

A 3D TIME OF FLIGHT CAMERA FOR OBJECT DETECTION

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ABSTRACT

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.

Moreover low cost 3D imaging has the potential to open a wide field of additional applications and solutions in markets like consumer electronics, multimedia, digital photography, robotics and medical technologies.

This article describes the modular design of a new generation of time-of-flight cameras, the so called PMD cameras. The key component is an array or line sensor which can measure the distance to the target pixelwise in parallel 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.

Each PMD-camera consists of a sensor chip in standard CMOS technology, a modulated optical transmitter, control and processing electronics and software package. Dependent on special demands of the different application and markets mentioned above each PMD camera component has to be adapted to these demands. The paper give some examples for costumer specific solutions and the possibilities of a flexible modular camera design.

1. INTRODUCTION

Photonic Mixer Devices, the so-called PMD sensors, base on time-of-flight principle. This new camera technology realizes three dimensional imaging without complex electronics and without scanning with a solid state imager similar to a CMOS device. This imager detects both the intensity and the distance in each PMD pixel or voxel respectively.

Today image processing systems are used in a wide field of application and base on CCD or CMOS cameras which detect intensity of the optical image in each pixel or the projection of real scenery, respectively. Therefore this system has lost the third dimension as an important information for object recognition as depicted in figure 1.

Other principles to provide technical systems with a three dimensional depth map of the scene need high computer power to find correlation in the grey value map like stereo cameras or they have mechanical components like scanning systems. Both systems are cost-intensive, have a low real-time capability and have no homogenous depth map in the case of stereo cameras.

Time of Flight systems consist of an optical transmitter and an optical receiver and they have already been described in detail in many technical publications [6,7,8].

Therefore only the basic principles will be discussed here. Figure 2 shows the basic Time-Of-Flight principle. In its most simple form, a light pulse is transmitted by a sender unit and the target distance is measured by determining the turn-around time the pulse needs to travel from the sender to the target and back to the receiver. With knowledge of the speed of light the distance can then

easily be calculated. However, the receiver needs to measure with pico-second-accuracy the delay between start and stop, if millimeter-precision is required (6,6ps for 1mm). To realize such system solutions with discrete components, as is done in today's TOF rangefinders, each component in the signal chain must have a very high system bandwidth.

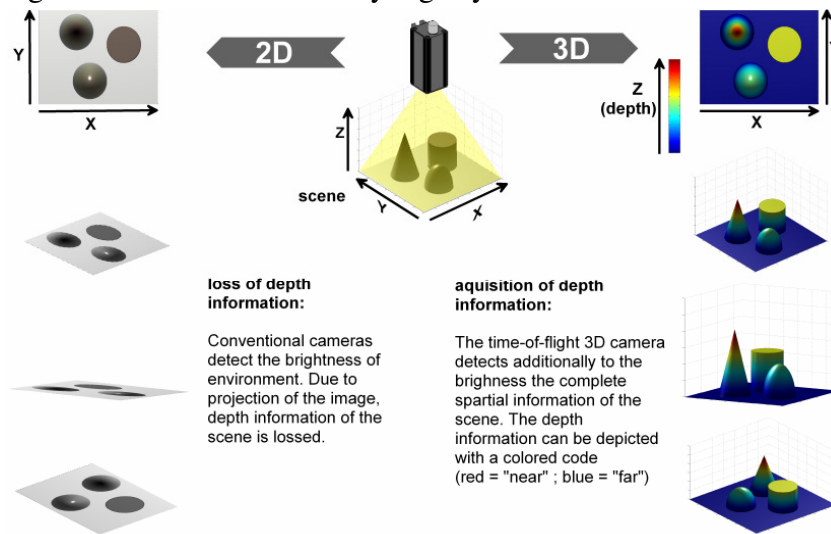


Figure 1: 2D- vs. 3D information

In contrast to figure 2, figure 3 shows the basic working principle of a PMD based range imaging camera. Rather than using a single laser beam (which would have to be scanned over the scene to obtain 3D) the entire scene is illuminated with modulated light. The advantage of PMD devices is that we can observe this illuminated scene with an intelligent pixel array, where each pixel can individually measure the turnaround time of the modulated light. Typically this is done by using continuous modulation and measuring the phase delay in each pixel. In addition to this robust method of obtaining 3D without scanning, the realization of the phase measurement in a quasi optical domain offers huge advantages compared to the above mentioned discrete solutions. This is one reason, why PMD systems do not require an optical reference channel for most applications.

