"FREE-FLYING" 3-D SENSORS FOR EFFICIENT CLOSE-RANGE MEASUREMENT AND REVERSE ENGINEERING

Reinhard W. Malz, Daimler-Benz AG, Research Center, Ulm, Germany

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ABSTRACT

Digitizing of three-dimensional objects is an important task in many applications with scales ranging from submicrons to kilometers. This paper discusses the basic principles and relative merits of camera based digitizing methods over a wide spectrum of applications. It then refines this discussion to solve applications in industrial reverse engineering where typical sizes are centimeters to several meters.
Three essential components for a new approach of optical 3D-measurement will be discussed more in detail: active optical sensor principles for measuring dense coordinate point clouds of unprepared surfaces, sensor calibration without positioning equipment, and automated sensor orientation for measuring multiple views. The integration of these components into a tripod mounted optical 3D-sensor will be shown. Those sensors can be fast, low cost substitutes for CMM mounted sensors.

KURZFASSUNG

Die Digitalisierung räumlicher Objekte ist eine wichtige Aufgabe in vielen Anwendungen, deren Maßstäbe von mehreren Kilometern bis hinein in Submikrometer reichen. In diesem Beitrag werden zunächst Grundprinzipien und Eigenheiten mehrerer kamerabasierter Verfahren diskutiert. Anschließend konzentriert sich die Diskussion auf die Aufgabenstellung der industriellen Meßtechnik mit typischen Objektgrößen von Zentimetern bis zu mehreren Metern.
Drei essentielle Komponenten für ein neues 3-D-Meßkonzept werden erläutert: Aktiv-optische Sensorverfahren, mit denen dichte Koordinatenpunktwolken von unpräparierten Oberflächen gewonnen werden können, Kalibrierungsverfahren für solche Sensoren sowie Verfahren zur Sensororientierung, mit deren Hilfe die Meßergebnisse mehrerer Ansichten automatisch in das Objektkoordinatensystem transformiert werden können. Die Integration dieser Komponenten in einen Sensor, der auf einem Stativ montiert sein kann, wird gezeigt. Solche Sensoren können kostengünstige Alternativen für Meßmaschinen mit optischen Sensorköpfen sein.

1. INTRODUCTION

Optical 3-D measurement of regular and free-form surfaces is an important task in many product development and reverse engineering processes (Figure 1). In such applications, the following sensor characteristics and properties are thought by the author to be desirable for good acceptance:

- acquisition of dense coordinate point clouds from unprepared object surfaces in every single view,
- fast acquisition of several millions of coordinate points in some minutes (not hours or more),
- low costs compared to mechanical or mechanical-optical coordinate measurement machines (CMMs),
- easy to use, for example like a photo apparatus or a video camera on a tripod,
- automatic registration of coordinate point clouds from several views,
- semi-automated construction of CAD models from the point clouds.

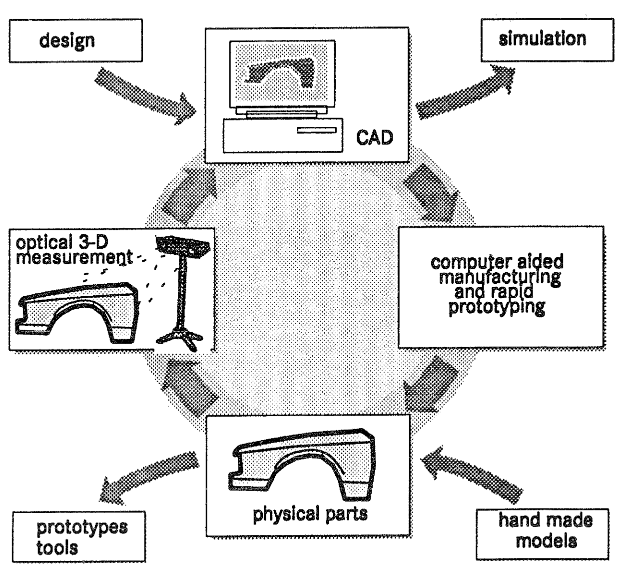


Figure 1: Optical 3-D measurement in reverse engineering and product development processes.

A sensor which has these characteristics could be used as indicated in Figure 2. The basic idea is to have a small sensor which can easily be moved step by step around (or along) an object, while a computer processes the information from the sensor to generate a dense point cloud of coordinates representing the surface of the object.

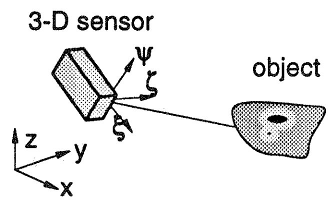


Figure 2 : Basic model for a "free-flying" 3-D sensor.

At Daimler-Benz, such a sensor is under development. This sensor was designed using a combination of sensor principles, namely photogrammetry and active optical techniques. This sensor does not require expensive, high-precision positioning systems, and it is expected that the cost of this sensor will be considerably less than CMMs. Hopefully, it will also lead to greater use of, and new applications for, digitization of physical objects.

The rest of this paper is divided into two parts. In the first part, the focus is mainly on providing a brief description of sensor principles and techniques relevant to the digitization of physical objects. In the second part, the particular combination of principles used in the Daimler Benz sensor is described. The second part also contains some measurements made using the sensor to illustrate its use.

2. SENSOR PRINCIPLES FOR OPTICAL 3-D SURFACE MEASUREMENT

There are many 3-D measurement principles used in different scales (see Figure 3). This chapter compares several sensor principles and discusses their fundamental constraints and practical assumptions.

