its limited lighting system and its low sensitivity.

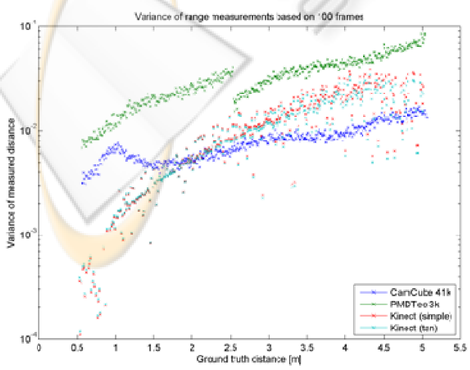


Figure 7: Variance of the measurements based on *100* recorded images.

In figure 8 the absolute distance errors for the Kinect are displayed using the different depth formulas in section 3.1. Again *100* frames were averaged and constant errors were neglected. The refined distance formulas perform significantly better.

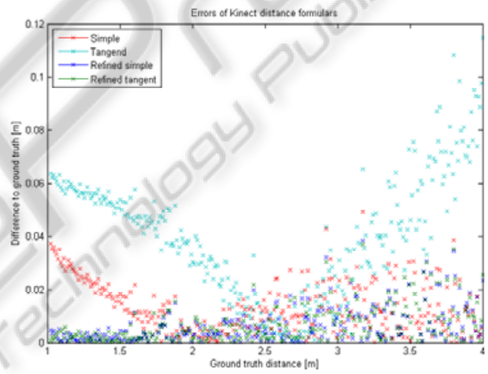


Figure 8: Comparison of the different depth formulas for the Kinect. Displayed is the absolute error neglecting constant offsets.

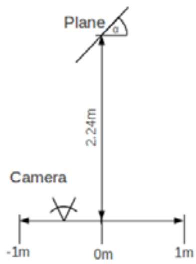


Figure 9: Setup to test the ability of depth cameras to measure plane objects with different angles and positions relative to a camera path.

4.4 Angular Dependency of Measurements

Since the measurements of the Kinect are based on triangulation, it is questionable under which angles objects can be measured accurately. To evaluate this property the camera is moved horizontally and a plane with a fixed distance to the camera path is Angles from *-40* to *-110* degrees and from *40* to *110* degrees with a step size of *5* degrees are applied and the camera is positioned with offsets from *-1* to *1* meter using a step size of *10cm*. High accuracy positioning and rotation devices are used for this purpose. This leads to a total number of *30x21* images. For each image the measurement quality is judged and grades are assigned: All pixels valid, more than *80%* valid, more than *20%* valid and less than *20%* valid.

In figure 10 the results for the test setup to identify difficulties in measuring sharp angles are shown. We encounter measuring errors for angles up to *20* degrees less than the theoretical limit, which is the angle under which the front side of the plane is invisible. Noteworthy is that the left side of the depth map displays significant higher sensibility. This is where the grayscale camera is located and therefore, the incident light on the plane has here a sharper angle than on the right side.

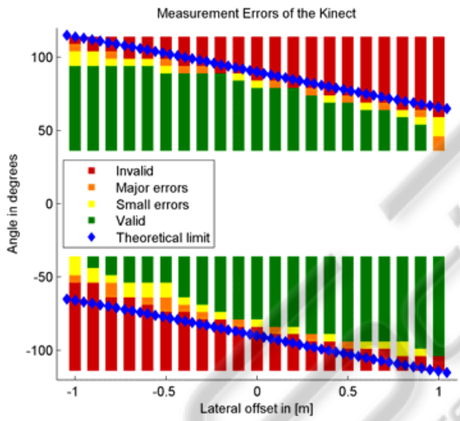


Figure 10: Results for the angular measuring setup using the Kinect.

4.5 Limitations

During the evaluation and in previous experiments the different types of cameras displayed different weaknesses. The Kinect showed problems with dull (LCD monitors) or shiny surfaces or surfaces under a sharp viewing angle. Obviously, the mounting is relatively difficult and its lens is not exchangeable, which limits its application. Different lenses in combination with different diffractive optical elements might for example allow for larger distances. These drawbacks might be solved in different hardware implementations, but the largest problems are caused by a systematic limitation. A significant part of a typical depth map contains no measurements due to shading: parts of the objects seen by the grayscale camera are not illuminated by the IR light beam. Depending on the application these areas can cause huge problems. In figure 11 a challenging test scene is shown. Here dark blue in the depth map for the Kinect indicates invalid measurements.

Daylight is another source of problems. Since the grayscale chip of the Kinect uses an optical filter only infrared light disturbs the measurements. Therefore, a high power infrared led with a peak wavelength at *850nm* and an infrared diode with corresponding characteristics have been utilized to give an impression at which levels of infrared ambient light the Kinect can be used. It has been determined that measuring errors occur for an irradiance of *6-7W/m²* depending on the distance. For comparison: sunlight at sea level has an irradiance of about *75W/m²* for wavelengths between *800* and *900nm*.

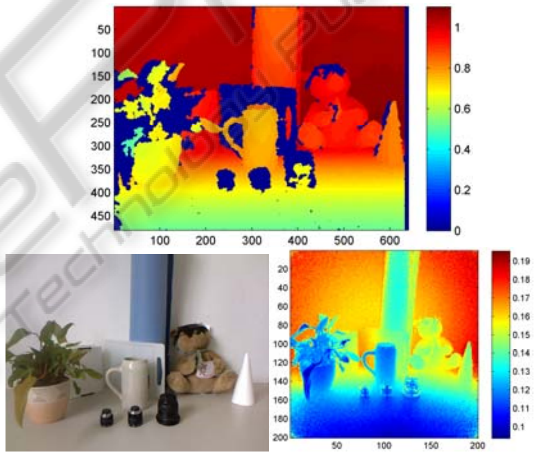


Figure 11: difficult test scene. Top depth map generated with the Kinect (dark blue: invalid), lower left color image and lower right scene acquired with the CamCube.

The limitations of PMD based ToF cameras are mainly motion artifacts, which occur when objects move significantly during the acquisition of the four phase images. Another problem are mixed phases, which are produced when a pixel observes modulated light with different phase shifts due to reflections or borders of objects inside a pixel. Additionally, the low resolution and the higher power requirements limit the application of ToF cameras to some degree.

5 CONCLUSIONS

In this paper a consumer depth camera, the

Microsoft Kinect, which uses a novel depth imaging technique, is compared to state of the art continuous wave amplitude modulation Time-of-Flight cameras. A set of experimental setups was devised to evaluate the respective strengths and weaknesses of the cameras as well as of the underlying technology.

It was found that the new technique as well as the concrete implementation poses a strong competition in at least the near field indoor area of application. Only the problems caused by the triangulation, namely shading due to different viewpoints, measuring difficulties of sharp angles and measuring of small structures, are major weaknesses of the Kinect.

Acquiring full frame depth measurements at high frame rates in an outdoor environment or for longer distances seem to be domain of ToF based depth measuring up until today. For indoor scenes higher resolutions like the currently developed 100k PMD chip by PMDTec may level the playing field again.

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