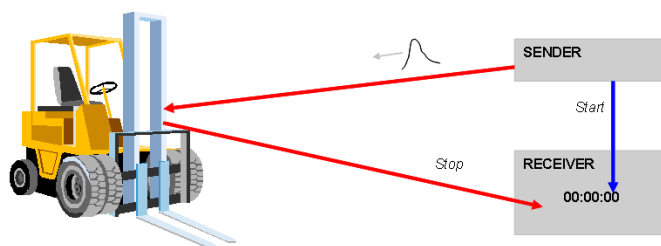


Figure 2: Time-of-Flight measurement principle with pulsed light

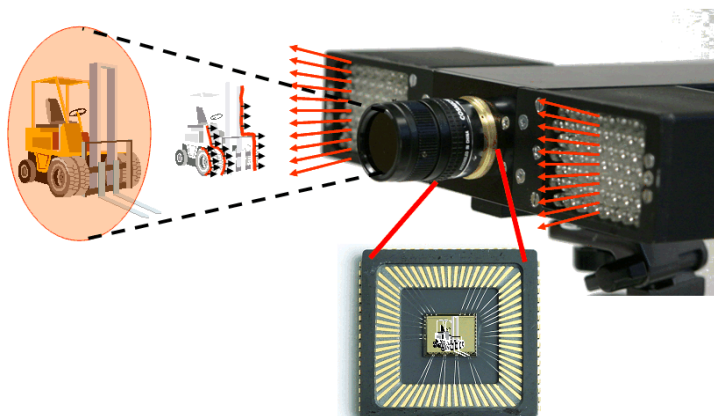


Figure 3: 3D imaging principle based on PMD time-of-flight camera

2. COMPONENTS OF A PMD SYSTEM

A PMD camera consists of the PMD chip and its peripheral electronics, an illumination source, the receiver optics, a system for controlling the camera including digital interfaces and software. Each component of this camera system more or less affects the key parameters as measurement range, field of view, frame rate and accuracy. Each application or market has different requirements concerning these parameters and additional conditions like sunlight stability, rejection of other IR-emitter systems, size and weight.

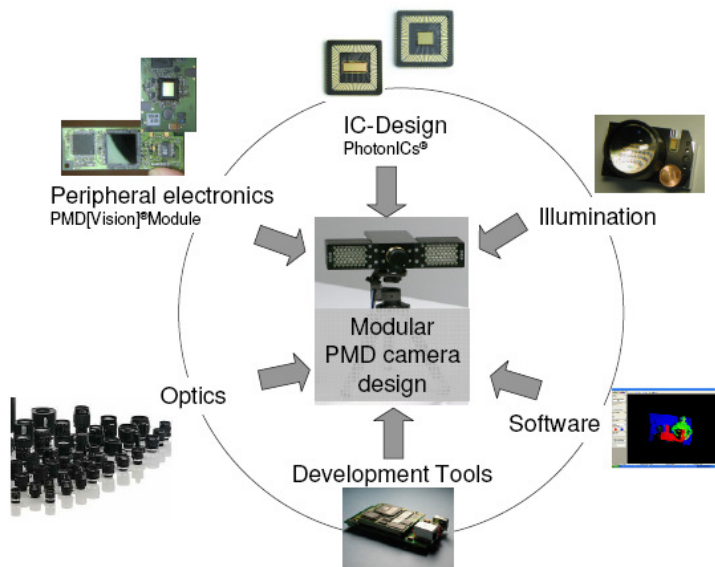


Figure 4: Components of a PMD System in a modular design

Because of the wide field of possible application, it is useful for technical evaluation to offer a flexible modular camera system design, depicted in figure 4. Such a system could be adapted to the requirements of an application in a feasibility study project phase. After checking technical issues, a customer can use some of the depicted camera parts in series development and built up his own system with special market requirements for housing, interfaces, special norms etc. Some examples of such successful products are given in chapter 4.