There are some principles, which need no mechanical positioning (left side in Figure 3). For example, acquisition of dense and accurate 3-D data from multiple views with reconstructed camera positions has been realized in many passive remote sensing applications using natural textures and cooperative features [Kon96].

In close-range applications, digital photogrammetry can measure some (10^1 ... 10^3) retroreflecting target points with high precision (e.g. 1 : 10^5). However, it is not possible to obtain the dense point clouds required for realistic surface descriptions and accurate CAD model reconstruction.

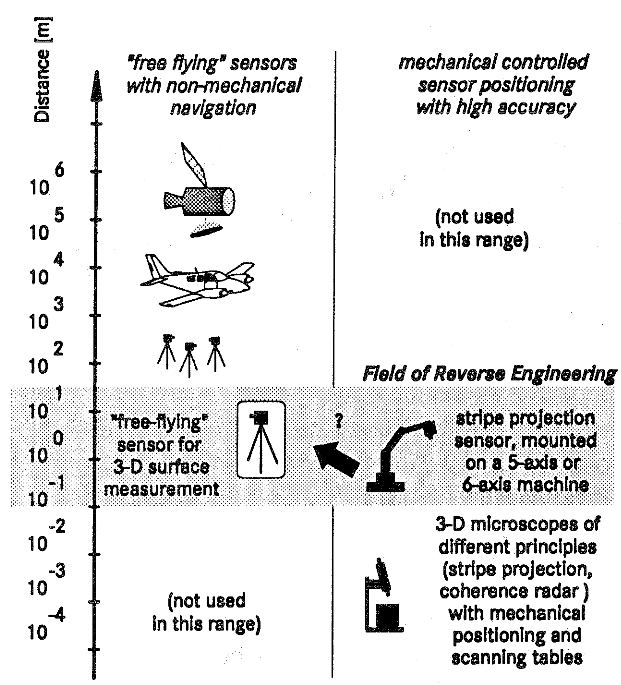


Figure 3: Applications for 3-D digitizing.

On the other hand, there are many active optical sensor methods used in medium and small scale applications that use well defined artificial illumination in combination with high accuracy mechanical positioning systems. For example, 3-D sensors consisting of a matrix camera and a coded stripe projector can measure a large number of coordinate points (10^5... 10^7) from unprepared surfaces with moderate resolution (e.g. 1 : 10^3).

However, to fully digitize 3-D objects using such active sensors, it is necessary to move the sensor or the surface while maintaining relative orientation information. In addition, the object area, which is measurable from a single view can not, in practice, be larger than approximately 1 m^2, because of limited projector light energy.

It should be mentioned here, that sensing principles, which are *not* based on matrix cameras, will not be discussed in this paper for several reasons. Those principles, for example laser spot triangulation with linear photo diode arrays or posicons, time-of-flight sensors or laser heterodyne interferometers with single photo diode detectors always need a scanning device of high accuracy. It is envisaged that devices with acceptable lateral accuracy and long-term stability will be too expensive compared to digital matrix cameras in the next few years.

2.1 Passive Sensing Principles and Their Limitations

2.2.1 Natural Features and Natural Illumination: Because active lighting is not applicable from satellites or airplanes, passive stereo photogrammetry based on natural textures and features is used in remote sensing application at optical wavelengths. To measure corresponding points in images from several views, many pixel value and object based techniques have been developed and used for digital photogrammetry [För86], [Luh95].

a) b) c) d) e)

Figure 4: Natural scenes and patterns at distances of a) 10000 km, b) 10 km, c) 10 m, d) 10 cm and e) 10 mm.

The basic assumption of all 3-D sensing techniques based on images from several views is the angular invariance of texture and feature images. In addition, a temporal invariance is required, if sequential imaging with a moving camera is used.

This assumption holds as long as the borders between regions in the image are borders between different diffuse materials only, and not borders between regions of the object which are different distances from the cameras.

In close range applications the assumption of spatial and temporal invariance of image structures is incorrect. Shadows, jump edges and intensity values are changing while light sources, objects and cameras are moving (Figure 4c, d, e and Figure 5). This is a major problem for passive photogrammetric principles, but there are still solutions as long as there are sufficient invariant features available (Figure 4c and d).

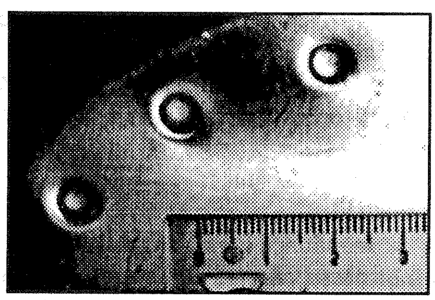


Figure 5 : Metal part with specular reflections.

Parts in industrial production processes are often made from one material. In addition, technical surfaces have highly non-isotropic optical properties. Because of the lack of invariant textures, those surfaces cannot be measured directly with passive photogrammetric techniques (Figure 5).

2.2 Active Sensing with Static Light Projection

For materials which diffuse light from the surface (and not from subsurface regions), light projection can be used to produce textures on that surface (Figure 6). Figure 7 shows some examples for patterns, which are used for creating textures and features on the object's surface (random painting would be optimal, but it is not acceptable in most applications).

