THE 3D-TOF-CAMERA AS AN INNOVATIVE AND LOW-COST TOOL FOR RECORDING, SURVEYING AND VISUALISATION - A SHORT DRAFT AND SOME FIRST EXPERIENCES –

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ABSTRACT:

A traditional camera delivers a two-dimensional image of the surrounding world. The 3D-time-of-flight camera (ToF) - which was developed in the last decade - captures not only two, but three dimensions in one step by measuring the distance from each pixel of the camera chip to the object. This way a large number of coordinates is determined for each exposure – a so called frame. More than 20 frames per second may be taken. The result is a point cloud similar to the familiar data gathered via terrestrial laserscanning (TLS). However, some fundamental differences concerning gathering data and interacting with the instrument have to be discussed.

Since handling is as simple as using a 2D-camera - making new ways of 3D-recording possible - there is huge potential for the development of new user-friendly measuring tools. Especially the introduction of the 3D-camera as a surveying instrument for architectural documentation is of interest. However, the particular method utilized to generate the point-cloud raises serious questions regarding the quality of the data.

All information is presented here with the further development of the 3D-camera in mind. The on-hand experience gained employing the current generation 3D-cameras can be applied to subsequent, improved generations. A major intention of this paper is to familiarise the reader with the new device, its problems and possibilities for its practical application.

1. WHY TO USE A 3D-CAMERA IN THE FIRST PLACE

When using a 3D-camera three specific reference values are of increased interest: The accuracy of coordinates, the resolution of the recording chip (number of pixels) and the maximum range procurable. With the development of the latest generation of 3D-cameras much progress has been made in regard to these three items: Accuracy is now in the range of a few centimetres, resolution goes up to 40k pixels and the maximum distance was raised to about 20m. In light of these developments the question whether the 3D-camera may be used as an instrument for surveying and recording is worth investigating. This may be done by extrapolating from the technical specifications of currently available 3D-cameras into the near future, which will most certainly bring higher resolution, increased accuracy and an expanded maximum distance. Further developments of this kind will be realised soon as prospective customers exist in the field of robotics, vehicle construction and many more areas. The main questions are as follows:

1. Are there any fundamental problems in the process of recording architecture?
2. Which new possibilities for recording of geometry and for visualisation purposes arise for practical work?
3. Is the proposed 2D- / 3D-system capable to replace current devices?

2. CHARACTERISTICS OF A 3D-PMD-CAMERA

2.1 Some general remarks

In order to answer the aforementioned main questions it has not been necessary to utilize the very latest generation of 3D-cameras. However, the device used for testing needed to meet some minimum requirements, which are sufficient short-term temperature-stability as well as adequate daylight suppression. Due to its high performance in the latter area a 3k camera of PMD-technologies (Siegen, Germany) was selected. This model, however, is soon to be succeeded by the camera 2.0 (41k). Figure 1 shows 2.0 - currently being the camera with the highest pixel-resolution available - 205 x 205 pixels - as well as the model PMD 3k with a 2D-colour-camera placed on top.

Figure 1a: 3D-camera 2.0, 41k (PMD-Technologies)
Figure 1b: 3D-camera 3k (PMD-Technologies) mounted with 2D-camera

On both sides of the 3D-camera's cubes diode arrays are mounted emitting an amplitude-modulated IR-light that illuminates the whole scene to be captured. Apart from the distances (resp. coordinates) and the grey-values (intensities) the signal-amplitudes of the returned signals are registered for each pixel as well. Additionally, the 2D- / 3D-camera system of Bochum University delivers a colour-image with higher resolution. The lateral positions of the pixels on the chip of the 3D-camera and of the colour-camera respectively present polar coordinates together with the distances. They allow the calculation of orthogonal coordinates of the object.

Figure 2 gives examples of the redundant data for the new 41k and for the 2D- / 3D-system. The significant advantage of a higher resolution is obvious.

