

3D-Camera of High 3D-Frame Rate, Depth-Resolution and Background Light Elimination Based on Improved PMD (Photonic Mixer Device)-Technologies

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ABSTRACT AND INTRODUCTION

The knowledge of three-dimensional data is essential for many control and navigation applications. Especially in the industrial and automotive environment a fast and reliable acquisition of 3D data has become a main requirement for future developments.

This contribution describes novel 3D camera modules used in Time-of-Flight measurement systems for 3D imaging applications. The key components are array and line sensors which can measure the distance to the target pixelwise in parallel, i.e. without scanning. Therefore these cameras have the advantages of fast imaging and high lateral resolution combined with the depth information of the captured scene. The sensors consist of smart pixels, called the Photonic Mixer Device (PMD) which enables fast optical sensing and demodulation of incoherent light signals in one component [1][2].

To realize a Photonic Mixer Device there are different techniques currently under investigation. Sensors are conceivable working with different types of electromagnetic waves, e.g. light, microwaves or ultrasound. In this paper two types of optical 3D-cameras with different PMDs are described. Each camera consists of a sensor chip, a modulated optical transmitter, control and processing electronics and software package. One camera is realized with standard CMOS technology based on Photogate (PG) PMD. The other sensor uses a different type of PMD, called Metal-Semiconductor-Metal (MSM) PMD.

Beginning from the description of both PMD types and their characteristics the system concept is shown. Based on realized cameras the sensor architectures and system environment are described. Finally measurements are presented to show the performance of the cameras in terms of accuracy, resolution and suppression of background illumination.

THE PHOTOGATE PMD (PG-PMD)

This section describes the principle of a simplified Photogate PMD realized in CMOS technology. The PG-PMD element is a smart pixel device because the mixing process of the electric and optical signal takes place in the device. **Figure 1** shows an illustration of a single pixel PG-PMD sensor element. It is a five-terminal device with an optical input window, i.e. two transparent modulation electrodes in the middle of the illustration. These photogates are isolated from the substrate by a thin oxide layer. The gates are conductive and transparent for the received light. On the left and the right there are readout diodes which are connected to the pixel readout circuitry. In a PG-PMD the charges do not only move in one direction, they move to the left or to the right depending on the reference signal applied to the modulation gates. The potential distribution in the surface region is influenced by these push-pull voltages leading to a "dynamic seesaw" for the generated charges. If the incident light is constant and the modulation is a rectangular signal with a duty cycle of 50% the generated charge carriers within a modulation period move to the left and to the right equally. At the end of such a modulation process the output voltage at the readout nodes are the same which is shown in **Figure 1 b)**. If both signals are, e.g. rectangular signals and there is no phase delay between them, all charges will be moved to one of both readout diodes which is shown in **Figure 1 c)**. The modulation of the light intensity and its phase delay to the electrical reference signal results in a difference between the two output voltages. Obviously the difference of both output nodes is directly dependent on the phase delay between light and pixel modulation and represents the correlation function. This data can be used to calculate the distance from a light-reflecting object to the sensor as described in a later section.

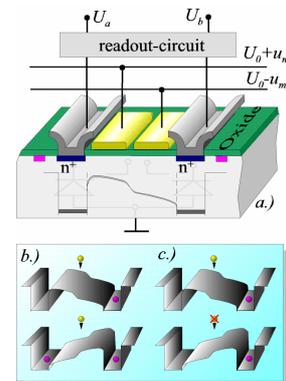


Figure 1: Operation principle of PG-PMD

THE METAL SEMICONDUCTOR METAL PMD (MSM-PMD)

The MSM-PMD that is used in one of our systems is based on photodiode structures using Schottky-barrier structures as shown in a later section. The bandwidth of these diodes is experimentally proven up to several GHz, depending on the material, the barrier realization, and so on. This fact offers a very fine resolution in a ranging system based on such a MSM-PMD reception principle. **Figure 2** shows the basic structure of such a MSM-PMD receiver. The electrical reference signal is used for modulation of the optical transmitter and for demodulation of the

reflected light signal $P_{opt}(t)$. For demodulation the reference signal is changed into push pull signals $+u_m(t)$ and $-u_m(t)$. The AC-part of these signals is applied to the MSM-diode via the decoupling networks $DN_{1,2}$.