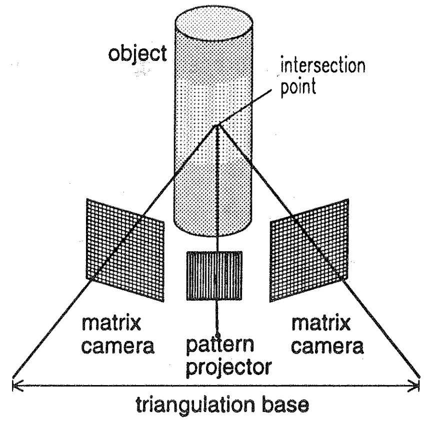
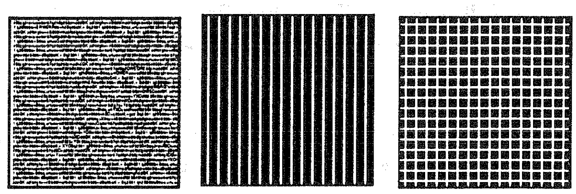


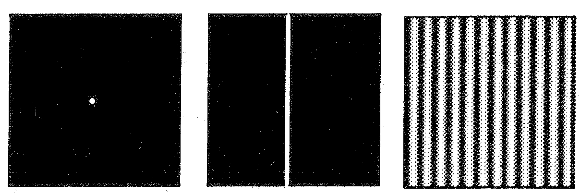
Figure 6: Stereo camera pair.

2.2.1 Uncalibrated Projectors with Two Cameras: The projection of pseudo noise (Figure 7a) is often used in digital photogrammetry with two or more views. It works quite well on smooth and non-specular surfaces, because the image correlation uses lateral image information. On specular surfaces as shown in Figure 5 the results are not acceptable.



a) b) c)

Figure 7 : Projected light patterns, commonly used in two-camera photogrammetry:
a) pseudo noise, b) line grid, c) crossed lines.



a) b) c)

Figure 8 : Projected light patterns, commonly used in one-camera sensors with calibrated projector:
a) light spot, b) single line, c) sine grid.

2.2.2 Calibrated Camera/Projector-Pairs: Here, each camera pixel 'sees' the light on the object which comes from a particular projector pixel. The information received by the camera pixels can therefore be used to identify which projector pixel the light seen by each camera pixel comes from, because a known pattern is projected. The location of the camera and projector pixels, together with the inner and outer orientation of camera and projector, can be used to find a coordinate on the object using triangulation. Regular patterns may also be useful for image matching, but in most application these patterns are projected by a calibrated device, so that triangulation can be made with one camera.

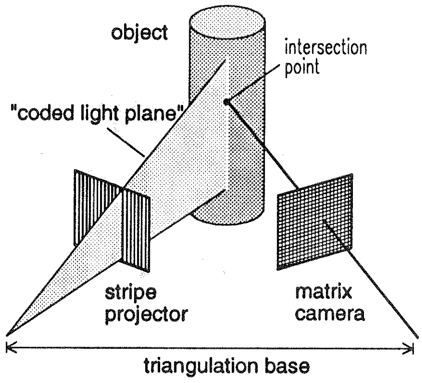


Figure 9 : Camera-projector pair.

Here the lateral continuity in remission and height is also important, because the image processing uses neighboring pixels to find the center of the spot, the center line(s) or the absolute phase of the sine grid [Tak82] (for further explanation see 2.3).

To derive the local parameters of light remission and finally to calculate the 3-D information at one pixel position, all single pattern/single image measurement principles use the intensity distribution in <u>small image areas</u>. This lateral image processing assumes lateral continuity of remission and topology on the object surface. In addition, it reduces the lateral resolution of 3-D information (for example: a 512 x 512 matrix camera cannot produce 512^2 independent 3-D coordinates !). This is not acceptable in most industrial applications with non-diffuse and non-smooth surfaces.

2.3 Sequential Light Processing

As mentioned before, one major problem of optical 3-D measurement is the fact that the local remission of projector light from the object surface is a priori unknown. If the camera is linear and the A/D converter clips hard (255, for example), the digitized value g can be described as

$$g = \min\left(u + r\,p,\ 255\right),$$

where u is an unknown offset value from camera electronics or environmental light and r the remission factor of the surface (Figure 10). Thus the projector intensity p and therefrom the projector coordinate ζ cannot be estimated from a single grey value.

The critical assumption of continuous surfaces can be suspended, if we accept, that sensor and object have to be kept in a fixed relative position, while the projector produces sequential patterns and the camera digitizes image sequences (Figure 11). This sequential concept is applicable in almost every industrial reverse engineering task (it would become a problem in robotics).

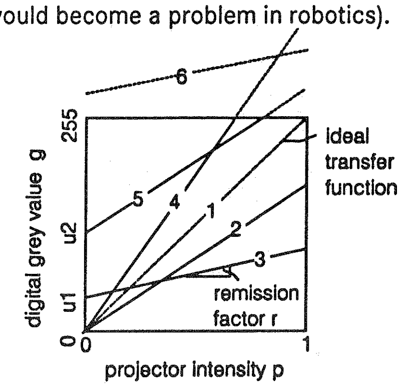


Figure 10 : Different intensity transfer functions.

The common idea of all subsequent discussed principles is the implicit or explicit estimation of the parameters u, r and p from at least three grey values under different projector light patterns. The simplest principle (which is only good for explanation) is shown in Figure 11: project black, white and a ramp and solve the linear equation system $g_0 = u + p\,r$, $g_1 = u + 1\,r$, $g_2 = u + 0\,r$, which results in $p = (g_0 - g_2)/(g_1 - g_2)$. This is the simplest 3-D sensor, where each pixel has independent range values, but it's range resolution is rather bad.

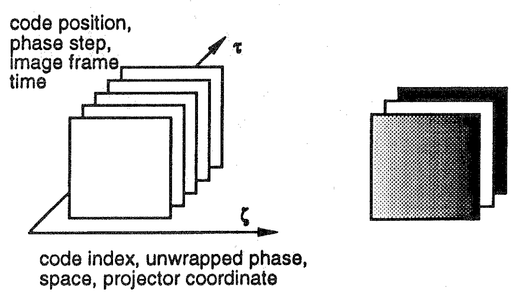


Figure 11: Temporal light encoding principle (left) and the simplest pattern for grey calibration (right).