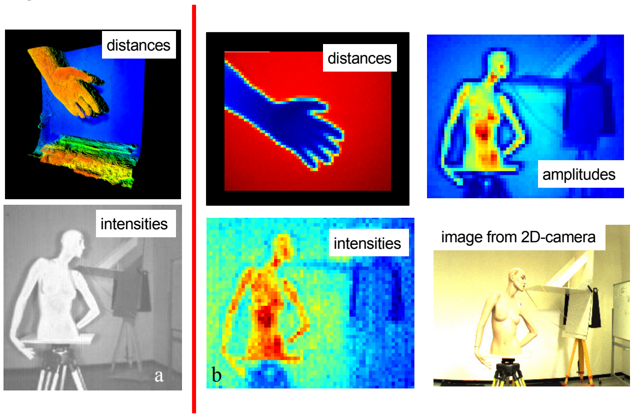

Figure 2a: 3D-camera 2.0 (41k) high resolution
Figure 2b: 3D-camera (3k) mounted with 2D-camera delivering redundant data with low resolution

2.2 Necessary information concerning the distance measurement

Different denotations exist as far as 3D-cameras are concerned: The ToF-camera, the PMD-camera as well as the range imaging camera (RIM or flash radar camera) denotation. They are all targeted at the same type of camera, which is capable of not only detecting intensity like traditional analogue or modern digital cameras, but also the distance of each pixel to the mapped part of the object. A more precise description for the term "range imaging camera" is the term "ToF (TOF)-camera" - indicating that an - optical - signal that has been emitted from the camera is reflected from the object, and also indicating that the reflected part of the emitted signal is then returned to the camera. The flight-time of the signal on its way to the object and back is measured. The ToF is proportional to the distance. However, this is only a very general explanation of electronic distance measurement (EDM). Often a modified method (phase modulation) is used (see fig. 3) that relies on the modulation of the signal strength (the amplitude of the emitted light).

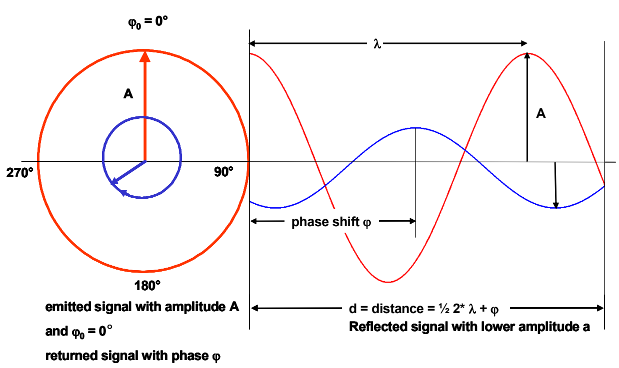

Figure 3: Emitted signal amplitude with phase $\varphi = 0°$ and reflected signal amplitude with phase shift $\varphi = 240°$ in two different forms of presentation

The wavelength λ of one modulation period depends on the modulation frequency f. It is calculated with the – actual - velocity of light c according to $\lambda = c/f$. Most 3D-cameras emit IR-light modulated with f = 20 MHz. In the example, figure 3, the corresponding wavelength of 15m (15m ≈ 300000km/s / 20 x 10^6/s) is reflected at a distance of about 22m. As the light passes to the object and back it runs the double distance, so the result needs to be divided by two. The so-called scale of the distance meter is 15m/2 = 7,5m. The whole distance is $d = ½ (n \times \lambda + \varphi)$, where n is the even multiple of wavelength λ, and φ is the rest of the wavelength which has to be measured, the so called phase difference between the emitted and the returned signal. Thus it follows that when a single modulation frequency is utilized, a direct distinct measurement is possible only up to 7,5m. So a distance of 8,05m would show as 0,55m.

This is a general description how distances can be measured by means of an amplitude modulated signal. The phase measurement –the determination of φ - may be done in different ways. In a 3D-camera it is done using the PMD-effect (Photonic-Mixer-Device (Schwarte)). In this case φ is represented by the difference in charge of two photo-sensitive areas of each respective pixel. Daylight may cause an overload of one of these areas. This may cause serious errors in the distance measured by a ToF-PMD camera, making daylight suppression a fundamental requirement for any 3D-camera to be used for surveying.

