DLP®/DSP-based Optical 3D Sensors for the Mass Market in Industrial Metrology and Life Sciences

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ABSTRACT

GFM has developed and constructed DLP-based optical 3D measuring devices based on structured light illumination. Over the years the devices have been used in industrial metrology and life sciences for different 3D measuring tasks. This lecture will discuss integration of DLP Pico technology and DSP technology from Texas Instruments for mass market optical 3D sensors. In comparison to existing mass market laser triangulation sensors, the new 3D sensors provide a full-field measurement of up to a million points in less than a second. The lecture will further discuss different fields of application and advantages of the new generation of 3D sensors for: OEM application in industrial measuring and inspection; 3D metrology in industry, life sciences and biometrics, and industrial image processing.

Keywords: DLP, Structured Light, Profilometry, 3D Scanner, Industrial Inspection, Automation, Intelligent 3D Camera, CMM, Biometrics, Medical Imaging

1. INTRODUCTION

Industrial image processing has been gaining importance for several decades now, and this goes on with improvements in computing power, allowing for faster and more sophisticated scene and object recognition. Yet as we ourselves gain a lot better information by seeing with both eyes, three-dimensional image acquisition holds major advantages against classical 2D camera pictures. The practical realization of 3D acquisition however proved to be difficult. Stereo cameras require considerable processing power, fail if there is no contrast, and may deliver wrong data due to optical ambiguities only an intelligent observer could recognize as such. Active, structured light projection solves this problem and is widely acceptable as illumination is a major prerequisite for proper image acquisition in any case. Time-of-flight systems (laser radar) have long been tried, but didn’t succeed because of high costs and poor depth resolution. The typical current solution are laser scanners, acquiring data dot by dot and line by line. 3D data is essentially gained by a triangulation between camera and light source perspective. This sounds simple, as any laser line delivers 3D shape data by its distortion. Alas, an entire camera picture has to be taken for any single line, making this a slow approach. Projecting complete area patterns is orders of magnitude faster, as it allows for 3D acquisition with just a few camera pictures. This is known as fringe projection. Stripes perpendicular to the stereo basis deliver a maximum of triangulation cues. With a combination of digital stripe codes and sinusoidal gray value gradients, even discontinuous objects deliver an unambiguous result, and phase detection allows for an at least ten times better distance accuracy than with mere triangulation.

This highly accurate approach is already used in numerous measurement applications, yet its speed also predestines it for industrial 3D data acquisition. GFM has a decade of experience with measurement applications and is now one of the first companies to implement the technology for the industrial image processing sector. In this article, we will discuss specific technology solutions and prospects for this field.

2. DLP/DSP-BASED OPTICAL 3D SENSORS

2.1 Principle and Choice of Components

Fringe projection is more precise than triangulation, because it exploits the fine position or ‘phase’ of the projected stripe patterns at high precision. This yields an at least 10-fold gain in distance resolution, up to 50-fold even if we allow for some area averaging. The key to this is phase accuracy, which in turn requires exact waveform generation, hence accurate gray levels for the entire pattern and especially at the stripe flanks.
DMD proved to be the best technology for this as it generates gray values by phase length modulation, which can be digitally controlled. Fast switching times of e.g. 5 µs allow for a modulation of a classical video sequence (17 ms frame duration) with a resolution and accuracy up to 1000:1 or 10 bits.

Another technology allowing for digital operation is ferroelectric liquid crystal on silicon (F-LCOS). F-LCOS (other than normal LCOS, with which it should not be mistaken) typically are about 10 times slower than DMD. This translates to a lower gray level resolution for a given frame rate.

Industrial sensors have to be compact. An important issue therefore is power dissipation. The LED lamps used for illumination should and will provide at last 1...2 Watts of actual light power to the chip, which is by no means negligible in case of micro displays. DMD are reflecting 90% of the light. In the OFF state, reflected light is absorbed by an external light trap. Hence, only 10% of the projector light remains in the display and has to be dissipated from there. F-LCOS do not only have an at least 2 times lower efficiency due to their polarizer filters, they also absorb 100% of the light energy in their OFF state. On the chip, this can result in up to ten times the energy intake of a DMD.

Although F-LCOS can be cooled through their underlying silicon chip, thermal influences on the chemical components (LC fluid) may be a matter of concern.

