Modeling and Simulation of Light Propagation for Multistatic 3D PMD-Camera and –illuminator Constellations

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Abstract

The progress in high-speed technical 3D-Vision development opens up completely new possibilities for many new and special kinds of applications. To make a conclusion whether uncommon or novel PMD sensor designs and -illuminator constellations will work in practice as expected, a simulation of the intended configurations is fundamental and supports the development of further 3D-Vision technologies.

This paper presents a modeling and simulation approach for light propagation for mono- and multistatic 3D camera systems and illuminator constellations. The simulator allows calculating the light intensity and the phased array for arbitrary scenarios with coherent and incoherent modulated light sources which, amongst others, are used in PMD cameras for environment illumination. The results of some simulated scenario including an error analysis and the comparison with real data are discussed.

Keywords: PMD, Simulation, Modeling, Light Propagation, Multistatic

Presenting Author's biography

Valerij Peters received the Diploma degree in electrical engineering from the University of Siegen in 2002. He is currently scientific assistant in the Center of Sensor Systems (ZESS) at the University of Siegen. His current research interests include 3D Vision, mono- and bistatic signal theory and simulations, multi sensor data fusion, computer based 2D and 3D sensor simulations, Synthetic Aperture Radar (SAR) raw signal simulations.

1 Introduction

In recent years the progress in high-speed technical 3D-Vision development aroused increasing interest in many industrial, automotive and safety-related applications. Especially the newest 3D camera generation with up to 41000 pixels (e.g. PMD[vision]® CamCube 2.0, MESA Imaging SR4000) and the ability to capture the entire environment in three dimensions open up completely new possibilities for many new kinds of applications in the fields of biometrics, mobile robotics machine vision, navigation, positioning etc.

Basically a 3D PMD[1] camera consists of two main parts - the camera itself with a CMOS technology based PMD-Sensor and the illuminator(s), which is responsible for environment illumination. Due to the design and required specified illuminated light intensity the illuminator(s) is mostly higher dimensioned and, hence, mounted outside of the camera. The illuminator consists of LEDs which transmit a signal regarding to a defined modulation frequency. In general there are LEDs in use that emit infrared light of the wavelength area of about 750-850nm. The light sources are intensity modulated so that they send out pulses of light that illuminate all target objects of the environment in which the camera is working. It is also possible to use other kind of LEDs. For PMD-applications that take place under water it is advantageous to use LEDs that emit green light caused by a favorable light detectability.

From the targets the emitted signal will be reflected back to the PMD sensor. The distance to the target can be calculated due to the proportionality to the signal's time of flight. The latest time of flight sensors as the PMD-sensor do not directly measure the time of flight but the difference of phase between the emitted and the received signal. This delivers accurate results especially in the near range area when the time of flight is very low. Besides the above mentioned properties, PMD-sensors have the ability to disable ambient incident light. For that purpose the PMD-sensor itself is connected to the modulation frequency of the illuminator. By the use of SBI (Suppression of Background Illumination) there is the possibility to filter only the correlative parts of the received light. The dynamic of each pixel then is completely available for the active light of the illuminators. This allows the PMD-camera to work at fully solar radiation of 150klux.

Additionally to the common light intensity image of the scene, the distance to the target objects can be identified and displayed (color coded distance picture). That means that a PMD camera delivers in one step depth information as well as gray values for each pixel.

[1] PMD (Photonic Mixer Device) is a real-time, time-of-flight 3D imaging sensor, developed in ZESS at the University of Siegen.

The construction-conditioned quasi monostatic constellation of the above-mentioned 3D cameras is not always advantageous in applications. Strictly speaking in near-range applications the illuminator and the sensor cannot be considered as a monostatic constellation, where both should be mounted at the same position in 3D. In this context we speak about solutions in which the sensor and the illuminator are positioned independently.

In such cases a simulation is useful, to make a conclusion whether the designated constellation of PMD-sensor and illuminator constellations will work in practice as intended.

The PMD-camera-simulator developed by ZESS [1] has the ability to calculate a theoretical PMD-sensor response from a given 3D scenario (in form of target points). The operator has the possibility to create a simulation environment according to his requirements. He can specify the number and size of PMD-sensors, PMD-illuminators and target points. All of them can be arranged completely independently.

