3D vision methods and selected experiences in micro and macro applications

H. Hügli, J. Mure-Dubois
Institute of microtechnology, University of Neuchâtel,
Rue Breguet 2, CH-2000 Neuchâtel, Switzerland

ABSTRACT

The paper provides considerations relative to the application of 3D vision methods and presents some lessons learnt in this respect by presenting four 3D vision tasks and discussing the selection of vision sensing devices meant to solving the task. After a short reminder of 3D vision methods of interest for optical range imaging for microvision and macrovision applications, the paper enumerates and comments some aspects which contribute to find a good solution. Then, it presents and discusses the four following tasks: 3D sensing for people surveillance, measurement of stamping burrs, sorting burred stamping parts and finally, hole filling algorithm.

Keywords: machine vision, optical range imaging, 3D vision, 3D sensing, vision applications, microvision, vision software, depth from focus, time-of-flight, interferometry

1. INTRODUCTION

The world in which we are living is three-dimensional and to evolve in it, most animals have developed means to sense their environment. Thus nature has developed different types of 3D vision systems, most based on optical sensing but some also using ranging by acoustic or electric signals. The predominant method, optical triangulation is found implemented in several flavors like stereovision, optical flow perception, parallax viewing, etc.

Nowadays, non-contact sensing can be performed by using different bands of energy waves. Ultrasonic waves are used in sonar systems and microwaves represent the active signal used for synthetic aperture radar (SAR) imaging. On the other side of the electromagnetic spectrum, x-rays are used for imaging the inside of bodies, producing directly classical x-ray images or providing the input for the reconstruction of 3D images by computed tomography (CT). Surrounded by x-rays and microwaves on the electromagnetic spectrum, light waves are finally the dominant support for 3D sensing.

A large number of techniques are available for the purpose of measuring 3D surfaces by optical means and there is not a unique way to classify them. A taxonomy proposed in [1] is close to the domains of application in the sense that it puts some needs of the user in the foreground. The main division is the classification in active and passive systems. The active systems are then divided according to basic physical differences, namely in triangulation and time-of-flight methods. Passive methods on the other hand, all based on geometry, are divided into several classes (stereo, silhouettes, shading, photogrammetry, focus) that differ basically in the reconstruction method they apply. A different taxonomy[2] is proposed to address the performance analysis and physical limitations and is therefore much closer to the physics of light. It proposes a division into triangulation, interferometry and time-of-flight.

From the application point of view, often the choice of the adequate 3D vision method is not obvious, not to mention the choice of a specific vision system. Each method comes with a number of specificities that suit the application more or less and it is not always clear a priori what the right perspectives or compromises are. This paper is devoted to the presentation of work carried on in the perspective of matching 3D vision methods and systems with the requirements of some given tasks. Next section provides a reminder of main 3D vision methods of interest for macro and micro range imaging. Next follows a section giving some considerations for applying them. To illustrate the work in a more specific way, we present in a final section, a selection of four specific 3D vision tasks we investigated in the past.

2. 3D VISION METHODS

This section provides a reminder of main 3D vision methods of interest for macro and micro range imaging.

2.1 Depth from focus – Multifocus 3D microscopy

The depth from focus process is based on the limited depth of field for scenes imaged with high magnification optics. Defocusing will introduce a blurring in the image. By scanning the vertical axis, it is possible to find, for each pixel, the depth corresponding to the best local sharpness. Depth can be computed from a limited number of defocused images or derived from all images obtained by a systematic exploration of the z-range under consideration. *Multifocus* is sometimes used to refer to the later method[3]. Once the scan has been completed, it is also possible to create a multifocus image, where the sharpness has been maximized for all regions of the image.

2.2 Stereo vision

The stereo vision process is based on the simultaneous acquisition of two images, each from a different viewpoint[4]. In stereo microscopy, each ocular corresponds to a different viewpoint. For machine vision, the oculars are replaced with video sensors. Image matching algorithms are then employed to compute the disparity of the image pair and to reconstruct 3D information. The use of a-priori information concerning the object geometry permits to speed up the matching[5].