2.3.1 Phase Shifting with a Single-Frequency Pattern: A great variety of interferometrical phase-shifting techniques has been developed since the 70's [Bru74], [Cre88]. Phase-calculating and phase-unwrapping algorithms can also be used in triangulation-based sensors where periodic patterns are projected [Zum87].

The advantage of a set of phase shifted fringes compared to a single fringe pattern is the following: from three grey values that are measured at the same pixel position, a local phase can be evaluated, that is independent from the lateral distribution of grey values. This local phase value, which is always in the range $(0, 2\pi)$ can be seen as an absolute phase ϕ modulo 2π, where ϕ corresponds to the projector coordinate ζ. If the object surface is continuous, the absolute phase can be calculated by an incremental phase unwrapping algorithm, which allows no phase increments between neighboring pixels larger than $\pi/2$.

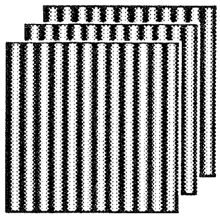


Figure 12 : Projected patterns with constant frequency and different phases (for example: 0°, 120° and 240°).

2.3.2 Phase Shifting with Two or More Frequencies: To produce absolute and local phase information $\phi(x,y)$ at non-continuous surfaces, multi-frequency (heterodyne) principles are used in interferometry. Independent phase shift measurements at slightly different light frequencies or wavelength (Figure 13) lead to a singular absolute phase value (to understand this principle, look at the vernier scale of a slide gauge). This principle has also been used for triangulation based sensors [Zum87].

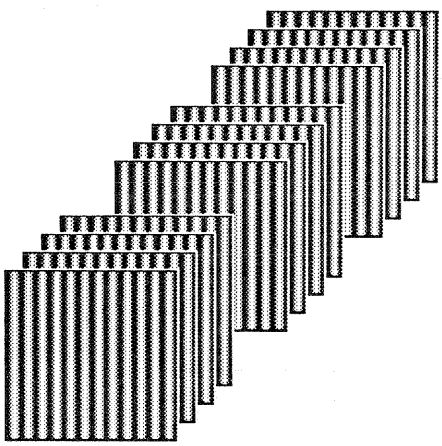


Figure 13 : Projected patterns with 3 groups of slightly different frequencies, each with different phases (for example: 0°, 90°, 180° and 270°).

2.3.3 Binary Codes: Binary Gray Codes [Gra53], [Yam86], [Wah86] as well as multi-frequency phase-shift techniques with periodical and continuous patterns [Zum87] have been widely used to acquire dense (i.e. in principle for each camera pixel) and unique 3-D point data from objects in short range.

To binarize the digitized images, it is necessary to know the local threshold (which may be different for each pixel). There are several ways of using additional images to calculate this threshold:

1. project a unstructured frame with 50 % intensity and use the acquired image as threshold,
2. project two unstructured frames with 100% and 0% intensity and use the averaged images as threshold,
3. project both normal and inverse patterns, and
4. use the sign (1,0) of the difference at each pixel as a binary digit.

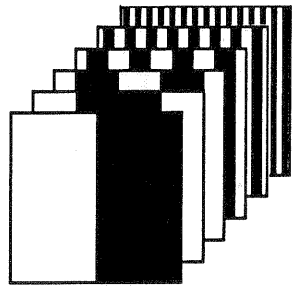


Figure 14 : Binary gray code (additional images for threshold generation are not shown).

2.4 Information Theory

A basic task of coding theory is to maximize the information flow in a given channel. In the context of optical 3-D measurement with matrix cameras, the projected temporal light patterns are transmitters of encoded projector coordinates. Each camera pixel is a receiver, which has to decode the sequential intensity signal.

The received signal quality at a pixel position is limited by typical channel parameters like signal-to-noise-ratio, nonlinearity and crosstalk from neighboring pixels. A phenomenological parameter which describes the sum effect is the number n_d of separable grey levels. If we use such a channel to describe the optical transmission of w projector intensities digitized in w images, the limits of information flow is described by the entropy [Mal92]:

$$H_{op} = \frac{1}{w} lb\left\{ n_d{}^{w} - 2\left(n_d - 1\right)^{w} + \left(n_d - 2\right)^{w} \right\} \quad \left[{}^{bit}\!/\!_{value}\right]$$

From this entropy, the theoretical limit Z_{max} can be calculated, which describes the resolution of projector coordinate ζ for a given number of separable grey values in the image sequence. Figure 15 shows calculations of resolutions for different projection coding techniques. These functions always start at the minimal value n_d that the coding principle was designed for (for example $n_d = 2$ for binary gray code). If the channel is worse, the decoding (or the calculation of absolute phase) will fail. If the channel is better, the resolution increases (but not for a pure digital code which just results in a integer number - or not, if signal is too noisy).

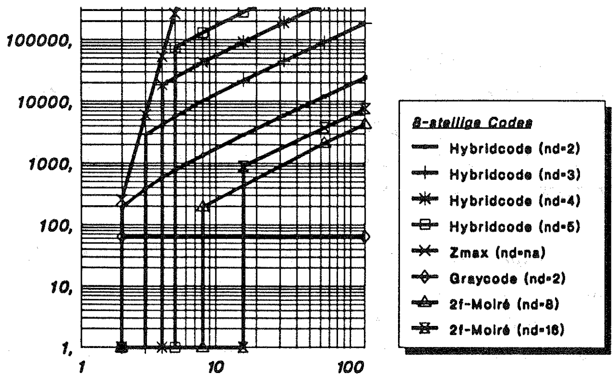


Figure 15: Resolution of projector coordinate ζ at given number of separable grey values.