To reduce the time-expensive data processing it is useful to make a pre-analysis after the simulation environment has been created. Due to the fact that some of the target points do not reflect enough illuminated light to be detected by the sensor or are completely hidden by other target points, it is not required to subject them to further calculation. Those target points do not contribute to the sensor response.

Regarding these facts leads to the consequence that it is necessary to be aware of the light intensity at each target point, to reject dispensable points from the scenario before doing the sensor response calculation.

2 Approach

A two-step method for the analysis of a complex scenario, which will be presented in this paper, leads on the one hand to a massive reduction of processing time of the PMD simulator and on the other hand it provides a pre-processed 3D scene in respect of time- and position-depended point target illumination.

For this purpose the light intensity simulator as a part of the ZESS-PMD-simulator has been developed.

As a result the simulation software delivers the light intensity (amplitude) at each selected target point of a defined 3D scene as a function of time. Additionally, target points which do not influence the response of the PMD sensor are refused.

The following parameters in the simulator can be modified by the user at any time to obtain accurate results:

- Configuration, orientation and movement of different illuminators and target objects in a global coordinate system
- The number, position and characteristics adjustment of the LEDs of each illuminator
- The modulation frequency for each illuminator
- The maximum light intensity for each LED illuminator
- The transmitted light intensity as a function of the illumination angle (LED characteristics, Fig.7)
- Influence on the interference phenomena of electromagnetic waves (simulation of coherent and incoherent light sources)

2.1 Simulation Environment

The simulation starts by creating a simulation environment, in which each object is specified by its coordinates. Additionally, the working parameters need to be provided. There are (almost) no restrictions in designing the PMD-components and target objects. Even unusual forms of PMD-sensors with a free eligible pixel size or illuminators with aslant arranged LEDs can be simulated.

In Fig. 1 the architecture of the preprocessing unit of the modular light propagation simulator is presented. After the coordinates of all objects are provided to the simulation software, the orientation and position of each target object in the 3D scene, the moving trajectories, the illuminators' design and some other parameters can be changed and specified by the user. The program then displays the complete simulation environment.

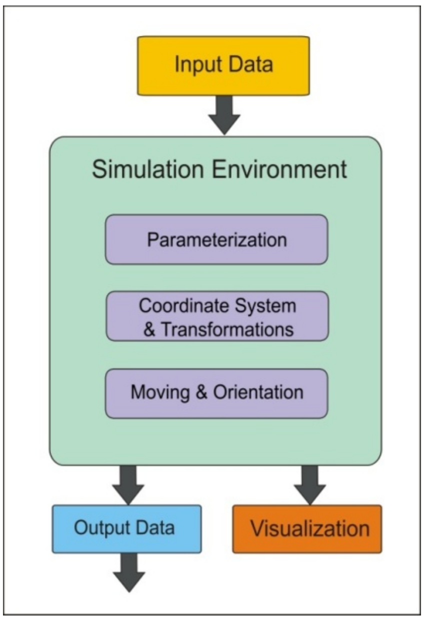

Fig.1: Architecture of the preprocessing unit of the modular light propagation simulator

To obtain a complete simulation environment there has to be at least one illuminator in the scene. The same is true for target points. As described above, the target points reflect a part of the incoming light back to the PMD-sensor. Without these essential components the PMD-technology will not work.
The following picture shows an exemplary scenario as a snap-shot. The target point P is illuminated by three illuminators with different spatial adjustments.

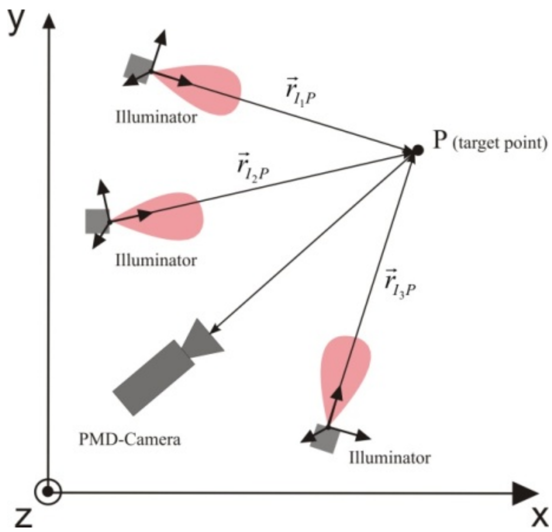

Fig.2: Example of a scenario with three different illuminators and one PMD-camera (PMD-sensor)