Fig. 1: Functional principle of fringe (stripe) projection
Another issue to be taken seriously with precision applications is the long term and also temperature stability of the absorption mechanisms connected with (F-)LCOS technology. While an absorption change for the entire chip has little influence with fringe projection methods, local changes within the chip area should in any case be avoided. An important issue connected to efficiency is ruggedness of the 3D acquisition against environmental light. An up to three times higher light output as achievable with DLP projection is a definitive advantage here. Conditions with stable, non modulated environment light can be accepted as long as the camera sees enough stripe contrast. Phase measurement works with relative modulation (AC components of the signal), it is ignorant to DC components. Hence, only a sufficient contrast has to be granted for a convenient signal-to-noise ratio. Modulated light sources may interfere with measurement results at lower levels. Yet in practice, even this is widely acceptable, as entire patterns are recorded in one image frame at a time, hence only beat effects between a light source (e.g. a fluorescent lamp) and the frame frequency of the camera may occur. Nevertheless, any single Lux may count in practical applications, deciding if additional light protection is required or not. For us, the various reasons given above led us to base our sensors on DLP projection.

In any case, the computing power that can nowadays be built into an intelligent camera allows to have the camera acquire complete 3D raw images at least. Interfacing to such a 3D sensor can simply be done by industrial Ethernet or other communication buses. The key to this is an intelligent camera powerful enough to execute the fundamental algorithms of fringe projection. Another prerequisite is an autonomous micro projector (pico DLP light engine), combined with a processor module delivering the projection sequences. Obviously it would be unacceptable to rely on projection patterns sent frame by frame, from an external computer by the network.

The software concept we are introducing is highly modular. It comprises a fundamental 3D acquisition module consisting of:

- Fringe projection generator
- Camera synchronization
- Frame sequence acquisition
- Raw distance image calculation

A second module, optional for autonomous sensors, contains image processing algorithms. For this module, several varieties and options are possible:

- 3D image contrasting with following 2D algorithms
- 3D algorithms such as shape matching
- And many more

A third module comprises PC software. This can work in different modes as well, e.g.:

- Setup for autonomous sensors.
- Data analysis for more complex inspection tasks.

2.2 System Architecture and Software

Industrial inspection sensors based on 2D cameras very often are autonomous systems today, with the intelligence built into the camera itself. A typical configuration has a graphical PC interface software for the configuration and test of inspection procedures. Once completed and tested, the inspection itself is carried out by the camera, delivering only such signals as typical for a simple sensor, ‘good’ or ‘bad’ for instance. This is not necessarily sufficient for all applications. In some cases we have complex inspection tasks, also required to deliver protocols with accurate numbers of several object parameters, for quality assurance. In these cases, the solution will more likely be a system with a sensor still performing the 3D acquisition, but with an analysis software running on a PC.
2.3 Hardware

New sensors implemented by GFM, realizing the above explained philosophy, are based on:

- A camera module
- A DLP light engine (pico projector)
- A Digital Signal Processor (TI Da Vinci)

The components fit into a compact, industrial grade sensor housing. We only need two optical windows (camera, projector), and electrical connection mainly relies on industrial Ethernet.

![Fig. 3: Processor stack with DSP and pico DLP light engine](image)

![Fig. 4: System concept with external configuration and autonomous operation](image)
2.4 Advantages of 3D Acquisition

3D images can resolve many details that are hardly recognized by conventional cameras. Fig. 5 shows how even well defined structures appear as meaningless, disconnected lines in a 2D image. The same structures are easily separated to full detail in a 3D image. The same applies to more natural structures, like the example in figure 6, a section of a tire surface (here taken with a GFM-MikroCAD 40x30 hand-held device). Here as well, 3D delivers image data that can easily be exploited by image processing software. Another example are relatively flat structures as in some rubber surfaces. Illumination alone is no means to resolve them properly. Only a 3D image with very good height resolution delivers useful data in this case (fig. 7).

Fig. 5: 2D contour image vs. a 3D height contrast image of the same structure. The 2D image does not reveal complete structures, edges and shapes remain to guessing.

Fig. 6: a practical example of a 2D camera image vs. a 3D height image. With the height contrasted image (left), structures are easily separated.

Fig. 7: Structures in a rubber surface. Although relatively flat, these structures are decisive in certain applications. Only 3D sensors with a good height resolution are adequate for the inspection.
3. APPLICATIONS OF AUTONOMOUS 3D SENSORS

3.1 Industrial Metrology

Originally, the application of fringe projection technology was confined to high-grade laboratory equipment for precision 3D form measurement and digitization. This resulted from the size of the projection equipment, size and power dissipation of light sources, and the computing power required, for image projection as well as for the complex calculations involved with unwrapping the 3D information from the phase images.

Fringe projection succeeded in a large variety of measurement applications in industry, research or medicine. The principle allows for acquisition areas from <1mm to >1m, the accuracy scaling with the field size, starting from fractions of a micron, mainly delimited by optical laws only.