The readout networks $RN_{1,2}$ on the right part suppress these RF-signals. Only that part of the signal which correlates to the modulation voltage, is *slow* enough to pass these networks. The readout circuit RC analyses the signal and delivers the results. The main feature of this circuit is that the mixing of the generated charge carriers takes place directly inside the light sensitive area of the diode. The closed circuit on the right side of the structure is the key to an improvement of the SBI (Suppression of Background Illumination)-functionality [3]. Any uncorrelated photocurrents $i_{uk1,2}$ are – on the average – equally distributed onto both arms. Therefore these uncorrelated signals compensate each other. This effect only depends on the symmetry of the structure and is attained without any additional components. The correlated part of the averaged photocurrent i_k has a flow-direction depending on modulation phase. This results in different voltages in the readout networks after a certain integration time. These voltages are the values that are analyzed by the readout circuit to deliver the measurement result.

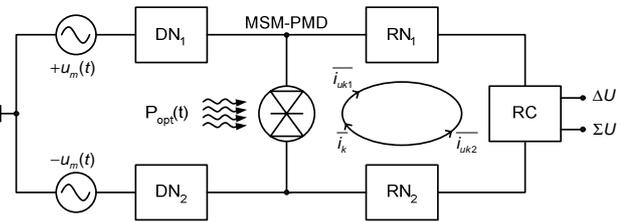


Figure 2: Basic structure of a SM-PMD-device based on a MSM-diode. The MSM-diode as central mixing unit is displayed with the symbol in the middle of the picture

SENSOR CONCEPT AND CAMERA DESCRIPTION

Smart optical sensor array based on PG-PMD

Our development in the past has led to a Photogate-pixel with scalable pixel pitch without a loss in the mixing efficiency. The active pixel size can be modified based on application requirements from $20\mu\text{m} \times 20\mu\text{m}$ up to $300\mu\text{m} \times 300\mu\text{m}$. Other application specific sizes and aspect ratios are also conceivable. This feature is based on a new kind of pixel layout. The structure of readout channels and modulation gates are independent of the pixel dimension and optimized for matrix structures. Photogate pixels with large dimensions can therefore offer almost the same performance as small designs. The channel width has been optimized for higher bandwidth (up to several 100 MHz) to increase pixel performance and accuracy. **Figure 3** shows the PG-structure of the 16×16 matrix in the described 3D camera. The active area consists of 2 rows with 9 fingers each and has a typical channel width of $10\mu\text{m}$. Single pixel and line pixel sensors can reach an optical fill factor up to 60% (designed in a typical $0.6\mu\text{m}$ process). A smaller process can offer a fill factor of approx. 75% in the optical active area.

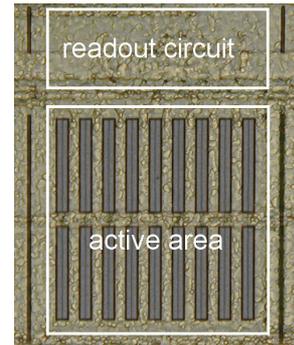


Figure 3: Photogate structure

Even if a PMD pixel looks a little exotic in comparison to a 2D active pixel, a PG-PMD sensor is build in a standard process. The sensor array was integrated in a $0.6\mu\text{m}$ triple metal n-well CMOS process. A 16×16 array with a pixel pitch of $210\mu\text{m} \times 155\mu\text{m}$ was developed. Photogate pixels normally have two output signals and so the read out circuitry consists of two separate branches. One of them is shown in **Figure 4**. A simple PG-pixel has a reset switch (M1), a pixel select switch (M3) and a read out buffer (M2) working as a source follower. All pixel source followers share one load transistor (M4) at the bottom of each column. The column