2.2 Environment Preprocessing

Based on the created simulation environment the first analysis of the given scene takes place. The coordinates of hidden target objects which do not contribute to the sensor response will be refused. To achieve this, the light rays from the LEDs to the target points will be analyzed. The light propagation is presumed to be linear. It is possible that there is more than one target object lying in the direction of the light ray. The nearest target object which is hit by a light ray on its way from the source will be the only one that reflects light back. The light ray then ends at this point. Behind this target point there will be shadow so that other target objects on the line of the light ray will not be illuminated.
The figure below shows a simple example of a simulation environment. It contains one LED as the illuminator and two identical detection panels on which the light intensity should be simulated. The coordinates of all objects are arranged in the x,y-plane. The distance between them, which is given by the z-value, differs. The detection panel in the foreground hides some part of the detection panel arranged behind so that there are target points on which no light arrives.

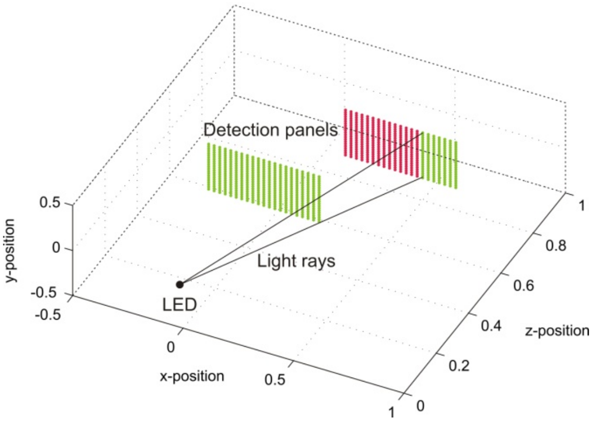

Fig.3: Arrangement of an illuminator and detection panels in a simulation environment

All target points colored in green are directly illuminated by the LED. The red colored points are located in the shadow of the first detection panel. The displayed light rays indicate where the influence of the shadow zone is determined.
The calculation of hidden target points is a very computationally intensive task. For each light ray it has to be checked which of the objects, achieved from the light ray, features the shortest distance to the light source.
There are several methods to accelerate these operations. It is advantageous to execute such calculations on a GPU[2] which is specialized for calculations that can be done in a parallel process. In connection with these analyses of the 3D scene, there are further calculation procedures in development. One of the approaches is based on finding abstract envelopes around complex target objects. There is no longer a comparison of every light ray with every target point required. It is only necessary to check whether there exists an intersection point between a light ray and one of the planes within the above mentioned envelopes. This leads to a massive reduction of the calculation process.
The specified method is qualified for both, doing a very fast calculation and obtaining very exact results of the hidden target points. Depending on how accurate the real target objects should be represented by envelopes, the operator can either choose a very fast or a very exact way of calculation.

2.3 Modular Light Propagation Simulator

After the pre-analysis of the 3D scene the calculations of the light intensity of the remaining target points take place. This calculation consists of several parts, which are mentioned in the figure below:

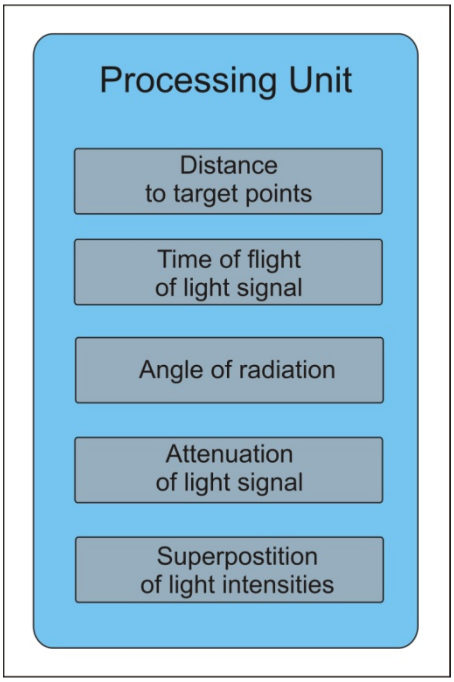

Fig.4: Architecture of the modular light propagation simulator

All operations are conducted in a vector based format. The coordinates of all objects within the simulation environment directly correspond to their position vectors. The light rays are expressed as direction vectors from the light source to the target points. The distance between a LED and a target point then comes up to the absolute value of the direction vector.
The time of flight t can be calculated on basis of the relation $t_d = \frac{r}{c}$ in which r denotes the distance and c the light's time of flight. As mentioned earlier, the emitted light signal is a modulated signal. A trapezoid-function is a possible way to emulate the intensity modulation. The incoming light signal at a target point is ideally identical to the emitted signal except for a time delay of t_d and a medium-specific weighting-factor.
The following picture shows an illuminator plane comprising three LEDs and a target point named P. Furthermore the main beam directions of all LEDs as well as the propagation direction of the LEDs' emitted light to the target point are plotted. From the figure arises that the target point has various distances to each of the LEDs. Moreover the angle of radiation differs in each case.

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[2] Graphics Processing Unit

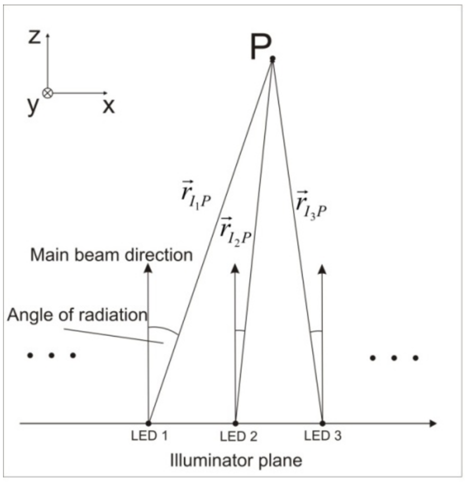

Fig.5: Illustration of an illuminator–target point configuration with respect to the light propagation

Due to the directional characteristic of the light sources there is a bunching of light in one advantage direction called main beam direction. The following figure shows a PMD camera with six LEDs as illuminators. The target point P is illuminated by multiple LEDs but is not located in the light cones of all LEDs.

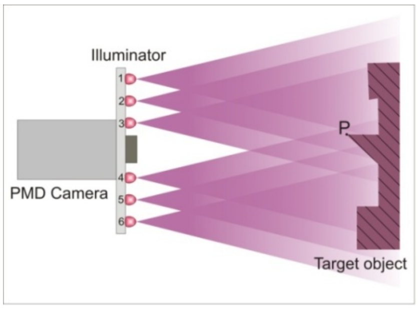

Fig.6: Moiré effect due to the non-uniform illumination

The more a target point is located at the margin of a light cone, the less will be the light amount arriving. This fact is considered by calculating the angle of radiation. This angle equates to the angle among the vector of the LED's main beam direction and the direction vector between the target point and the LED.

According to the type of light source used, the directional characteristic is different. The following figure presents an example of a directional characteristic of a LED shown in polar coordinates.

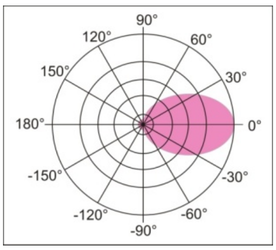

Fig.7: Example of a directional characteristic of a LED in polar coordinates

In the software the attenuation of the light output is considered by a functional relation between the angle of radiation and a weighting factor.

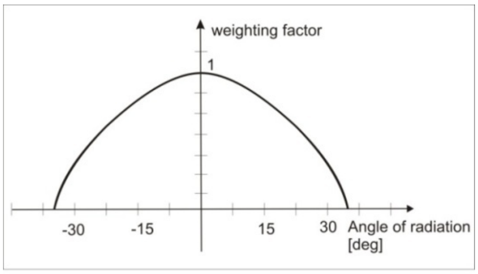

Fig.8: Example of a weighting factor function

This function can either be manually provided by a table consisting of a dataset relating to a known directional characteristic or it will be fitted by a $cos^n(\propto)$ – function. The factor n controls the maximum angle of radiation. $\propto$ is the angle of radiation for which the weighting factor should be calculated.

Furthermore there is an attenuation of the emitted signal at the point P which depends on the distance between the illuminator and the target point. The light intensity declines by the factor of $\frac{1}{(1+r)^2}$. The factor $(1+r)^2$ of the denominator ensures that the value of the weighting factor will always be less than one in the case of small distances $r < 1m$ because the denominator is always greater than the numerator.