At the lower end of the scale, it competes with white light interferometry for example, which is more accurate at height measurements in the nanometer range, but also extremely slow in comparison.

The high speed of fringe projection could further be increased with progress in computation power and advanced algorithms. For example, we developed biomedical and person identification systems acquiring a 3D point cloud in 1/15 second. This involves conventional projection and camera frequencies (60 Hz). Even much faster acquisition is possible, as our DLP systems already allow for a full gray scale fringe projection up to 200 Hz.

High acquisition speed, robustness of data acquisition against artifacts, and suitable measuring fields available, led to considerations about industrial sensor applications very early. Many dedicated applications have been realized with the traditional technology already, many also as real-time, in-line measuring an inspection systems.

Compact 3D sensors are well suited as additional components in coordinate measuring machines or in tool presetters. The optical area acquisition can either be used self sustained or in combination with tactile sensors or 2D cameras. The left side of Fig. 8 shows an application in a 3D coordinate measurement system.

Autonomous sensors also allow for economical implementation of standard measurement procedures, such as the measurement of tool cutting edges, very important as a defined and perfect edge radius improves cutting speed and quality as well as tool life cycle. Fig. 8 (right side) shows such an autonomous sensor. The only additional component here needed for operating the device is an external touch screen. The most important advantage of this solution is its comparably low cost, making the technology affordable for small workshops and tool grinders.

Fig. 8: 3D-coordinate measurement system with compact 3D sensor (above), Autonomous sensor for tool cutting edge inspection (right)
3.2 Industrial Inspection

With the compactness and small weight of new pico projection based sensors, applications in mobile data acquisition are possible as well. Yet another perfect ingredient for such applications is autonomous operation, and communications via standard networks such as Ethernet, WLAN, or GPRS. The very low power consumption of these sensors even allows for battery operation. This renders the usually required nearby computer or laptop completely unnecessary and leads to a new level of mobility.

Very important with applications of this kind is speed. Hand-held devices cannot rely on a solid tripod, hence unavoidable motions by the operator’s hand have to be countered by a short ‘exposure time’. Recently developed pico projection based units are fast enough for hand-held acquisition even with micrometer resolution, with only a rudimentary mechanical support using a small funnel. Fig. 9 shows operation and data analysis of a mobile weld spot inspection, profiting from these advances. The measuring area here is 18 x 13 mm, the lateral resolution 24 µm, and the height resolution about 3 µm. A complete data set is acquired in a fraction of a second.

Fig. 9: Weld spot inspection with GFM compact hand-held 3D sensor

3.3 Industrial Image Processing

The method’s high accuracy potential allows to build calibrated sensors, enabling in-line measurement (parameter checks etc). A new sensor of this kind is the AreaScan3D, shown in Fig. 10 [4, 7]. This device has a measuring volume of approx. 120 x 75 x 50 mm. It comes in an IP65 compliant housing. The sensor sends recorded 3D data to the evaluation computer via the Industrial Ethernet. Provided are a point cloud or a grayscale-coded range map. The sensor is addressed via a GenICam transport layer (GenTL), whereby it is compatible with any image processing libraries and packages that can communicate with a GenTL, such as CommonVisionBlox [8], HALCON [9] or LabVIEW [10].

Inspections directly in the production line are calling for an entirely automated acquisition and evaluation process. While 3D sensors may be operated by their network connection, the actual inspection being processed in a remote computer, the processing of 3D information directly within the sensor has become another option, with the advent of compact yet powerful processor modules.
Matchbox-sized intelligent cameras and DSPs already deliver enough processing power for basic image recognition algorithms at least. Moreover, 3D delivers edge information a lot easier than with 2D. 2D cameras rely on sophisticated illumination setups to guarantee edge contrast, and even then the recognition of shapes remains difficult. In case of low contrast objects, edge recognition may fail entirely.

3D directly delivers sharp contrast at edges, and there remains no doubt what is higher or lower. This saves a great part of the computing power that 2D usually assigns just for edge recognition. Many other algorithms profit even more, for example the detection of presence or non-presence of specific parts. The advantages are eminent even if 3D is just use for contrasting (replacing intensity contrast by height contrast). In addition, 3D can deliver results such as evenness, or shape fidelity - direct matching of a product form with a taught-in reference part, for example.
3.4 Life Sciences

3.4.1 Skin roughness measurement

Acquisition and evaluation of the surface of human skin is a task that has become a standard aspect of medical and cosmetic dermatology. In particular, for the validation of crèmes and medical active ingredients that affect skin roughness. Apart from more obvious features such as wrinkles and craw’s feet, the fine structure or roughness of the skin is a major concern in these applications. Especially the latter ones are calling for a very high resolution, both for the camera image and for the final 3D image, i.e. height resolution. This high resolution has to be provided for a measurement area of several cm², in order to acquire complete skin features such as wrinkles or scars, and also for a sufficient artistically representation of roughness.