2.3 Typical faults of the 3D-camera

The emitted light illuminates the whole 3D-scene at once. This is a very important difference to common electronic distance measurement (EDM). At EDM the distance measuring ray is precisely focussed. The emitted signal amplitude is $D(t_0) = A \cos \omega t_0$. The remitted light signal comprises the distance information in terms of a phase delay φ of the emitted signal: $d(t) = k + a \cos(\omega t + \varphi)$. The phase delay φ contains the distance information. The remitted signal amplitude a is generally much smaller than the sent amplitude A. Additionally, the returning signal may be superimposed with a term k which contains various very different kinds of influences on the signal, like, for instance, a delay that might be caused by daylight or by temperature effects.

In order to understand the difficulties concerning the application of 3D-cameras for architectural recording it is necessary to take a closer look at the instrument's faults.

Most faults are well-known either from the field of photogrammetry – e.g. distortion of pictures – or from electronic distance measurement (EDM) - like phase shifts caused by optical or electrical superimposition of the direct signal with error signals (crosstalk). Most of the faults of 3D-PMD-cameras can be sufficiently modelled in a calibration process. Certain errors may also be suppressed, e.g. daylight via the SBI–circuit (Suppression of Background Light Intensity). The short time random inaccuracy of neighbouring pixels may nowadays be estimated to generally not exceeding ± 1cm in a distance-range of some meters. However, two fundamental influences on the distances have a systematic nature. They can considerably compromise the general accuracy. Both are resulting from unwelcome reflections of the distance measuring signals.

The first influence may be characterised as "internal superimposition", the second as "external superimposition". Superimposition in general terms means that the periodic amplitude modulated signal, which is characterised by frequency, amplitude and phase (see fig. 3), is superimposed by a signal of the same frequency, but with another phase and a generally much lower amplitude. By this process the resulting signal may deviate significantly from the undisturbed one in regards to phase. The amount of the phase shift depends on the phase difference between both signals as well as on the ratio of the amplitudes of the signals (see fig. 4): Signal a with phase φ is superimposed by a small –reflected- signal b with phase φ'. Resulting is a signal with phase φ + τ. The influence of b depends on its individual phase. A phase shift is equivalent to an error in distance. The grave influence of internal and external superimposition respectively on distances measured with the 3D-camera has to be regarded in more detail in order to access the possibilities to use the tool for architectural recording.

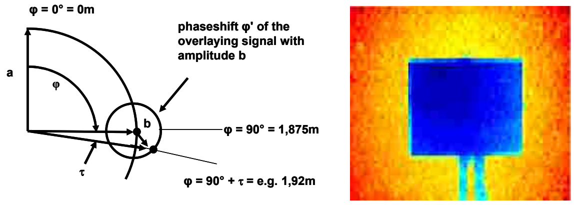

Figure 4: Internal superimposition effecting “distance shadows” that encircle the foreground like a small ribbon

In literature internal superimposition is also characterised as scattering: Small parts of incoming signals are reflected in the camera itself, overlaying the directly reflected incoming signals on their way to the pixel. Thus the stronger direct signal is changed in phase by the reflected parts belonging to neighbouring pixels. Scattering predominantly effects neighbouring pixels with very different phases (see fig. 4).

As the lens of the camera has to be focussed to a fixed distance, e.g. 5m, the blurring effect favours scattering at distances which are shorter or longer than the one the camera is focussed on. However, efforts and advances made by the manufacturers in order to minimize the influence of scattering raise hope that scattering will be overcome in the future. Mathematical models also help to minimize it (Mure-Dubois, 2007).

External superimposition seems to be the most dangerous error. It might very well ultimately prove to fundamentally limit the possibilities to use 3D-cameras for architectural recording. The reason for the occurrence of this effect lies in the fact that the array of diodes emitting the IR-Signal always illuminates the whole scene all at once. Small parts of diffusely reflected light from different parts of the object may superimpose the directly reflected signals on their way back to the camera. The possible influence of diffuse reflections on a wall, causing a phase shift of a directly reflected signal, can be depicted only schematically (see fig. 5, 6).