2.3 Structured light

Light is said to be structured if it is spatially modulated in intensity[6]. If the illumination axis is different from the camera axis, it may be possible to infer the 3D object structure from 2D images obtained with different light structures. From a detection point of view, structured light methods are very easy to implement: the hardware needed is a video camera (with appropriate optics). The difficulty is in the generation and usage of the appropriate illumination pattern. In general, an optimum illumination pattern must be defined for each object to observe[7].

2.4 Chromatic aberration

This method uses chromatic aberration introduced by lenses to find height information. However, the very principle of this measurement makes this method a punctual method. The volume to image must be scanned horizontally with the sensor to obtain a complete image. This method is mostly useful to find range information for a single point and tends to be slow for acquiring range images.

2.5 White light interferometry

White light interferometry is an interferometric method that uses light from a broadband spectral source. During measurement, the object is displaced in z-direction with respect to the microscope and the corresponding interferometric signal is recorded at each pixel location. The range image is derived from the signals recorded by a smart imager[8].

2.6 Confocal microscopy

This method uses the small depth of focus of microscopes. A pinhole light source is imaged onto the object and light from the object is focused onto a pinhole detector. The detected signal is exactly maximal, when the object surface is located in the common focus plane of source and detector. The signal intensity decreases the more the illumination on the surface and the surface image on the detector become blurred. The method requires a scanning in x, y and z in order to generate a range image. The achieved resolution depends on the pinhole size. The use of microlenses permits to remedy the dramatic decrease in measured light intensity due to the pinholes[9].

3. APPLIED 3D VISION

Given a vision task, several aspects contribute to finding a good solution.

3.1 Avoiding 3D complexity whenever possible

Many inspection problems relative to 3D objects can be transformed into 2D problems, which then can be solved more easily by conventional image processing tools. Some means available for this transformation are:

- Enhancing the standard 2D view of an object with additional object sub-images provided by simple ***mirrors*** and reflecting lateral views of the object of interest;
- Using adequate ***illumination*** schemes that contribute to improve the visibility of interesting features;

- Taking advantage of ***color*** and ***spectral*** characteristics of the object or the illumination, as well as possible **polarization** properties;
- Considering the ***spatial*** distribution of sensors;
- Exploiting the ***temporal*** characteristics of the object under study.

3.2 Selecting the right 3D sensor

3D inspection is complex not only because 3D is intrinsically more complex than 2D. A main difference between 3D inspection and 2D inspection is related to the sensing devices used for the acquisition. For 2D inspection, the video camera is widely used. Of course, there are other devices, with different geometries or different spectral sensitivities like multispectral imagers or IR-imagers. It remains that the video camera is ubiquitous. Combined with suited optics, it is in a position to cover a field of view that ranges from roughly 1 µm up to astronomical distances.

This contrasts with 3D vision. 3D sensing methods are numerous and each method has its own specificities. They differ for instance in resolution and in the covered field of view. They also differ by other characteristics like speed, sensitivity to ambient light, robustness, etc. It means that, even if a 3D vision system suits some application, it may possibly not work anymore with a very similar application that however differs in only one of these characteristics. Translating an application to a new scale or moving from an application to another similar application may require a system redesign.

Looking at practically available 3D sensing systems, we obtain specifications for vision methods and corresponding vision systems. As an example, tables 1 and 2 below report possible specifications of vision systems belonging to categories of given vision method. With fields of views in the millimeter range, the systems of table 1 address microvision; table 2 concerns macrovision with metric fields of views.

Table 1: rough example specifications of range imaging systems suited for microvision

method	multifocus 3d microscopy	white light interferometry		chromatic aberration	confocal microscopy	
z-accuracy	2µm	0.01 µm	10 µm	0.01 µm	0.05 µm	1 µm
x-field of view	1mm	0.2 mm	2 mm	scan	0.2 mm	40 mm

Table 2: rough example specifications of range imaging systems suited for macrovision

method	stereo vision		structured light		time-of-flight	
z-accuracy	varies with z^2	varies with z^2	0.1 mm	10 mm	5 mm	50 mm
z-range	0.1 m	10m	0.1m	10 m	1m	10 m