Finally it should be mentioned, that the above discussion always is related to a single pixel position in an image sequence. However, in almost very application the conditions will vary very much from pixel to pixel. Because a decision for specific sensor parameters (code, camera shutter time, video signal amplification, ...) affects the whole sensor system, an optimization strategy should be knowledge based [Mal92].

2.5 Signal Limitations and Basic Errors

The spatial resolution of an active optical sensor is a very complex result of different technological factors and interactions with the surface. For a first and rough estimation of spatial sensor resolution the technological parameters of camera (number of pixels in x and y) and projector (number of separable stripes or projector pels) may be used.

But from Figure 16, we see that this will be a rather poor estimation: in close-range applications, object/camera and object/projector distances can vary greatly, and this affects the lateral image and the longitudinal range resolution in a more geometrical sense. From Figure 16, we can see that throughout the measurement space there is a variety of voxel sizes and shapes. Voxels are more square near N, more rhomboid near F, and more rectangular near L and R.

In a more optical sense, diffraction and defocusing, as well as the variation of surface orientation relative to camera and projector axes, lead to additional problems. The apertures of camera and projector lenses are rather bad compromises: they should be opened for higher contrast and signal-to-noise ratios at limited projector intensities. On the other hand they should be closed for a wide depth of focus (from N to F).

Another effect, which can be a problem, is the variation in the projector-to-camera frequency transfer function. Figure 17 shows the variation in the projector-to-camera frequency transfer function for a cylindrical object (see also Figures 6, 9 and 16). We can see, that only the regions Ia and Ib fulfill the Nyquist criteria (the sampling frequency should be at least twice the upper limit of the object spectrum). The increasing spatial frequency seen by the camera in region Ic leads to a strong undersampling and cross-talk between neighboring pixels and finally results in decoding errors. Regions II, III and IV are not measurable.

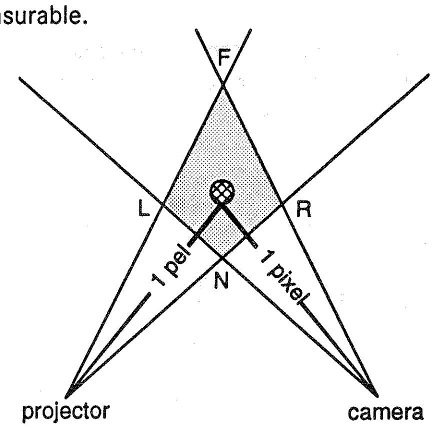


Figure 16: Variable spatial resolution.

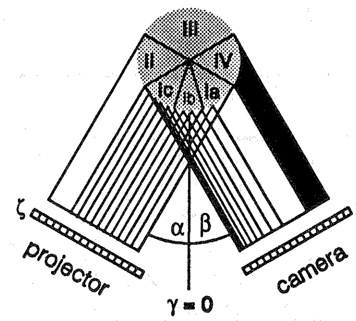


Figure 17: Variable spatial frequency transfer function.

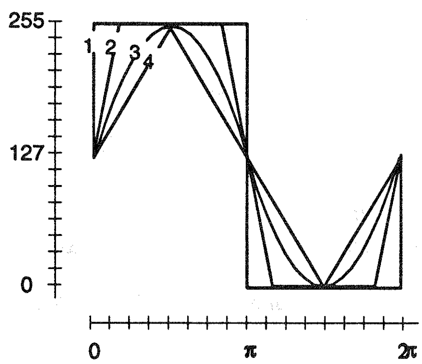
In addition to optical resolution effects, the changing of surface normal angles causes extreme intensity variations on non-diffuse surfaces. Even on a perfect lambertian surface, the camera sees lower intensities in region Ia. So, finally, there remains a very small measurable region, Ib, on the cylinder.

In the middle of the sensor's measuring volume, we find the best conditions for measurement, provided that the projector is continuous.

From the above discussions we understand the following better: the only pattern, which doesn't change its basic lateral intensity distribution, when we scan and sample it with a varying sampling window (relative size of camera pixel aperture, optical point spread function), is a sine function (number 3 in Figure 18). Symmetric optical low-pass filtering of sine patterns only causes lower modulation, but no shift in the measured phase.

There are several reasons for using other than sine patterns. First, there is the fact that some technical projectors can only produce rectangular grids. For example, the width of the striped electrodes for switching LCD-shutters has a lower limit, which is up to ten times larger than the pixel size of a camera. The problem of these rectangular grids in phase shift applications is, that even when three or four patterns are relatively shifted, there are no gradients available for monotonic phase calculation.

Another fact is that trapezoid functions will result in much better signal-to-noise ratio and higher phase resolution than sine functions.



intensity function	projector principle (example)	quality of phase output (3-D)
rectangular (1)	programmable LCD projectors (focused)	non-continuous, systematic errors
trapezoid (2)	bucket integrating [Mal92]	best signal-to-noise ratio*
sine (3)	interferometry, fixed mask projectors	insensitive to varying MTF**
triangular (4)	crossed rectangular grids [Zum87]	lowest signal-to-noise ratio*

*at full modulation without signal clipping (e.g. 0...255)

** the opto-electronic system's modulation transfer function

Figure 18: Basic patterns used for phase shift

3. THE "FREE-FLYING" 3-D SENSOR

The following section describes light encoding principle, sensor calibration and sensor orientation (navigation). These are important capabilities for fulfilling the list of required characteristics given in the introduction.