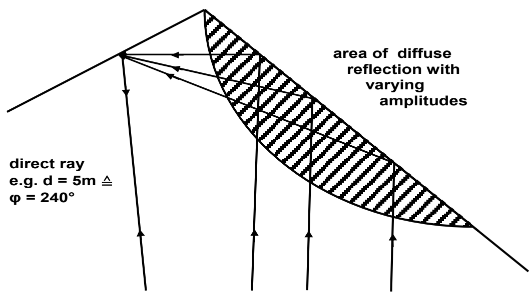

Figure 5: Possible influence of diffuse reflection on direct measurement

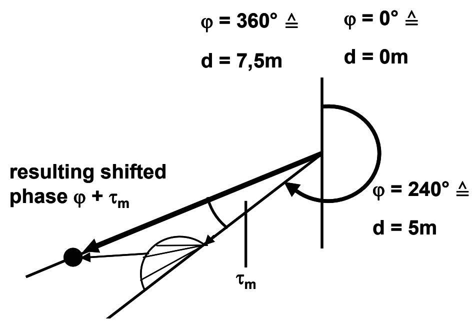

Figure 6: External superimposition effecting a phase delay, respectively a distance shift

The impact of the effect is demonstrated in figure 7. Appropriate measurements were made to a vertical edge, formed by two flexible planes. In the experiment the angle between the planes was modified while the position of the edge itself did not move. The smaller the angle between the planes, the more deformed the edge will appear. However, the distances measured more or less exactly into the centre of the corner, into the intersection of the planes, are those which are less deformed by the superimposition. The amount of error thus may reach considerable amounts.

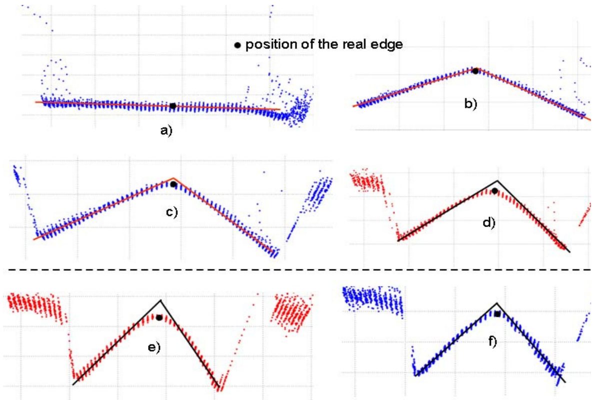

Figure 7: Interaction between topography of the architecture and the measurement with a)…d) increasing deformation with smaller angle; e),f) same angle but f) one plane less reflecting

3. PRACTICAL USE OF THE 2D- / 3D-SYSTEM

The examples prove the wide range of possibilities inherent in the new methodology, which can be applied to a variety of tasks that currently require several different measuring devices, like the electronic-distance-meter, tacheometer, laserscanner or camera. The possibilities of the new system are demonstrated in regards to distance-measurement, angle-measurement, taking images, measuring point clouds or using it like a video-camera at a high frame-rate. The 2D- / 3D-system has all the fundamental capabilities of common contemporary measuring devices. Will it be possible to discard these instruments in favour of the 3D-camera in the future? Will it be possible to use it efficiently despite the handicap provided by external superimposition? The following experiments try to find some answers.

Figure 8 shows the graphical user interface of the 2D- /3D-system developed in the course of a doctoral thesis at Bochum University (Schröder, 2009).