3.3 Considering optimal data processing

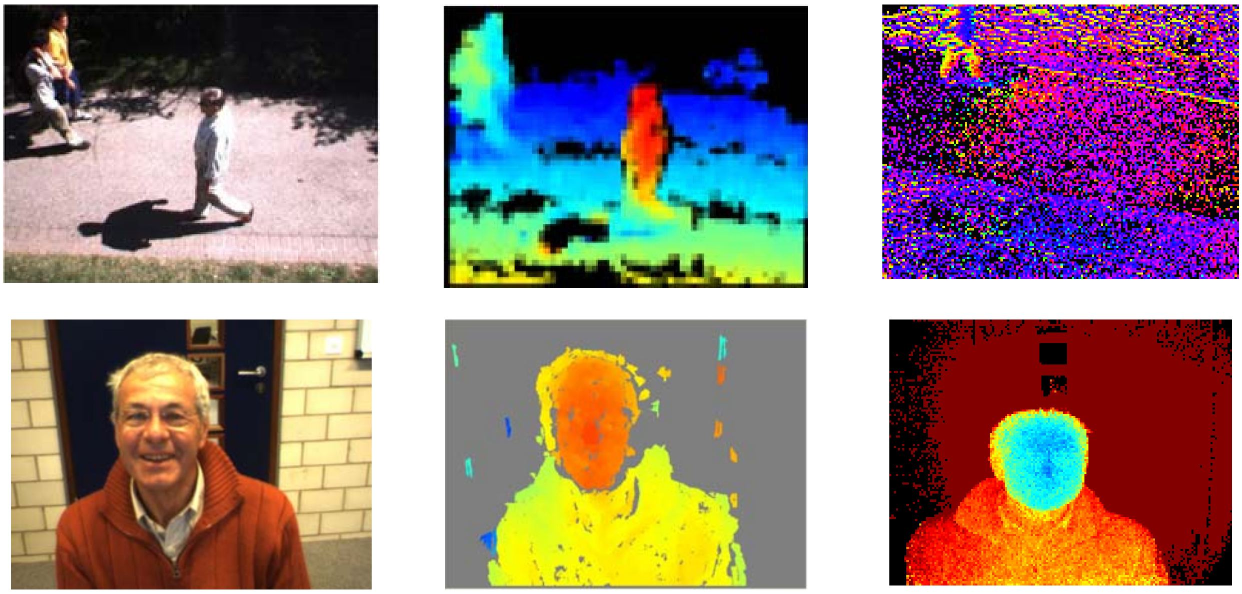
3D vision is not complete without data processing. This aspect comprises a first category of data processing intrinsically required by the measurement principle and in absence of which, obtained measurements are not range values. This category comprises for instance range recovery from the interferometric signal in white light interferometry or similar operation in multifocus. Also the image matching required for 3D reconstruction from stereo belongs to it. The second data processing category addresses postprocessing issues for conditioning the signal and compensating certain errors. Signal offset and gain compensation, signal scaling, data filtering belong to it.

4. SELECTED EXPERIENCES

This section presents four 3D vision tasks and discusses the selection of vision sensing devices for solving the task.

4.1 3D sensing for people surveillance

We consider in this example the task of people sensing for people detection, people counting and general surveillance purposes. A common approach for detecting moving objects in presence of a static camera relies on the principle of change detection and the principle is usually applied to conventional video. Conventional video cameras are thus a straightforward and low-cost solution.



a) video　　b) depth from stereo　　c) depth form TOF

Fig. 1. 3D vision for *pathway site* (top row) and *showroom site* (bottom row)

However, video-based change detection has a number of pitfalls like false-alarms in presence of shadows or foreign light sources. To remedy these errors, we consider therefore 3D change detection and discuss in the following the selection of a suited 3D vision sensor for the two sites illustrated in figure 1a, namely the *pathway site*, which is characterized by outdoors conditions and medium distance range, and the *showroom site*, itself characterized by indoor conditions and close distance range.