In the following, the parts of a TOF System are described in detail.

The PMD Chip is the key component of the system although it is not the only part which affects performance. The number of pixels defines the lateral resolution of the camera well known from digital 2D cameras. Additionally each pixel provides the system with depth information of the corresponding point in the object plane. Depth accuracy is defined by the amount of active light which arrives at this pixel and is affected by optics and illumination but also by fill factor, spectral sensitivity, modulation contrast and last but not least by the active area of the pixel. Therefore pixel size must be considered very well for each application because the highest lateral resolution for PMD Chip is not in all cases the absolutely best solution considering also the necessary depth accuracy together with demands for illumination and receiver optics. A combination of high resolution 2D camera and 3D PMD camera is another option for application, where lateral resolution is absolutely necessary.

Next to pure optical and electro-optical issues the standard CMOS process opens the capability to integrate more functionality in a PMD chip. The patented suppression of background illumination e.g. makes 3D measurement possible in bright sunlight conditions up to 150klux. More considerations concerning these issues could be found in [11].

Moreover many components of peripheral electronics will be also integrated into the chip like AD-converter or modulation driver electronics.

Nevertheless **peripheral electronics** implemented on PMD frontend-modules are important for PMD performance and additional systematic features. The modulation driver defines modulation frequency and signal characteristic which is important for phase stability and accuracy of the system (chapter 3; equation 3.5). Moreover a programmable logic device provides PMD with phase signals (A1...A4, chapter 3) and could vary modulation frequency for increasing ambiguity range or integrating PMD cameras in multi TOF sensor environments. These issues are described more in detail in chapter 4.

The **Illumination** source(s) has a similar significance to system performance as the PMD device itself. The field-of-view is defined by illumination source in consideration of maximal optical power and best optical efficiency. Moreover, modulation contrast has to be optimised towards 100% and modulation frequency has to be increased under consideration of equation 3.5.

In principle two kinds of illumination sources could be used, light emitting diodes (LED) or laser diodes which have special advantages or disadvantages described in the following. Special types of interesting illumination sources like vertical cavity lasers (VCSEL) or superluminescent diodes (SLED) are not considered.

Development of brighter and more efficient LEDs have been accelerated in the last 10 years by needs in all kinds of illumination efforts from automotive lights to imaging processing. The efficiency (electrical to optical power) of modern LEDs is up to 30%. The modulation circuitry could be implemented easily due to a linear electro-optical characteristic and beam shaping is done by an integrated LED optics. Disadvantages of LEDs are a considerable part of light in the border area of the beam, which could be not used for illumination of the field-of-view. Additionally the limit of modulation capability of commercial LEDs is up to 20MHz to 30MHz at an acceptable modulation contrast.

Laser diodes have efficiencies up to 50% dependent on optical output power, threshold etc. Due to spartial coherence the beam profile can be adapted much better to field-of-view for PMD sensor than LED radiation and the possible modulation frequency is higher than 100MHz. On the other hand the circuitry for modulating a laser diode is more complicated and there are some additional steps necessary to guarantee phase stability. Moreover the implementation of laser systems needs more attention concerning eye safety than LED systems do.

In summary it depends on the application which illumination source should be implemented. Dependent on the required optical power cooling concepts could be an additional important issue and challenge.

Similar to standard 2D cameras receiver **Optics** make an image of the scene. The difference to the 2D world is the detection of time-of-flight of the optical path in each PMD Pixel next to illumination. Therefore blur effects or other disturbances like multiple reflexions also cause distance errors. A careful selection of appropriate objectives is demanded considering a large aperture or small f-number because of the direct relationship between accuracy and the active incoming light. PMD cameras with C or CS-mount adapter as a standard mechanical interface could be provided with a large selection of different objectives with different focal length or different field-of-views. The receiver optic in combination with illumination source is one important part in the modular and flexible PMD camera design.

Development Tools and **Software** are complementing the modularity of the design by providing customer with fast digital interfaces and with flexible driver software to implement specific applications. Furthermore the development system in combination with software supports the system with necessary plausibility-checks and calibration. In PMD cameras as in each phase sensitive ToF system nonlinearity of distances, a fixed pattern phase noise (so called FPPN in correlation to fixed pattern noise in 2D imagers) and distance dependence on incoming illuminating (the so called black-white drift) could be determined. These effects are determined by PMDTec in cooperation with University of Siegen and first promising results for calibration algorithms have been published [12].