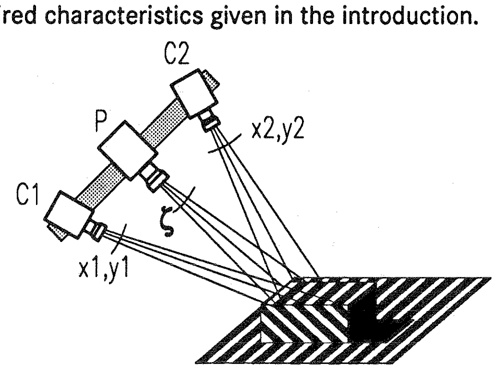


Figure 19 : The "free-flying" sensor with two cameras and calibrated projector which can be used with one camera.

3.1 Hybrid Codes

The sensor uses hybrid codes of several types. As developed in [Mal89], hybrid codes combine the advantages of digital and analogue principles and yield nearly the theoretical limits of resolution which can be achieved with *temporal* encoded light structures.

For example, the zoomed area in Figure 20 shows the trapezoid light distribution of a MZXpX-hybrid code which is continuous in space and intensity. This code can be used with variable numbers of images ($w \geq 3$) and also with variable digital code bases (binary, ternary, quaterary gray codes). It has the highest resolution compared to all other temporal principles (under equal conditions, namely the number of images used, and the lowest acceptable number of separable grey levels. See also Figure 15).

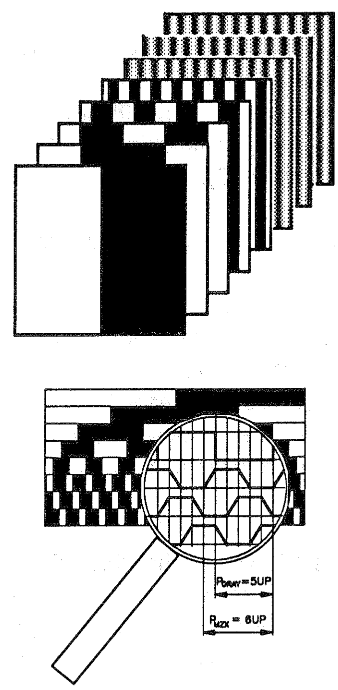


Figure 20: Binary MZXpX hybrid code. The lower part shows the continuous MZX sub-code.

3.2 Calibration Concepts

A measurement system for production environments should be "stable under all circumstances". Because this is not realistic, a system should have an integrated self checking tool and an easy-to-use calibration functionality. There are different calibration principles which can be used for active optical 3-D sensors in which the projector has to be calibrated. They will be briefly discussed.

3.2.1 Approximation of 3-D Sensor Data to a Three-Dimensional Mechanical Reference can be one solution of the 3-D calibration problem. Some calibration algorithms do not require an understanding of how the 3D-sensor works. Their only assumption is that the sensor has a mapping function $\underline{X}_{out} = F\ (x, y, \zeta)_{image}$ that is unique and smooth. This means that the higher order frequency terms of the deviations from the orthogonal reference coordinate system are negligible, and the mapping function F can be sampled and approximated by a rather coarse three-dimensional grid of distinct points. For example, the measured 3-D target positions can be fitted to the well known coordinates of a moved plate (Figure 22) by polynomial functions.

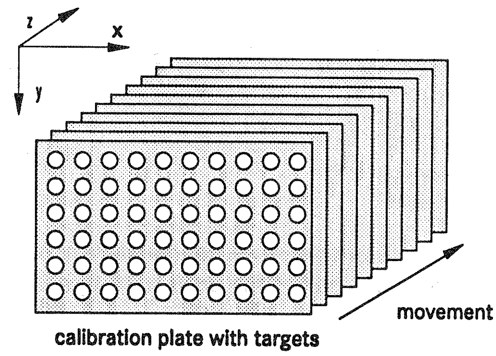


Figure 21: Representation of a 3-D grid by moving a 2-D grid in normal direction.

This calibration concept has certain limitations:

- it needs accurate, long-term-stable three-dimensional reference systems (e.g. a flat calibration plate with targets and a mechanical positioning system with high accuracy [Bre95]),
- data reconstruction requires grid interpolation, which is a time consuming numerical operation, and
- sub-pixel precision is sufficient for 3-D measurement, but is not suitable for photogrammetrical applications.

3.2.2 Estimation of Matrix Camera and Matrix Projector Model Parameters: Photogrammetrical algorithms for camera calibration are based on physical camera models. To find the model parameters, the image coordinates of targets (output) are measured with very high sub-pixel precision and compared to the actual object coordinates (input).

A light projector can be seen as an inverse camera. To calibrate the projector, the object coordinates (output) of projected targets (e.g. crossed stripes) are measured with other cameras and compared to the known projector coordinates (input) (stripe numbers in x and y) [Str93]. Unfortunately, this concept is not suitable for high resolution matrix/projector 3D-sensors. Presently, high resolution projectors cannot send cross type patterns (e.g. orthogonal stripes) which can be measured by photogrammetry.

3.2.3 Estimation of Matrix Camera and Linear Projector Model Parameters: Basically a matrix camera needs a stripe pattern for triangulations. In addition most projector technologies obtain higher resolution and signal quality when only one stripe direction is necessary. Therefor it was necessary to develop a new self calibration technique. This new calibration method makes use of a simple hand-positioned calibration plate to simultaneously calibrate all parts of the measurement system. The light projector is seen as an *inverse camera with "long" pixels (stripes).* In terms of photogrammetry, matrix/projector sensors can be seen as stereo camera pairs where one camera is an inverse camera.