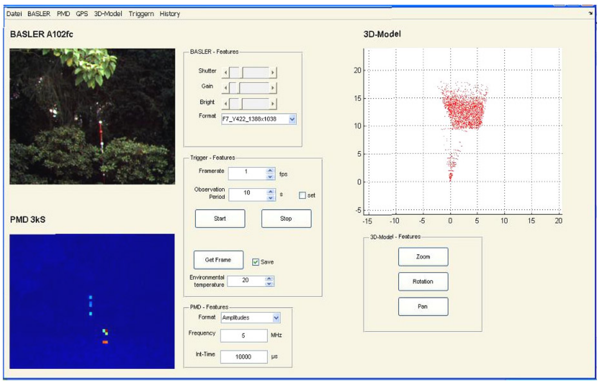

Figure 8: User interface of the 2D- / 3D-system

3.1 The 2D- / 3D-system in exchange to a tacheometer

With the tacheometer polar coordinates are measured in reference to the vertical: the zenith distance, the horizontal angle and the distance. In architectural surveying it is often used to establish a network or to capture single points. Whether the 3D-camera can replace a tacheometer is largely dependent on the orientation of the camera and on its accuracy. To prove this, the 2D- / 3D-camera-system was mounted on a tacheometer tripod and levelled with a bubble-tube. The 3D-camera was used for distance measurement, the 2D-camera for angle measurement because of its higher angle resolution. Different types of special targets were developed. E.g. in various sectors rods were marked with reflecting film or reflecting spheres (see fig. 9).

Figure 9: Targets for automatic identification of single points

Although the camera's angle resolution is rather poor, distances could still be detected sufficiently well, especially as far as measurements to spherical-reflectors are concerned. In order to carry out angle-measurement well-defined points in the same line e.g. the reflecting spheres could be chosen automatically. Thus automated extraction and identification of reflecting points of high intensity was possible. Distances of more than 20 m were reached, however with rapidly decreasing accuracy down to ± 5cm. Faults caused by excessive intensity of the signal amplitude at the reflecting points had to be considered. If necessary, these strongly reflecting points can be used for identification purposes only, while less reflecting adjacent (red) spheres may be utilized for angle measurement respectively for distance measurement. The latest generation cameras, however, should yield better results. It will also be easier to measure distances longer than half a wavelength, because increased switching times of the measuring frequency make it possible to determine n in the equation $d = ½ (n \times \lambda + \varphi)$ using different frequencies.

The present means of interaction using a measuring rod is a typical modus operandi of the 3D-camera. It cannot be realised with other instruments this way. Only here different targets can be reached all at once. The eventual replacement of the tacheometer by the 3D-camera seems a likely future course for certain areas, e.g. for documenting the advancing process of measurements at an archaeological excavation site, or for topographical purposes at short distances. In these applications of measurements to reflecting targets faults caused by external superimposition may be sufficiently suppressed.
It has also been proved that a network can easily be referenced by moving a GPS-antenna across the field of sight with the camera positioned on a tripod. Single-frame exposure time and GPS-coordinate measurement were synced.

3.2 Scanning with the 3D-camera

With the 3D-system being used as a scanner special attention should be paid to two different working modes: In the first one, the camera is mounted on a tripod to be turned around a fixed – e.g. vertical - axis, whereas in the second one the camera may be moved freely around an object or moved about in a room. In both cases every single frame delivers a cloud of thousands of points that are fixed to the camera system. In either of the two modes good starting points for matching are obtained by the procedure – thanks to the high frame rate and the frames overlapping heavily. However, external superimposition may cause considerable deformations and will deteriorate the quality of matched point-clouds in any case. To minimize the influence the point-clouds of structures scanned with the 3D-system should preferably only be neighbouring small reflecting areas. Figure 10 gives an example of a suitable object. The point-cloud was constructed from 50 frames, taken from only three positions with the camera on a tripod. This unfavourable way of recording can easily be identified by the characteristic structure of points forming rows.

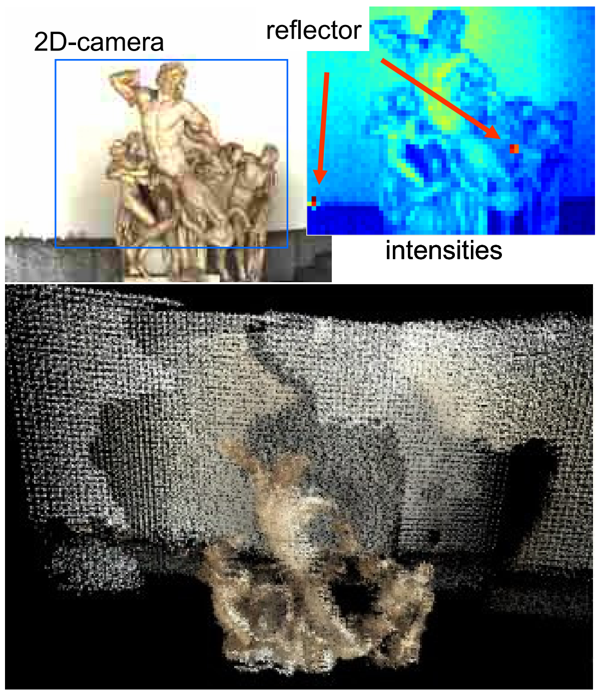

Figure 10: Rough data of Laocoön-Group
Copy at Museum of Art at Ruhr University Bochum