3. PMD PRINCIPLE

3.1 Operation principle of PMD

This section describes the principle of a simplified PMD sensor realized in CMOS technology. As the complete mixing process of the electric and optical signal takes place within each pixel we call the PMD elements “smart pixels”. Figure 5a) shows an illustration of a single pixel 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 light sensitive 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 PMD pixel the movement of generated charge carriers can be controlled by the reference signal applied to the modulation gates. This way one can influence a charge transport to the left or to the right side. The potential distribution in the surface region is influenced by these push-pull voltages leading to a “dynamic seesaw” for the generated charge carriers [6].

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 voltages at the readout nodes are the same as those shown in figure 5b).

If the incident light is modulated (e.g. also as a rectangular signal) with the same signal as the PMD receiver the difference of voltages of both output nodes is directly dependent on the phase delay between light and pixel modulation (figure 5c). This data can be used to calculate the distance from a light-reflecting object to the sensor [11].

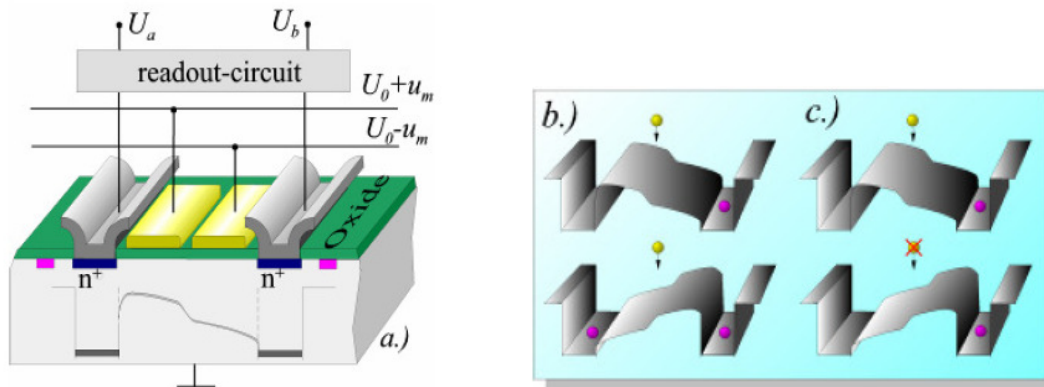


Figure 5: Operation principle of the photonic mixer device (PMD)

3.2 Analysis of the ACF (autocorrelation function)

To calculate the distance between target and camera, the autocorrelation function of electrical and optical signal is analyzed by a phase-shift algorithm (figure 6). Using four samples A_1 , A_2 , A_3 and A_4 - each shifted by 90 degrees - the phase, which is proportional to the distance, can be calculated using the following equation.

$$\varphi = \arctan\left(\frac{A_1 - A_3}{A_2 - A_4}\right) \tag{equation 3.1}$$

In addition to the phase-shift of the signal, two other values can be extracted. At first, the signal strength of the received signal (amplitude):

$$a = \frac{\sqrt{(A_1 - A_3)^2 + (A_2 - A_4)^2}}{2} \tag{equation 3.2}$$

And the second value, the offset b of the samples, represents the gray-scale value of each pixel.

$$b = \frac{A_1 + A_2 + A_3 + A_4}{4} \quad \text{equation 3.3}$$

The distance d to the target is given by equation 3.4. At a modulation frequency of $f_{\text{mod}}=20\text{MHz}$, for example, the wavelength λ_{mod} is 15 meters. The maximum distance for the target is $d_{\text{max}}=\lambda_{\text{mod}}/2$ because the active illumination has to cover the distance twice: from the sender to the target and back to the sensor chip.

$$d = \frac{c \cdot \varphi}{4\pi \cdot f_{\text{mod}}} \quad \text{equation 3.4}$$