The new principle combines several advantages:

- the calibration delivers inner and outer orientations of camera(s) and projector,
- all calibration tasks can be done in a few minutes,
- the calibration plate may be hand-positioned,
- a calibration check can be done during measurement,
- the sensor system is suitable for photogrammetric tasks such as autonomous sensor orientation, and
- 3-D coordinates can be calculated fast in either a sensor or a world coordinate system.

3.3 Orientation and Navigation of 3-D Sensors

In general, 3-D objects should be measured from several views to get a complete representation. To find the sensor's orientation relative to the measured object in every single view, several principles may be used. This part discusses different methods for determining sensor orientation. It then discusses how information from these sources can be combined to extract sensor orientation for the new sensor system.

3.3.1 Mechanical Positioning Systems of High Accuracy: In principle, object and sensor can be "coupled" to each other by a mechanical positioning system that defines six degrees of freedom.

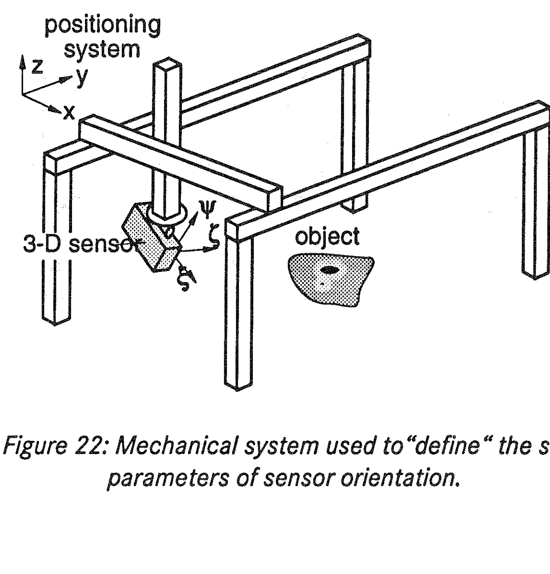


Figure 22: Mechanical system used to "define" the six parameters of sensor orientation.

However, there are some disadvantages to this method:

- high accuracy mechanics are very expensive, and will remain so,
- the path of mechanical connectors and interfaces has a complex error propagation that is difficult to calibrate,
- it yields the mechanical coordinate system, not the optical coordinate system, and therefore a hand-eye calibration is needed, and
- the principle is very sensitive to angular errors.

3.3.2 Orientation with External High-Accuracy Navigation Instruments: Theodolites or laser interferometers can be used to measure the absolute positions of sensor and work piece. However, there are similar problems as in mechanical positioning systems. In addition, external navigation instruments with sufficient accuracy in all 6 degrees of freedom are very expensive.

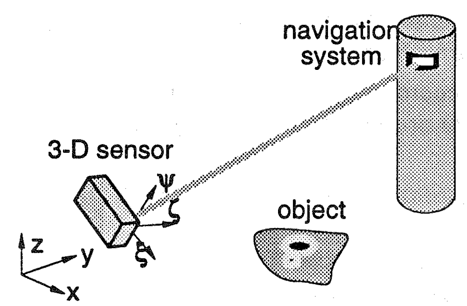


Figure 23: External navigation system to measure the sensor orientation.

3.3.3 Feature-Based Registration of Point Clouds ("Navigation of Data"): Some objects have "geometric contrast" from edges and other discontinuities which can result in features. Features extracted in several point clouds can be used to fit these point clouds to each other. This method should be used with care, because point clouds can be incomplete with respect to other views. This can lead to matching errors.

3.3.4 Autonomous Orientation of 3-D sensors ("Free- Flying" Sensors): A basic principle in photogrammetry is the orientation of cameras by differential measurements of several image objects. The measured (2-D) image coordinates (e.g. of retro-reflecting target points with ring codes) correspond to their (3-D) world coordinates which are either known a priori or constrained by other measurements in a bundle adjustment.

The dependency of the visibility of more than three reference points can become a problem on large surfaces. This can be solved by different means, for example by applying additional targets (in every form), by feature-based methods or by simple mechanical positioning systems.

We have developed a new orientation principle based on photogrammetric methods with extensions for active optical 3-D sensors. The primary information for every sensor position is derived from image sequences acquired under coded stripe illumination and retro-target illumination.

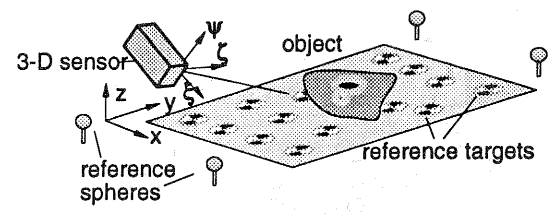


Figure 24: Autonomous sensor orientation, based on natural features and additional targets.

3.4 Implemented sensor system

The flexible software system we developed for the "free-flying" sensor integrates all standard software functions. For a non-expert, complex operations are reduced to a few commands or buttons.

The software can drive many types of cameras and projectors. Figure 25 shows one of the first setups of a "free-flying" 3-D sensor in our laboratory: a tripod mounted system with two CCD standard cameras and a calibrated programmable LCD projector.

Further development has to be done in the fields of automated sensor optimization, signal evaluation and error checking.