Moreover, the measurement has to be fast, as they are carried out on living persons and slight movements are always present in any practical application.

Phase measuring stripe fringe projection delivers both speed and accuracy, moreover only 4 single phase images are sufficient for almost any application concerning body surfaces (surfaces are continuous). This translates to total exposure times of about 1/15 sec. with standard speed (60 Hz) projectors and cameras.

In cosmetic or pharmaceutical tests, comparative measurements of an identical area are made before and after a treatment with cosmetics or medical agents. Line-, star- and area roughness parameters (Ra, Rz …), derived from industrial standards DIN/ISO 4288, have proven very useful for these.

Fig. 12: Free-hand acquisition of 3D area data (left), statistical analysis of wrinkle depth (PRIMOS software, right)

Fig. 13: 3D reconstruction of a measured skin area (left) with a section line set, and height profile along the section (right)

Fig. 14: 3D reconstruction of a measured skin area (left) and calculation of roughness parameters (PRIMOS software, right)
3.4.2 Large scale 3D acquisition in medicine and surgery

Pico projection technology offers sufficient light output for measuring areas as well. The principle of an integrated sensor with DSP processing and connection via Ethernet has been conducted to the FaceSCAN 3D and BodySCAN 3D measuring devices by GFM, allowing for fast 3D measurement in combination with the acquisition of color textures. An face can be captured with one single measurement in only 140ms, using one device with one projector and one camera (figure 15). The measurement field of the unit is 500 x 400 mm². Because of the Ethernet connection and autonomous data acquisition, up to four of these units can be combined to get a view up to 360°. Fig. 16 shows a combination of two units, for the documentation of surgical treatments and many other applications. This also allows for a comprehensive, wide-angle face measurement; a slightly smaller field of view is used in this case (fig. 17). The use of the newest camera technology in combination with the digital 3D stripe projection provides objective measuring results with high geometric accuracy. Comparative measurements are simplified with a special alignment mode, showing old data and camera images combined and allowing to take 3D scans from the same position even if some time lies in between.

![Fig. 15: Stripe fringe projection using pico DLP technology (left), captured face with color texture (3D reconstruction from measured data, right)](image)

![Fig. 16: Combination of two sensor units (seen to the left and right of the mount) for wide angle 3D acquisition (BodySCAN 3D).](image)

![Fig. 17: Face acquired with twin sensor BodySCAN 3D device, 3D reconstruction with texture (left) and without texture (right).](image)
Compact, autonomous 3D sensors will soon be enabling large new areas of applications, far beyond the realm of laboratory measurement. Hence, an entirely fresh view on possible application areas is necessary. We are still far from recognizing all of these. Some that can yet be anticipated are:

- **Mobile inspection**: Small, hand-held units will allow for perfectly mobile field inspection. The units can be battery operated and may communicate by WLAN or mobile phone channels (GPRS, UMTS) if so desired. Besides inspection, documentation e.g. of material defects or damages will be an important application.
- **Industrial in-line inspection**: This large application area requires autonomous sensors in most cases. 2D cameras with built-in image processing and good/bad decision or parts selection abilities are state of the art. A 3D device as easy to use and as fast as 2D, will bring entirely new abilities, more inspection jobs can be automated, robustness of recognition is improved, and new types of inspection (e.g. shape matching) can be accomplished.
- **Person recognition and surveillance**: Intelligent sensors offer the advantage that the image data acquired does not necessarily have to leave the sensor. This is a requirement due to privacy issues in many cases. Applications of this kind have been realized with 2D cameras already, but 3D may deliver considerable advantages.
- **Robot vision**: Fast frame sequences and large acquisition areas can be accomplished with fringe projection systems, ideal prerequisites for a 3D vision guiding system for robots. Another advantage, speed is not declined by heavy processing requirements as with stereo cameras, and optical artifacts or deceptions are most certainly avoided. Compact, self-sustained 3D image sensors as presented here, are rendering this application a viable solution to many existing problems.

## 5. OUTLOOK AND CONCLUSIONS

We have demonstrated how compact, light weight and fast 3D image sensors can be accomplished by combining intelligent cameras, pico DLP projection and fast DSP modules. First sensor heads with integrated intelligence have been realized. Products currently under development or in their industrial testing phase will integrate image processing and decision abilities.

### REFERENCES


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