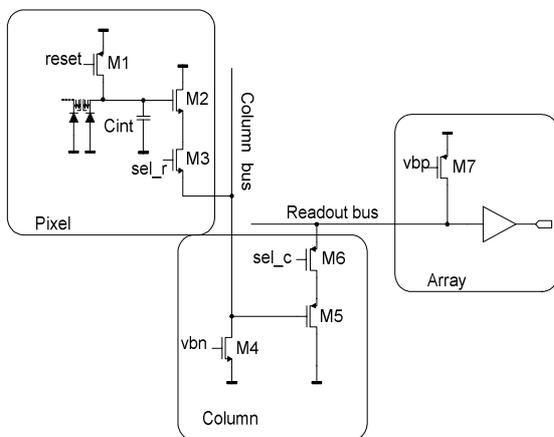


Figure 4: Simplified schematic of the PG-pixel and readout circuitry in the PMD array

circuitry consists of a PMOS source follower (M5) with the column select switch (M6). At the end of the row a load transistor (M7) and the output stage are placed. The output signal is converted to digital values off chip. In further designs the analog-digital converter could be integrated on the sensor chip achieving higher frame rates with lower system costs. All bias currents are proper calculated to realize a maximum settling time of 150ns. In combination with our actual camera system a pixel read out speed of 2MSamples/s resulting in a total read out time of $128\mu\text{s}$ is realized. Standard CMOS active pixel sensors need a correlated double sampling for each column and a double delta sampling for the whole array. With these techniques fixed pattern noise can be reduced. Our PG-PMD sensor doesn't need these additional circuits. For calculating the 3D data several integration cycles respectively their output values are needed so that a kind of double or even multi sampling is done, therefore fixed pattern noise is eliminated. Using the absolute values of both integration voltages grayscale data can be calculated as additional information of the observed scene. [1]

High resistance of the modulation lines and the capacity of the modulation gates of each PMD may result in a phase shift of modulation and so in a distance offset variation from pixel to pixel. In comparison to previous designs the modulation lines are more symmetrical and they have a lower resistance to avoid this error. The root-like modulation line design can be seen in top of the chip layout in **Figure 5**. The digital control circuit consists of two units which are the row and the column control circuit. Standard logic blocks are used achieving higher read out speed than 2MHz. **Figure 6** shows the camera module with active illumination, optical components and periphery.

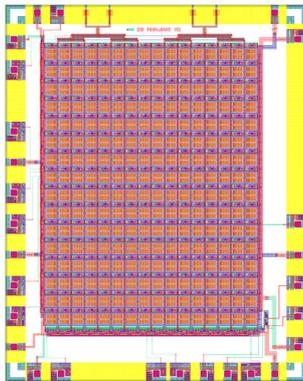


Figure 5: Layout of PG-PMD chip



Figure 6: 3D camera module on tripod

Smart Optical sensor line based on MSM-PMD

The usage of MSM-PMD has enormous advantages for applications with disturbing illumination, i.e. uncorrelated background light, without adding additional circuitry for SBI. Furthermore these structures are proven with modulation frequencies up to several GHz allowing a very fine resolution of the 3D information [3]. The following figure illustrates the principle of a smart optical pixel with MSM-PMD in our 3D-camera. In contrast to the description given above a technique of single sided modulation and readout is used. Using this method a high on-chip integration level can be achieved to realize multipixel sensors without additional off-chip filtering.