Thus, there is a diminished light intensity (amplitude) measured at a target point.

The attenuation is emulated by weighting factors. The light intensity at a target point is at first calculated in an ideal case when there is no attenuation at all. For each point these factors are calculated individually before the values of the light intensity get assessed with the respective factor. Usually the entire attenuation depends on the distance and the angle of radiation. There are no limits to include other influences which decrease the light intensity (e.g. medium: water, oil etc.)

The light intensity at the target point P is a superposition of all light waves arriving at P and is given by

$$I(P) = \sum_{m=1}^{M} I_m \cdot \frac{J_m(P)}{r^2_{I_mP}}$$

I_m is the specific damping factor of the light emitting diode m (depending on the quality of the diode, characteristics of the optical wave propagation medium etc.). $J_m(P)$ is the diagram based value of the illumination in the direction of the vector $\vec{r}_{I_mP}$. M is equal to the number of light sources, which can illuminate the point P.

The calculation of the superposition depends on the kind of light sources. The presented simulation software is not specially designed for PMD camera illuminators only. The propagation of all kinds of electromagnetic wave emitting sources can be simulated. The simulator is able to calculate not only the intensity in an arbitrary point, but also the phase components of the modulated illuminator signals (phased array) for arbitrary scenarios.

3 Simulation Results

The following example shows an exemplary simulation environment consisting of two light sources and one detection panel. The light cones are directly aligned to the detection panel. The detection panel consists of various single target points which are arranged in a rectangular form in one layer. In order to determine the distribution of the light intensity, this kind of detection arrangement is advantageous. In the single target points the light intensity is calculated exactly. Among them, the value of the light intensity will be approached by the help of an interpolation function.

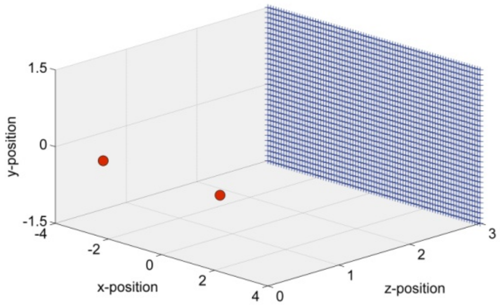

Fig.9: Arrangement of illuminators and detection panel in the simulation environment

The emitted light of the two illuminators is incoherent as it is by the use of LEDs. The figure below shows the distribution of the light intensity on the detection panel.

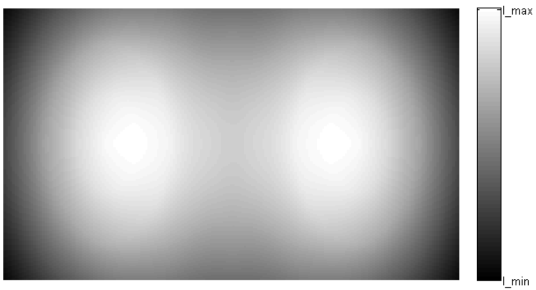

Fig.10: Simulated light intensity distribution of two incoherent light sources

By the simulation of sources which emit coherent light (e.g. laser) or other kinds of coherent radiation (e.g. microwave exciters) the appearance of interference phenomena has to be considered. The following figure shows a simulated amplitude distribution on a detection panel. The demonstrated interference pattern is caused by two coherent radiation sources which are aligned directly to the detection panel. The emitted signal is not especially modulated.

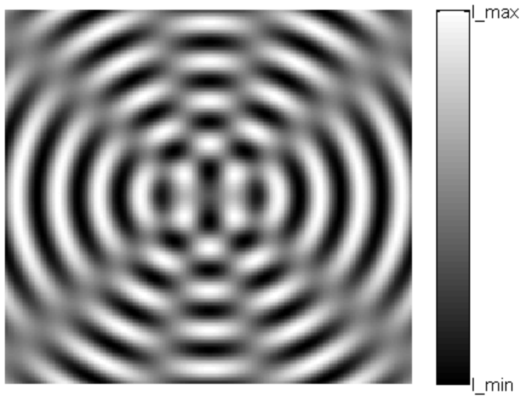

Fig.11: Simulated amplitude distribution of two microwave emitting exciters (coherent light sources)

The light signal of a laser in that case is comparable to an amplitude modulated (AM) signal. The carrier frequency equates the frequency of the light (e.g. infrared light). The amplitude of the carrier wave is varying in relation to an information signal. As mentioned earlier, the light sources are intensity modulated. This signal corresponds to the information signal which then varies the carrier frequency according to his parameters (e.g. form, frequency).