This effect and similar difficulties still existing with the system will very likely be overcome in the very near future (see fig.1

and fig.2). - The resulting point cloud may be evaluated using the software tools known from TLS.

3.3 Visualisation

Photorealistic texturing requires geometry data and pre-rectified images. The images used for photorealistic modelling were taken with the 2D-camera and matched with the coordinates taken by the 3D-camera. Mapping and rectifying of the images was done here using the technology and the algorithms of phototacheometry (Scherer, 2006). Figure 11 shows an image of a three-dimensional work of art consisting of coloured planes facing each other in different angles. In this example no effects by external superimposition on the coordinates were to be expected. Changes in colour result from to the lower quality of the 2D video camera.

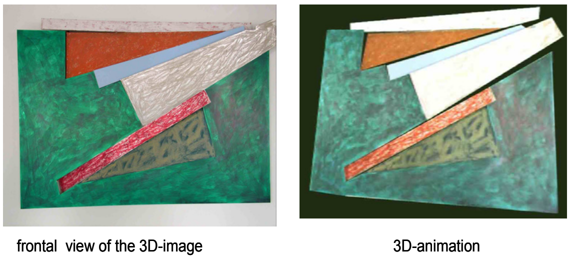

Figure. 11: Three-dimensional work of art “Arpoador II” of Frank Stella 1975 (photo and 3D-model)

In the visualisation of built structures the level of detail (LOD) is characterised by four degrees. LOD3 describes models of buildings that have been texturized on the outside. In these cases the general geometry recording resolution goes down to a few decimetres. LOD4 is reserved to describe the most detailed models, the interior of buildings as well as detailed textures. The visualisation of the niche in example figure 12 shows that - in spite of superimposition-effects - planes can be extracted sufficiently well to build a LOD3-model.

With a 2D-camera of better resolution the quality of the mapped texture can be improved easily.

Figure 12: Visualisation (b) with data (a) from the 2D-/3D-system

It should be stressed that all necessary data was gained with only two single shots taken with the 2D- / 3D-camera-system.

4. CONCLUSION

This paper has two primary goals: On the one side, fundamental difficulties using 3D-cameras for architectural surveying are to be outlined, and on the other side possibilities for the use of a 2D- / 3D-system replacing traditional measuring instruments are to be shown.

The experiences laid out here refer to work with the camera PMD-3K (3072 pixel). It was chosen because of its comparably high efficiency in terms of suppression of daylight influences. That said, the current latest generation of cameras offers a ten-times higher density of pixels 41k (205 x 205 pixel) with superior pixel-sensitivity balance. It also offers increased automation concerning adaptation to the reflectivity of the given object. Thus all results and reflections will be easily adapted to the new type.

The most important results from these first experiences are as follows:

- When modelling structures the geometrical accuracy depends on the structures themselves and on the geometrical relation between the camera and the object. The strong interdependence caused by external superimposition has to be taken into account.
- Geometrical correctness can often not be guaranteed.
- A sufficient resolution of point-clouds can be reached only with a large number of frames; the most efficient way to arrange them will have to be examined.
- The aforementioned method of recording with the 3D-camera is suited for recording and visualisation with LOD3-quality.
- The combination of a 3D-camera with a 2D-camera of higher resolution yields improved coordinate quality.
- The large variety of possibilities to combine the different functionalities may allow to replace traditional measuring instruments and measuring methods under certain conditions.

Although many instrumental parameters will see additional improvements in the future, the external superimposition error is inherent in the technology itself. It may cause uncontrollable alterations in the distances measured. Determining accurate boundaries for widespread and common use of 3D-cameras in surveying might prove to be a long way.

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