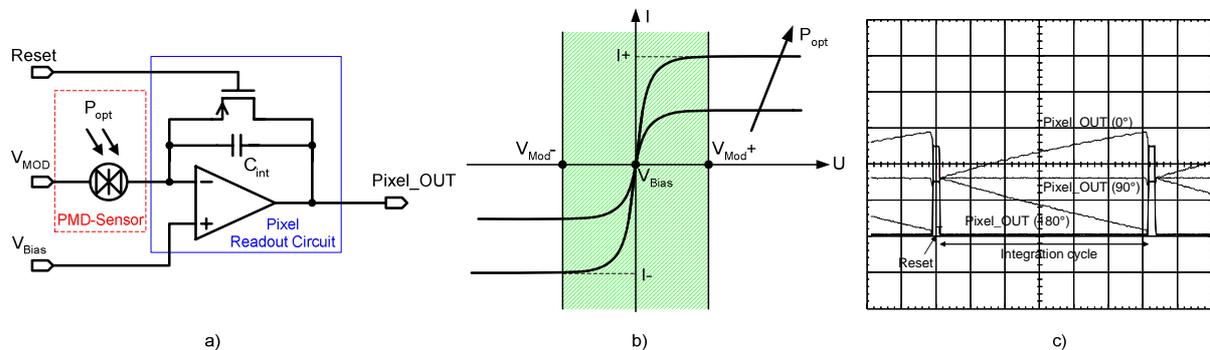


Figure 7: a) Pixel schematic b) typical IV-characteristics of a MSM structure: The switching of the operation points provides the mixing and the SBI functionality c) Integration examples with different phases (0°, 90°, 180°)

For first applications a line sensor of 8 MSM-PMD elements has been defined. Each pixel consists of a MSM-PMD sensor and a specific readout circuit which is based on an active op-amp integrator with reset. This integrator ensures a constant voltage at the readout side of the PMD element (approx. V_{Bias}). All pixels use the same modulation source (V_{MOD}) and have a global reset. After a reset the correlation of the electrical modulation signal and the incident light reflected by the 3D scene (P_{OPT}) is analyzed by integration of the photocurrent as shown above.

The correlation result due to the phase shift between these signals is indicated by a voltage (Pixel_OUT). The readout of the sensor line is done sequentially at the end of the integration cycle. The output voltage of each pixel is processed by an external signal processing unit and is used to calculate the distance from the sensor to the target for each pixel separately as described in the next section. The realization of such a 1x8 line MSM-PMD sensor chip is shown in **Figure 8**.

To combine state-of-the-art MSM structures with application specific CMOS circuitry a first multichip approach has been realized. The MSM-PMD sensor line itself consists of 8 interdigitated Schottky diodes realized with gallium arsenide MSM structures. The outputs of these diodes are connected to a silicon die with an 8 stage readout circuitry using a standard wire bonding technology. Using integrable MSM devices, e.g. silicon based Schottky structures high dense single chip solutions are possible and currently under investigation.

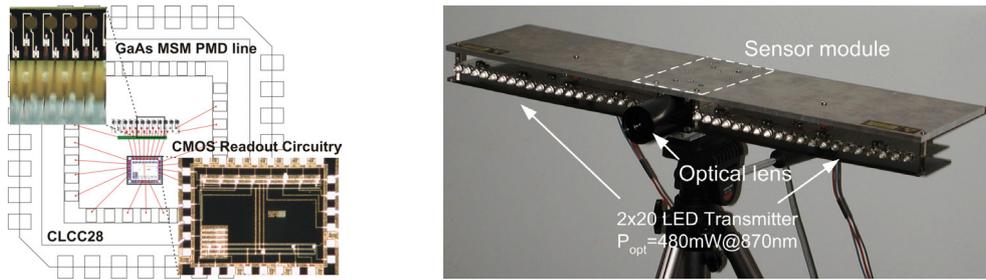


Figure 8: Left: MSM sensor line with CMOS readout circuitry in a multichip approach. Each MSM structure has a diameter of 150µm, the pixel pitch is 250µm. Right: 3D camera module with active illumination on a tripod.

Description of camera system environment

In principle the system environments for both cameras are the same. It can be divided into four main parts. The first part is the system board consisting of a power supply, a microcontroller, an analog-to-digital converter and a programmable logic device. A PMD-chip (PG or MSM) and its required peripheral devices are comprised in the second part, the so called “frontend”.

To generate the optical signal a third part is needed. The light source mostly consists of an LED-array and an adapted power supply. The last part that is needed is the case of the camera including the optical components (lens, optical filter, ...). **Figure 9** shows an overview of these parts and their function in the camera system.