An amplitude modulated signal is mathematically expressed by trigonometrical functions.

For the calculations in this software it is useful to describe all harmonic waves in form of complex numbers. A complex number can visually be represented as a vector, pointing to the number in the complex plane. The characteristics of this vector are his absolute value and his angle, measured from the positive real axis.

If this vector rotates one time a complete turn and the angle represents the horizontal axis of a new coordinate system, the value of the imaginary axis will describe a harmonic sine wave. This is shown in the following figure.

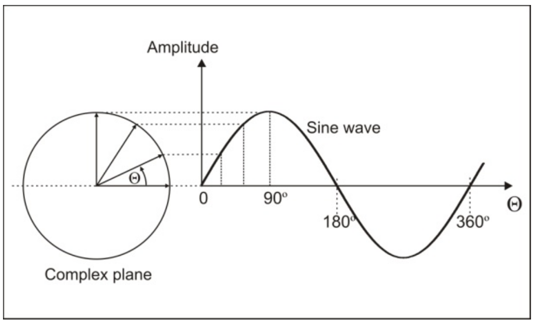

Fig.12: Conversion: sine-wave ↔ vector form

The conversion can easily be done in both directions. A sine wave, as illustrated in the picture, leads to a rotation vector of a constant length. In the case of an amplitude modulated signal, the vector (AM-vector) varies his length. A variation of the vector length without influence on his direction is used in a double sideband amplitude modulation.

The length variation is done in the way that the total AM-vector is assembled of the vector (V_C) which represents the carrier frequency and two vectors (V_S) which represent the sideband frequency (envelope). Each of these vectors has a constant length, but differs in their direction. The envelope vectors V_C both have half the length of the maximum amplitude deflection and rotate with the rotational frequency of the information signal $\omega_S = 2\pi \cdot f_S$ in opposite directions. Their instantaneous positions have to be adapted to the vector V_C of the carrier frequency. The vectors V_S are reflected about the axis of the vector V_C at each point of time. This fact causes that the addition of these three vectors produces the complete AM-vector V_{AM} that has the same direction as the vector V_C of the carrier frequency. The parameters (length and rotational position) represent the amplitude modulated signal at the selected point of time. The following figure demonstrates all these procedures in a graphically way. The construction of the Vector V_{AM} is shown for two different points of time.

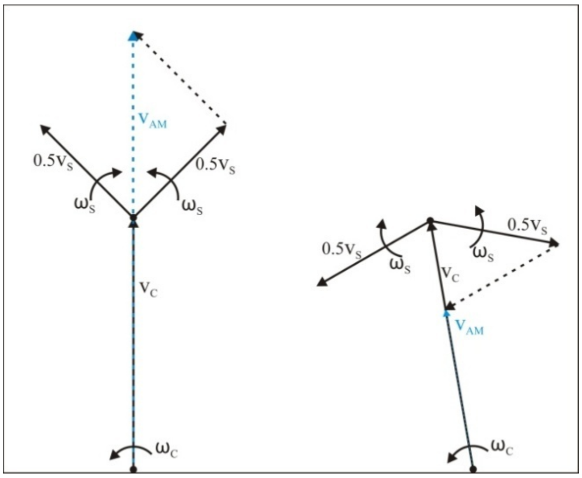

Fig.13: Generation of the AM-vector

In this way, an amplitude modulated signal can be represented by a vector with a specified length, which depends on the information signal.

The superposition of the incoming waves in a target point can easily be calculated when the waves are represented as vectors. To calculate the light intensity in a target point, the wave interaction of all possible light sources needs to be considered.

At a fixed point of time a wave arriving at a target point is characterized by the instantaneous phase and the instantaneous amplitude. In the case of multiple coherent illuminators in the scene, there are multiple waves arriving at a target point. The overall phase and amplitude occurs by the addition of the vectors of all waves at the target point. The final vector contains the information about the overall phase and amplitude at the target point.