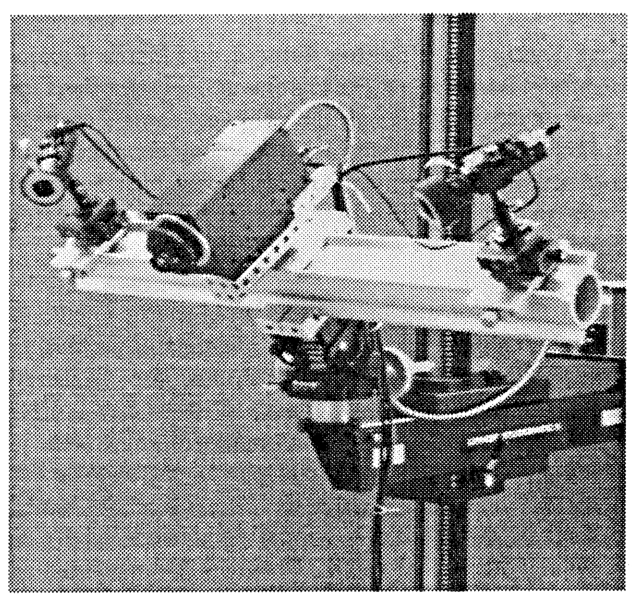


Figure 25: One of the first setups of a "free-flying" 3-D sensor in our laboratory.

3.5 Applications and Results

For a measurement example an aluminum part with specular surface was used (Figure 26). This part was developed for testing purposes and has been measured and reproduced by rapid prototyping from several institutions [IMS94].

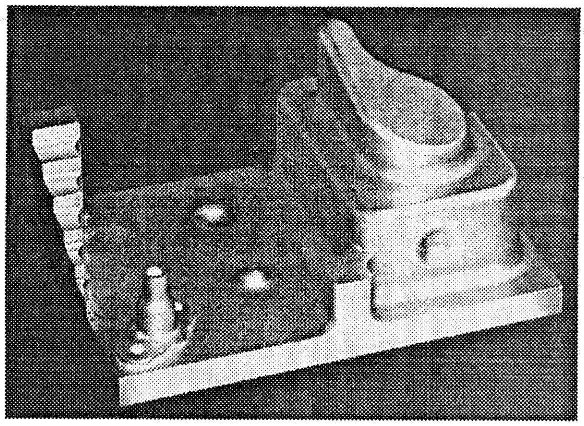


Figure 26 : IMS test-part, made of aluminum.

Figure 27 shows measured data from twelve different views which were acquired to obtain one point cloud that was suitable for model reconstruction (Figure 28). The rms-noise was below 50 microns, which is approximately 0.025 % of the field of view.

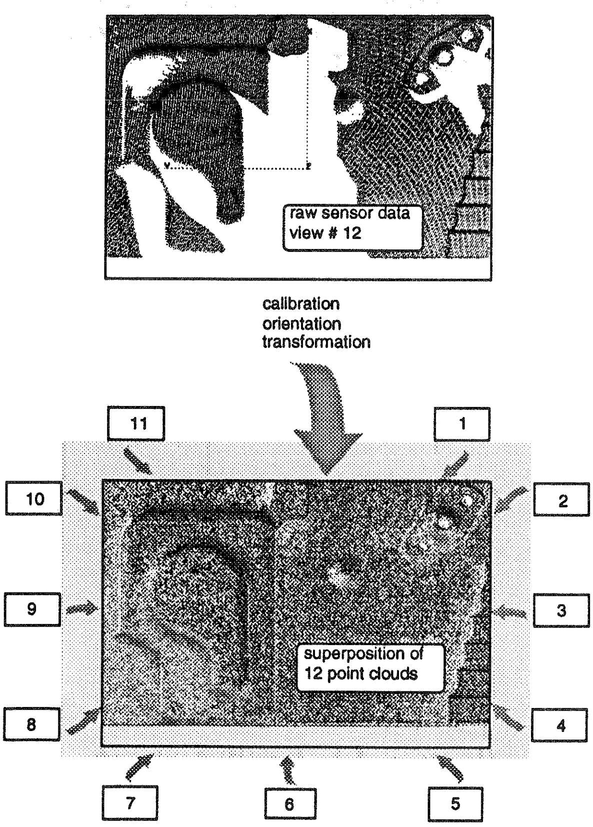


Figure 27: Measurement of IMS test part (single point cloud and superposition of twelve point clouds).

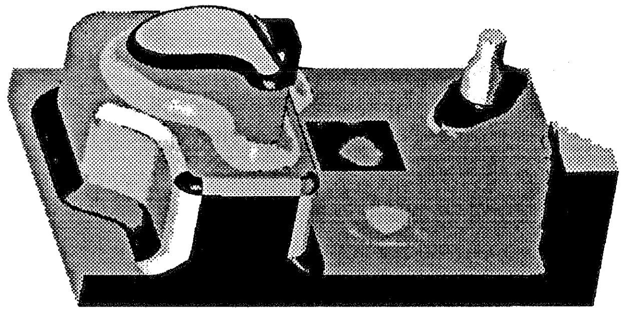


Figure 28: CAD model based on point cloud.

4. CONCLUSIONS

There are many existing and new application areas for "mechanic-free" self calibrating, autonomously navigating optical measurement systems:

- fast digitization of hand-made models,
- measurement and documentation of tools,
- on-line production control (automotive parts),
- geometric control of turbine blades and wings,
- flexible programmable checking fixtures,
- collision control (e.g. for mobile robots).

Several sensor principles have to be combined to build "free-flying" sensors for 3-D surface measurement. As an example, a new sensor system has been shown which integrates active optical and photogrammetric techniques. It can produce 3-D coordinates for each camera pixel (which can be 1 million or more in a few minutes). A self-calibration principle with a simple hand-positioned calibration plate is used for the camera/projector combination. In this system a new orientation principle based on 2-D and 3-D data is used for point-cloud registration from several views. The registrated point clouds can be sent to a CAD system for further 3-D processing.

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