In this context, major requirements for 3D sensing are real-time (>5 Hz) acquisition of range images with a depth resolution of 10 cm. Two candidates for the 3D sensor are stereovision[10] and time-of-flight (TOF)[11] cameras. Some basic differences of the two technologies considered are compared in table 3 below.

Table 3: Comparison of TOF and stereo ranging

	TOF	*stereo*
range calculation method	phase shift of sent and received light	disparity computation of stereo pairs
range resolution over Z range	constant over Z	decreases with increasing Z
range accuracy	decreases with increasing Z	depends on surface texture
sensitive to ambient light	yes	no
uses own light	yes, active	no, passive
sensitive to bad surface structure	no	yes
additional processing needed	no	yes

A first critical issue is the maximum range of the systems. TOF has a maximum range, bound to the periodicity of the phase shift measurement, and defined by the manufacturer. It has also a maximum range bound to illumination. Given that TOF is an active method, it has a range limit bound to the value of its S/N ratio. No limit is set to the indoor range, but the range for sunlit outdoor scenes is practically too small for considering this method for the *pathway site*. Figure 2 shows ranges for indoor and outdoor and figure 1.c illustrates the image degradation outdoors very well. Regarding stereo, the range limit is bound to the degradation of resolution as illustrated in figure 2. Practically, using a stereo head with a basis of 10 cm, the resolution becomes quite low at the maximum range of 10 m of the *pathway site*. The resolution is fine for the *showroom site*.

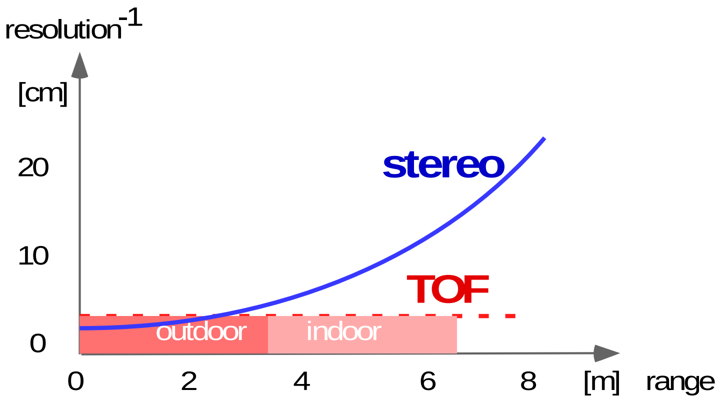


Fig. 2. Performance comparison of stereo with respect to TOF (approx. values)

Regarding the comparison of the two methods in the *showroom site*, both systems provide sufficient range and good resolution. The comparison is dominated by the nature of the active TOF method and the passive stereo method. While stereo tends to fail in low contrast regions, TOF provides more robustness.

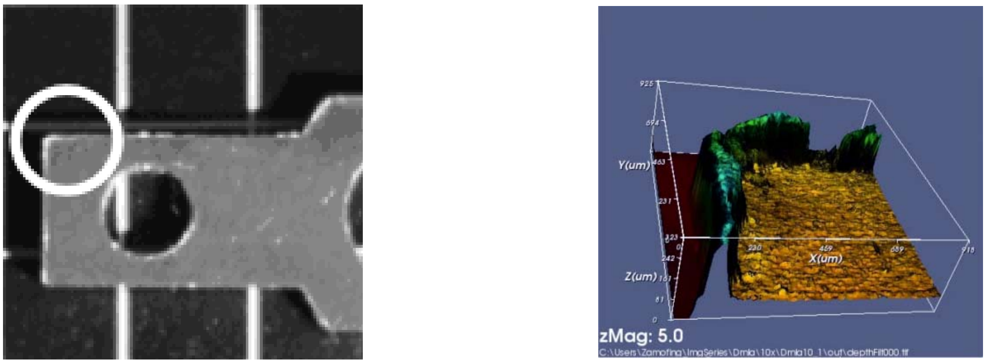
4.2 Measurement of stamping burrs

This example concerns metallic burr measurements. Burrs are a nuisance that almost any tool generate while working on a component. Any deviation of the component from its nominal (i.e. CAD) geometry could be considered as a burr. The smallest burrs of interest, though, seem to have a minimum height of about 5 µm but can be as high as 1mm. Noticeable burrs are often located along the discontinuities (i.e. edges) of the component. Burrs are often irregular and appear as fractured and rough surfaces. There is a real interest to measure the burr height, width, angle at one or few locations of the component, sometimes even to measure the full component.