The following figure demonstrates the simulated amplitude distribution generated by two coherent radiation sources, which are amplitude modulated. The information signal in this case is a cosine function. The frequency of the carrier signal (infrared light: 10-100 THz) is up to five million times greater than the frequency of the information signal (intensity modulation frequency: 20Mhz).

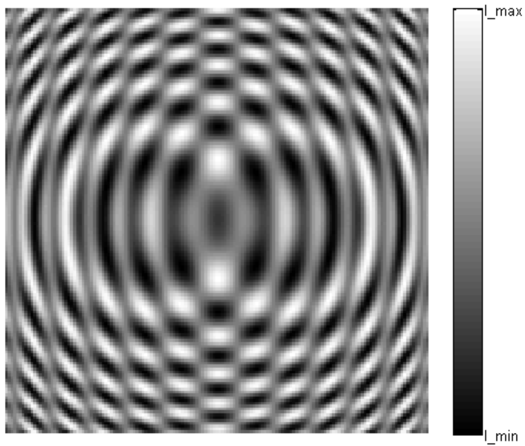

Fig.14: Simulated amplitude distribution of two AM-modulated microwave emitting exciters (coherent light sources)

4 Comparison with Real Data

To make a conclusion about the suitability of a simulation software like this light intensity simulator, the simulated results have to be verified. This can be done by a comparison of simulated results with real measured data. If the accordance is accurate, it is an indication that the simulation software will generate accurate results as well in various simulation configurations and with different simulation parameters. For easier result demonstration and data presentation in this paper, the light intensity of only one light source will be considered. Illustration of overlapping of more than 100 LEDs by the use of multiple illuminators, which are usually used in reality, could be less representative.

This chapter deals with experiments to verify the simulated results. The main aspects to be analyzed are:

- Absolute value of the light intensity prevailing at a defined point
- Attenuation of the light intensity with respect to distance and angle of radiation
- Superposition of the light intensity by multiple light sources

One suitable experiment to confirm the simulated results is the measuring of the light intensity on a detection panel of an incoherent light source. Therefore, one LED is positioned in a defined distance in front of the detection panel and its light cone is directly aligned to the detection panel. To obtain a better bunching of the light cone there is a collimator attached to the light source. This leads to a more precise directive efficiency of the light source. The directional characteristic of the light source is known and the LED is actuated by a defined electric current, so that the overall light output is known as well. The following picture illustrates the measured distribution of the light intensity as grey image.

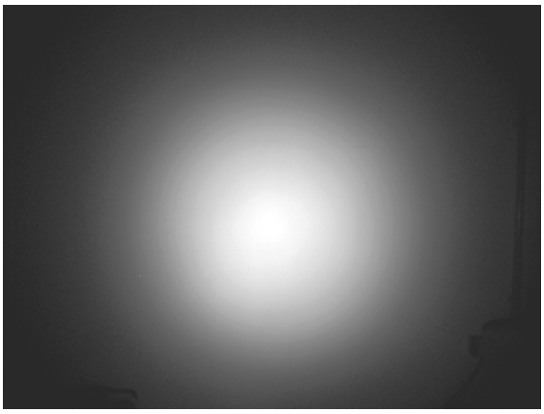

Fig.15: Measured distribution of the light intensity

This experiment delivers measured raw data to be processed in further steps. The dataset can be presented as three dimensional surface plot. The x,y-plane constitutes the plane of the detection panel. The z-value then represents the size of the measured light intensity. In this case it is normalized to the value of one. This conduces to a better comparability of the distribution of the light intensity.

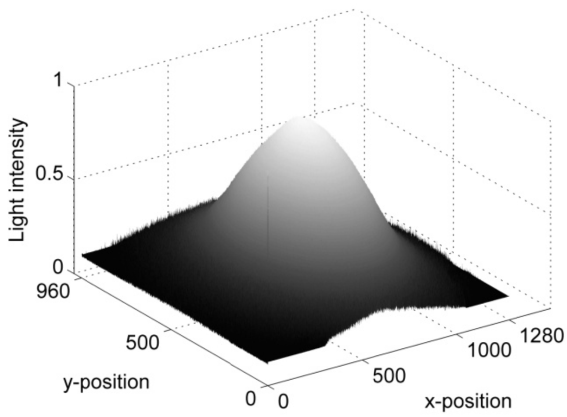

Fig.16: Three dimensional plot of the measured distribution of the light intensity

In a first step this dataset can be compared graphically with simulated results of the experiment's parameters.