The function of the programmable logic device is to generate two rectangular signals with the same frequency and duty cycle. The first signal, whose phase can be shifted, is converted into an optical one via the LED array. This optical signal is sent to the objects and the reflected light is received by the PMD-array (PG or MSM).

The second signal of the programmable logic device is directly connected to the PMD-array. The main function of the PMD-array is to correlate the received optical signals with the electrical reference signal and send the results via the analog-to-digital converter to the microcontroller. The microcontroller collects the results of four different measurements. The measurements only differ in the phase (0°, 90°, 180°, 270°) between electrical and optical signal. The results are four equidistant points of the correlation function of the received optical signal in one PMD-pixel and the electrical reference signal. With these points it is possible to determine the offset, the amplitude and the phase delay of the correlation function. The phase delay itself is proportional to the distance which the light has to cover on its way to the object and back, therefore the distance matrix can be calculated.

The communication between the camera system and its environment is based on standard serial interface. The camera system can be connected to industrial control units or a PC via this interface. The incoming data may be used to control a robotic unit, for monitoring purposes or just for visualization of the captured 3D image. Different kinds of visualization are already implemented in C++ and Matlab software.

In the current version of this camera the whole timing control and the readout of the measurement results are implemented in the microcontroller. In the next version which is currently under development the programmable logic device will take over these functions. Additionally the microcontroller will be faster and therefore frame rates like video frame rates or higher will be possible in the next generation of high resolution 3D camera.

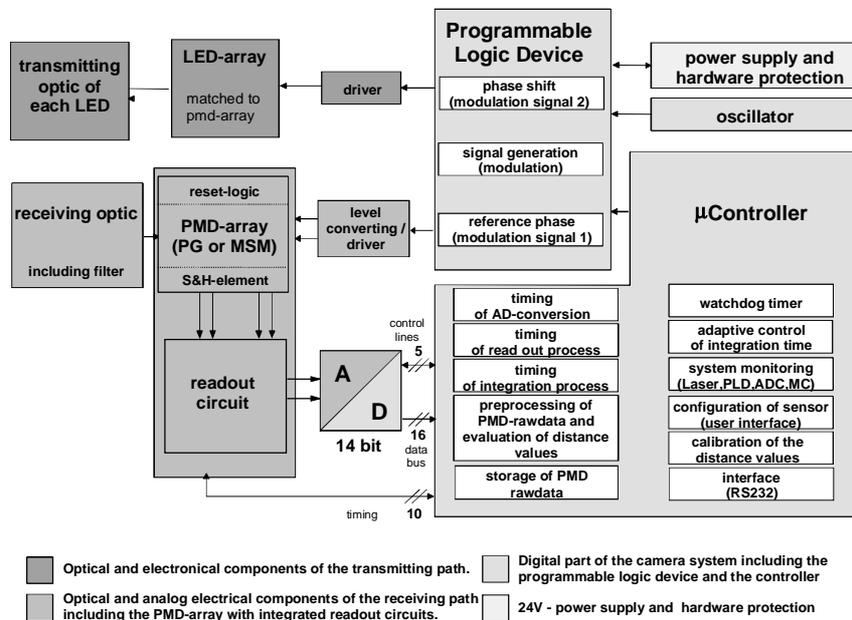


Figure 9: Basic structure of a MSM-PMD- or PG-PMD-camera system

Legend for Figure 9:
 - Dark grey box: Optical and electronic components of the transmitting path.
 - Light grey box: Digital part of the camera system including the programmable logic device and the controller.
 - Medium grey box: Optical and analog electrical components of the receiving path including the PMD-array with integrated readout circuits.
 - White box: 24V - power supply and hardware protection.