In this context, major expectations for 3D sensing are real-time acquisition of range images with a depth resolution of 5 µm. Two candidates for the 3D sensor are white-light interferometry[12] and multifocus 3D microscopy[3]. Some basic differences of the two technologies considered are compared in table 3 below.

Table 4: Properties of white light interferometry and multifocus

Property	*White-light interferometry*	*Multifocus*
range calculation method	depth of optimal interference	depth of optimal contrast
uses own light	yes, active	no, passive
Field of view	2 × 2 mm	from 1×1mm to 10×10mm
x-y resolution	14 × 22 µm	1 × 1 µm to 10 × 10 µm
z-resolution	15 µm	10 µm
z-range	1.4 mm	2 − 5 mm
Frame-rate (3D)	1 fps	0.2 fps
System size	40 × 20 × 20 cm3	50 × 50 × 50 cm3
System mass	3 kg	5 kg



(a) Stamping part on a 4 mm x 4 mm grid (b) range map of the marked 50µm burr

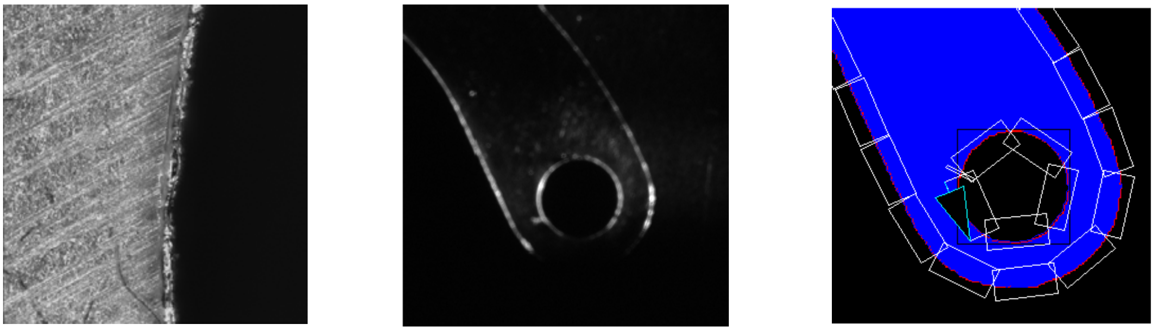
Fig. 3: Measurements of stamping burrs

The quality of range measurements performed by the two mentioned methods does not differ significantly. It is illustrated in figure 3b in the case of a 50µm high, primary stamping burr located on the left corner of the stamping part of figure 3a, and marked by the circle. Thus, both systems seem to qualify from the point of view of measurement quality. None satisfies, however, the speed ultimate goals.

Indeed, considering the problem of measuring the total burr volume of a stamping part of, let's say 200 mm total edge length. A white light interferometer with the properties of table 4 would need to acquire approximately 100 images and this would last for 100 s, opening perspectives of performing off-line quality control. Similar on-line quality control cannot be envisaged yet.