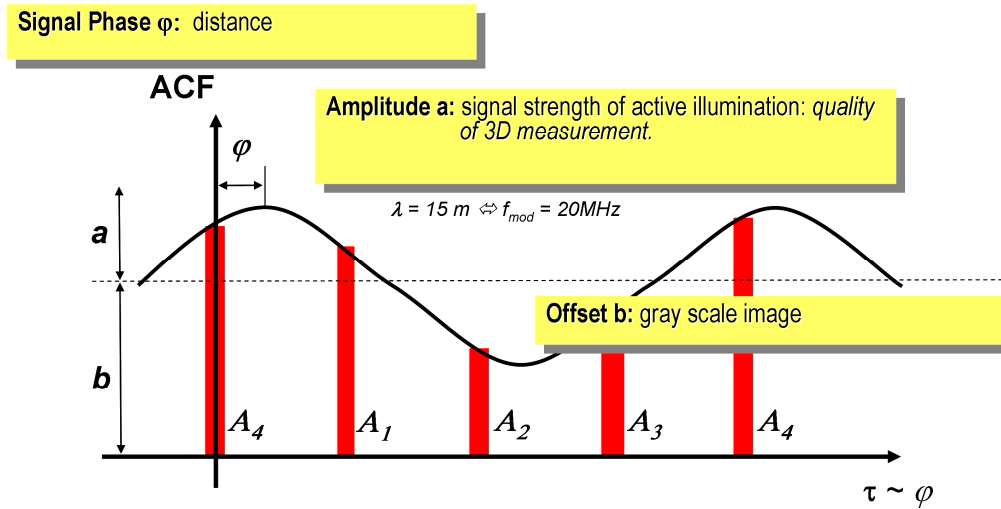


Figure 6: ACF (autocorrelation function), Signal Phase, Amplitude und Offset

Of course, a TOF System has also physical limits concerning accuracy of the measurement. It is obvious that for an active optical measurement system the reliability is directly influenced by the amount of (active) light which arrives at the sensor. In [4,5] the dependency of statistical measurement uncertainty as a function of optical signal strength and system noise is derived. The measurement uncertainty dR of a PMD time of flight system can be calculated as:

$$dR = \frac{1}{\sqrt{N_{\text{phase}}}} \cdot \frac{1}{k_{\text{tot}} \cdot \frac{S}{N}} \cdot \frac{\lambda_{\text{mod}}}{\sqrt{8} \cdot \pi} \quad \text{equation 3.5}$$

Where k_{tot} is the modulation contrast, S is the number of (active) signal electrons, N is the equivalent number of noise electrons (including shot noise of active light, background light and dark current as well as thermal noise, reset noise, system noise and ADC noise), N_{phase} is the number of measurements and λ_{mod} is the wavelength of the modulation signal in meters. An alternative notation of this product of k'_{tot} and S' is fully equivalent, where S' represents the complete number of integrated electrons, including background light and dark current and k'_{tot} represents the overall system contrast, also including dark current and background light offset. Please note that for both cases the product of k_{tot} and S represents the “active signal share” after integration (demodulation amplitude).

All parameters are influenced by each part of modular time-of-flight system described in [11].

4. APPLICATION EXAMPLES

As mentioned in chapter 2, several products have been or will be developed by adapting modular components to the needs of customer.

One very successful example is the efector PMD, a 1D laser distance sensor (figure 7). The efector PMD has been developed together with our partner and shareholder ifm electronic gmbh and ranks among the most successful products of ifm since the company was founded in 1969. A wide field of applications could be solved with this new sensor. To mentioned one example: More than 1 billion passengers pass the airports worldwide. Transportation of luggage is a huge logistic challenge and up to now, pieces of luggage are adjusted by airport employees to pass the security check parallelly.

One customer of ifm electronic has developed a transportation unit which adjusts luggage automatically. Eight distance sensors efector PMD are used for recognition of the position. Distorted luggage is turned as long as all sensors measure the same distance to the object. In this case, the luggage is adjusted and could pass the x-ray security gate.