MEASUREMENT RESULTS

16x16 PG-PMD 3D camera

Figure 10 shows an exemplary measurement of 8 arbitrary pixels within the given matrix in the 3D PG-PMD camera. The target was a plain surface of white paper, the integration time was kept constant. The modulation frequency was 20 MHz which allows a range of unambiguously of 7.5m [1]. The standard deviations of the measured values were in the range from approx. 12mm (@1500mm) to approx. 35mm (@3500mm). Of course, the accuracy of the measurement depends on several parameters shown below. For example, the signal to noise ratio is affected by many things like optical power, the distance to the target, background light, system noise and so on.

$$\Delta L = \frac{\lambda_{RF}}{4\pi} \cdot \frac{1}{\sqrt{N}} \cdot \frac{\sqrt{2+K^2}}{K \cdot SNR}$$

ΔL	distance resolution in standard deviation
N	number of measurements
K	modulation contrast
SNR	signal to noise ratio
λ_{RF}	modulation wavelength

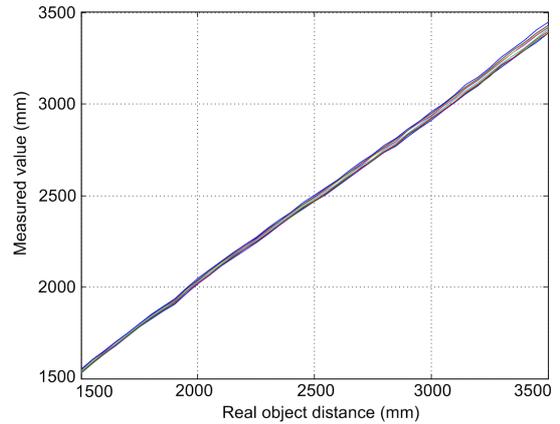


Figure 10: Measurement (mean value) of 8 arbitrary pixels within the PG-PMD camera. The integration time was constant (5ms). Target was a plain surface of white paper.

As described our camera has a total number of 256 pixels for parallel 3D measurement without scanning. In contrast to other low resolution 3D ranging systems, e.g. radar, this camera is already suitable for many applications in industrial and automotive field. In addition to the 3D information our camera has an additional benefit with the acquisition of 2D grayscale information for enhanced image processing. An exemplary measurement of the 16x16 camera is given in **Figure 11** on the left side. It shows a 3D image of a human hand in front of a plain surface. The measured distance is visualized in different hues. Additionally the 3D image has been rotated and smoothed for a better three dimensional perception. For comparison a high resolution 2D image is given on the right side in **Figure 11**.

With our sensor array such 3D images can be taken within a few microseconds which allows the acquisition of a moving scene in realtime.

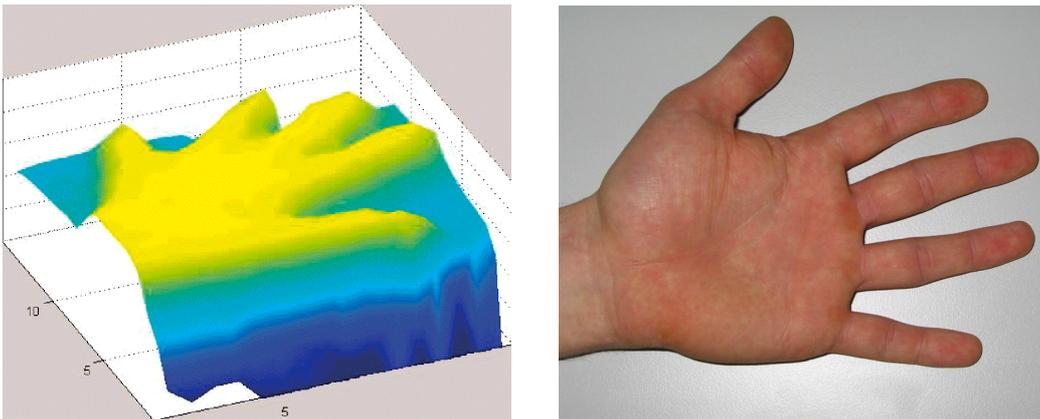


Figure 11: Left: 3D image of a human hand taken with 3D PG camera. 3D Image has been rotated and smoothed to visualize the depth information. Right: A high resolution 2D image for comparison

1x8 MSM-PMD line sensor camera

Figure 12 shows a measurement done with an arbitrary pixel in the described MSM line sensor camera. The used modulation frequency was 10 MHz which allows a range of unambiguously of 15m. The target was a plain surface of white paper in different distances. The standard deviations under these conditions were in the range from approx. 5mm (@1m) to 70mm (@15m).