Due to the fact of a rotation-symmetric directional characteristic of the light source, the distribution of the light intensity is nearly rotation-symmetric (on a z-axis in the center of the plot) as well. The following figure demonstrates this fact on the basis of a top view of the figure 16. The distribution of the light intensity in the x,y-plane is presented in different colors depending on the value of the measured light intensity (z-value).

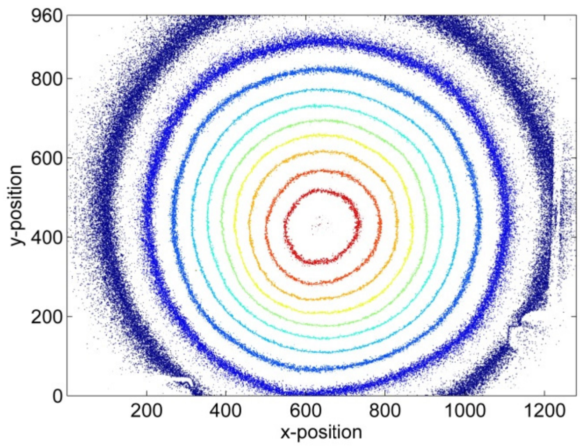

Fig.17: Colored light intensity distribution on different intensity levels (cuts through the figure 16)

For better result comparison in a first approximation it is allowed to reduce the three dimensional data (fig.16) to a two dimensional function by doing a cut through the center of the plot along the y or x axis (due to rotation symmetry). The following figure shows the distribution of the measured light intensity of figure 16 reduced into a two dimensional coordinate system (blue graph). Additionally, the mapped red graph represents the results of a simulation of the experiment considering ideal conditions.

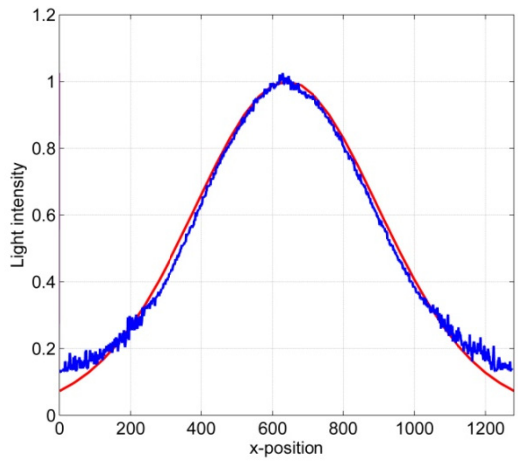

Fig.18: Comparison of simulated and measured data of the light intensity

In an ideal case both of the graphs should be lying upon each other. Mainly in the area of the maximum value of the functions this condition is achieved. There are variations of the two functions that become more obvious to either side of the diagram.

This fact is mainly caused due to fabrication tolerances of the used electronic devices and variations due to experimental adjustments. As an example, the directional characteristic of a LED can be considered. If the angle of radiation is not exactly represented by the simulation program, it will have an influence on the light intensity mainly on the margin of the detected light cone.

All electronic devices like the used light source and the experimental environment are succumbed to technical tolerances. Simulation software however, can produce results of ideal electronic devices in ideal environments. On the other hand it is also able to pay regard to technical limited tolerances and miscellaneous influences.

The operator can choose whether to simulate an ideal scenario to compare in how far his deployed devices approximate an ideal case or to simulate with concrete data of known technical tolerances whether an intended scenario will work in practice.

5 Conclusions and Future Works

This paper presents a modeling and simulation approach for light propagation for mono- and multistatic 3D camera systems and illuminator constellations. The simulator allows calculating the light intensity and the phased array for arbitrary scenarios with coherent and incoherent modulated light sources which, amongst others, are used in PMD cameras for environment illumination. The results of some simulated scenario including an error analysis and the comparison with real data are discussed.

Future work will focus on refinements of the simulator including arbitrary motions of target objects and illuminators in a simulated scenario along a specified trajectory. Furthermore, the findings of this approach will be integrated into the existing PMD-simulation software [1]. Additionally, further simulation results will be compared and verified with real measurement data.

Acknowledgment

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