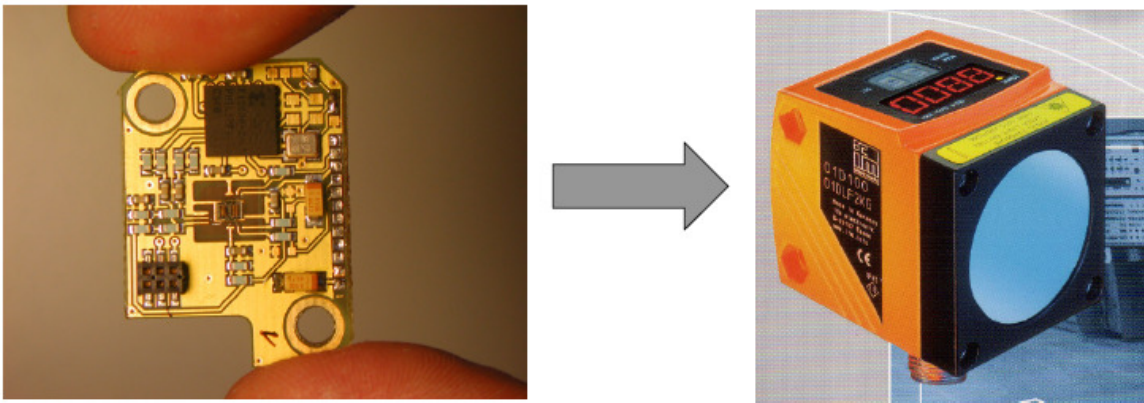


Figure 7: efector PMD: Module with PMD Sensor and finished product

While the 1D distance sensor is very successful in the market, a second industrial sensor is already under development: The first 3D serial ToF camera with 64x48 pixels for industrial applications.

PMD technology, as described above, does not only deliver pure distance information but also permits the validation of geometric characteristics such as volume, fill level or surface area.

The necessary object recognition algorithms run on an embedded system in the intelligent sensor. This makes applications possible that could not be realized up to now or only with high effort. Examples for such applications include bulk goods counting, occupied case detection and quick volume detection within a logistics centre.

Additionally, a new 12 million Euro german government project called “Lynkeus” has started in 2007 for several robotic applications like bin-picking problem, human-machine-interaction and autonomous vehicles.

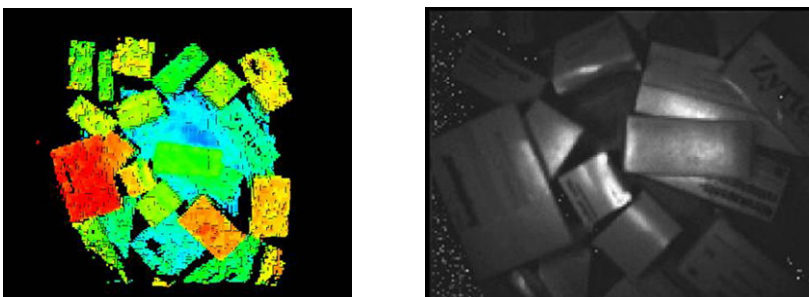


Figure 8: Typical scenario for bin-picking problem (“Griff in die Kiste”)

Partners in this consortium are robotic OEMs, and industrial sensor manufacturers, different supplier companies specialized on optics and illumination sources and several companies and institutes, which implements algorithm for the different applications. Aim of Lynkeus is to improve

the whole value chain of a small integrated real-time PMD camera system including a high resolution PMD chip to realized a intelligent object recognition and environment detection. Next to industrial products and robotics activities there is much activity for automotive application. A rough environment for optical systems in those applications requires hard specification and innovative solutions for a time-of-flight camera system, which is depicted in figure 9. This A-Muster camera is designed to demonstrate solutions for several front view application like Stop&Go, PreCrash and Pedestrian Safety therefore additional IR-illumination sources are implemented inside the head lights to increase transmitted power and measurement range respectively. Other design spaces for illumination are determined and tested until beginning of 2007.