To show the influence of uncorrelated background light a measurement is given in **Figure 13**. Despite of background light, a measurement can be done with slightly increased standard deviation. It has to be kept in mind that this feature is achieved *without any additional* circuitry. The suppression of uncorrelated signals is provided only by the sensor and the function principle as described above.

The suppression of background illumination has been proven up to a ratio of 1000 in laboratory environment. These measurements were done with a modulated laser source whereas the DC background light was generated with a cold-light lamp (3400K). The MSM pixel has been exposed with the modulated laser light (20nW @635nm) and the background illumination directly. In this configuration phase measurements were possible even if the optical power of the background light was 1000 times higher than the active illumination. The standard deviation of the measured phase was approx. 11° at highest background level. For example, with these conditions the measured distance of an object in the range of 10m has a standard deviation of approx. 0.45m (modulation frequency 10MHz).

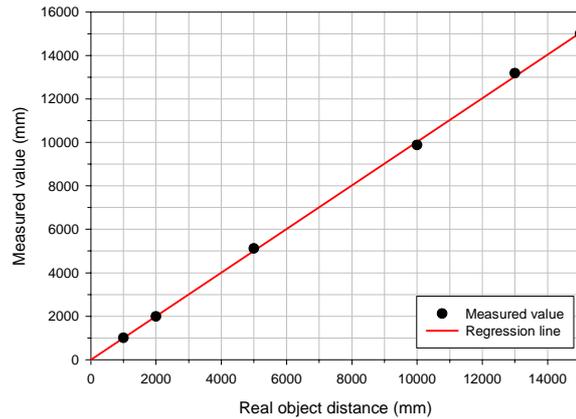


Figure 12: Measurement (mean value) of an arbitrary pixel in the range of 1 to 15m. The integration time was 10ms. Target was a plain surface of white paper.

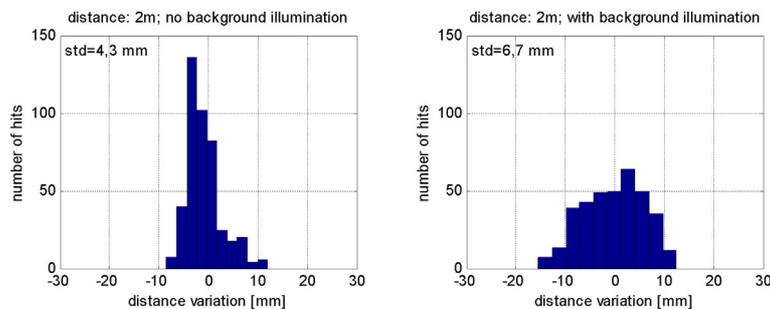


Figure 13: Measurements with a plain surface of white paper in a distance of 2m. Left: only active illumination on target ($160\mu\text{W}/\text{cm}^2$). Right: Same measurement conditions but with additional background illumination ($720\mu\text{W}/\text{cm}^2$). The integration time was 20ms

CONCLUSION AND PERSPECTIVES

In this paper two types of 3D cameras based on different PMD principles are described. The use of PG-PMD devices allows a high integration level in a standard CMOS process. The advantages are the low production costs and the possibility to integrate additional on chip system components (SOC). In addition to the 3D data the grayscale image of the scene can be detected for an enhanced image processing. The advantage of the MSM-PMD is the high modulation frequency and the inherent suppression of background illumination without additional circuitry.

Because of the mentioned features both concepts are suitable for a wide field of applications, e.g. automotive, safety, industrial control and navigation, robotics and virtual reality. New generations of 3D sensors are currently under development. A PG-camera with resolution of 160x120 will be available this year as well as a MSM-camera with the resolution of 16x4.

ACKNOWLEDGEMENT

The authors would like to thank the INV, PMDTechnologies, S-Tec and ZESS staff for technical support, as well as partly financial support from BMBF.

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