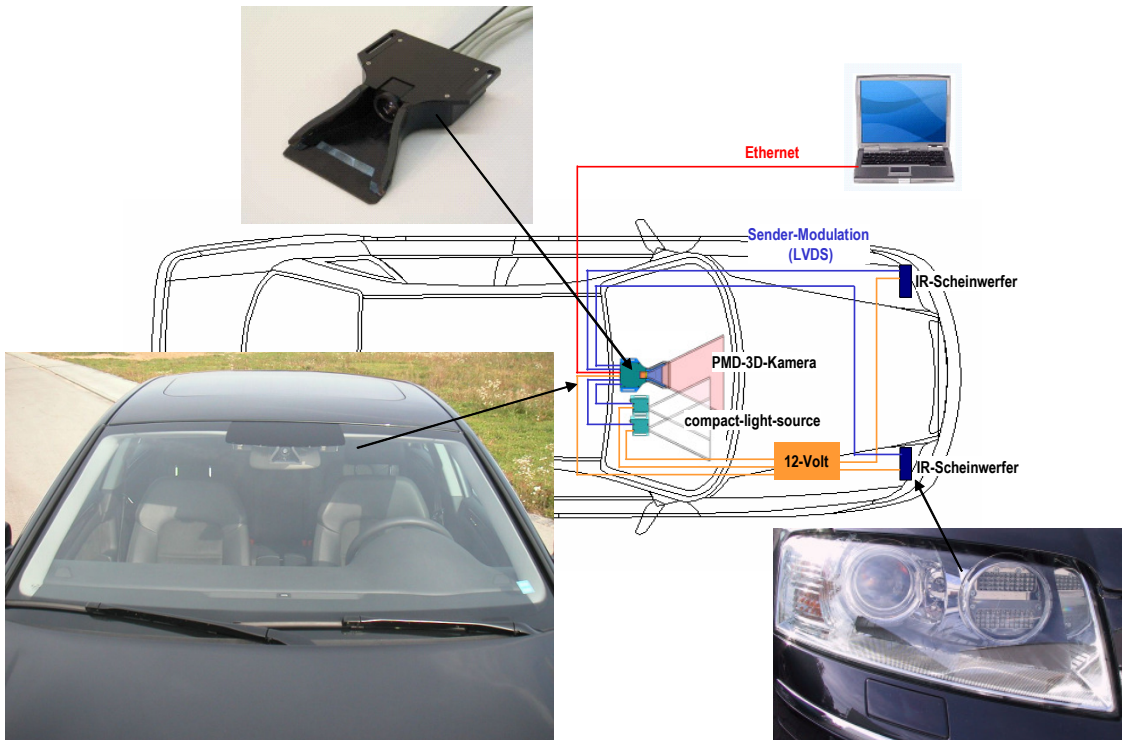


Figure 9: Test car from 2006 with an A-sample PMD camera system for pedestrian safety or Pre-Crash detection respectively.

An actual sensor is available with the specification depicted in figure 10. The measurement range depends on illumination source. A range of 10m is realized by an Illumination Source with 1W optical power next to the camera system. A measurement range of above 35m could be realized with illumination source in front of the car (i.g. inside the head lights) with and optical power more than 8W.

	Measurement Range	10m / 35m
	Field of view	52° vertical 18° horizontal
	DataUpdate Rate	60Hz
	Distance Resolution per Pixel	±10cm
	Operation Current of camera module	Max. 600mA
	Temperature Range	-10° to 85°C)
	Operating Voltage	11 bis 18 DC

Figure 10: Technical Specification of the A-sample

5. FURTHER OPTIONS FOR A NEW GENERATION OF TOF SYSTEMS

Even if the lateral resolution is sufficient for most applications, there is sometimes the demand on even higher resolution PMD matrices. First developments in this direction are a combination of 2D and 3D camera. The high resolution 2D image is matched on the TOF 3D image. As distinguish from well known stereo vision system with two or more high resolution 2D cameras, the correspondence problem is solved directly. Because a PMD camera delivers the distance of each Pixel, an elaborated and error-prone search for corresponding pixels is avoided. Therefore calculation power of a camera system could be used for application algorithms and not for reproducing a 3D data.

In figure 11, such a matched 2D/3D image is depicted.



Figure 11: Matching of a high resolution 2D grey scale image with an 3-dimensional depth map.

6. CONCLUSION

Time-Of-Flight systems based on the PMD-principle give the possibility of fast 3D measurement with customizable resolutions depending on the application. With a modular system customer get the possibility to implement a specific solution for his market. Some successful examples in industrial and automotive markets illustrate the flexible design of PMD technology.

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