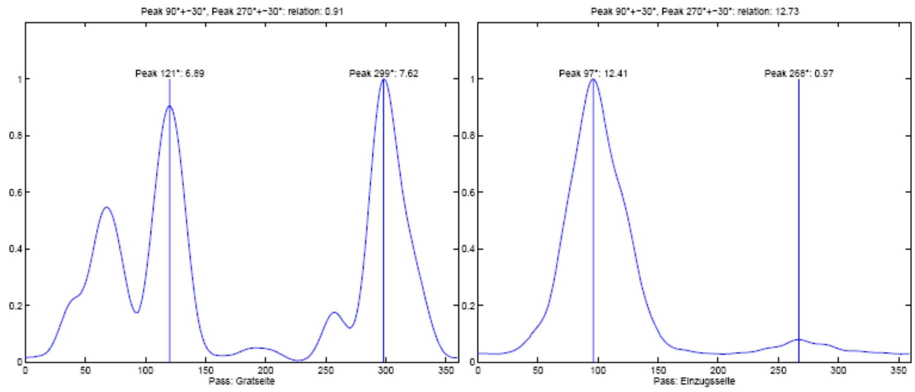
4.3 Sorting burred stamping parts

Let us reconsider above burred stamping parts. Given the nature of the stamping process, stamped parts exhibit different edges on both sides. Clean edges characterize the introduction side while the presence of burrs characterizes the other side. We consider here the task of automatic stamping side detection for the purpose of side sorting prior to specific subsequent processing steps like burr removal, a process which applies differently on both sides of the parts.



a) Detail of burr-side b) Part with oblique illumination c) Edge analysis along the contour

Fig. 4. Burr and non-burr side detection of stamping parts

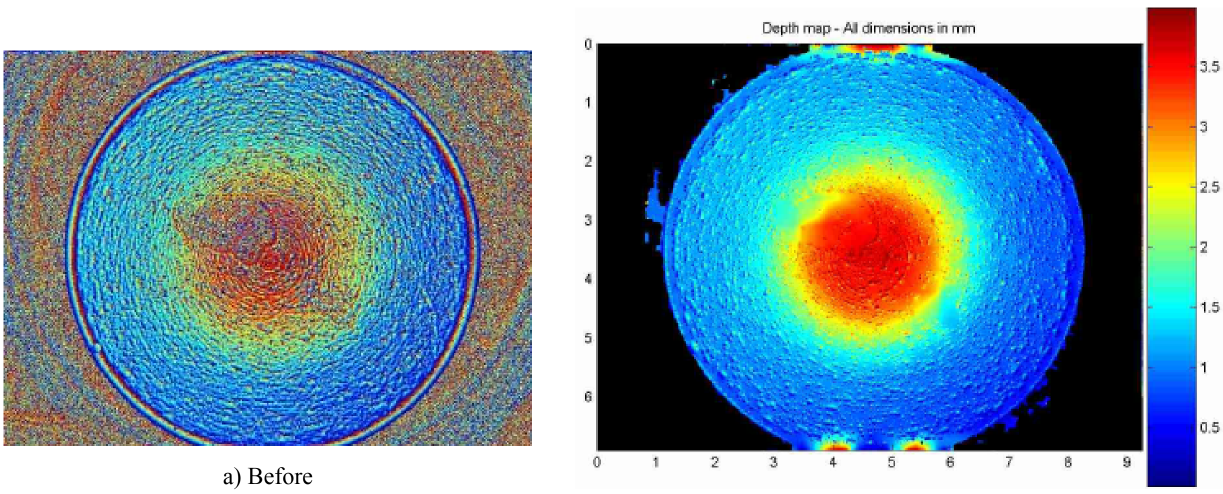


a) Burr-side b) Non burr-side

Fig. 5. Typical contour histograms for the two different stamping part sides

Considering the burr/non-burr side detection problem as a 3D measurement problem, we end up with requirements that are quite difficult to satisfy. Considering namely stamping parts with burrs as small as 10 µm being transported on a 200 mm wide belt running at a speed of 100 mm/s, the requirements would be to acquire 200 M three-dimensional measurements per second, something which is far beyond the capability of 3D sensing systems.

The affordable solution consists in this example in the choice of adequate illumination. Considering namely oblique lighting, it appear that shading is different on edges with and without burrs and thus, this property can be used for discrimination. More specifically, in[13] a method is proposed that relies on the observation that the strongest discrimination between clean and burred edges appears in the two positions when the contour is perpendicular to the incident light: the two positions are characterized by contours facing the light source on one hand and contours facing the opposite direction on the other one. Given I_1 and I_2 the contour intensities for the facing respectively opposite contour intensities, then the ratio $R=I_2/I_1$ is a good discriminator for side detection. It is close to 1 for burred edges and tends to zero for clean edges. Figure 5 illustrates the contour histograms used to extract the I_1 and I_2 value (180 degree shifted peaks). With this method, it appears finally that the stamping side detection problem is solved by a conventional high resolution 2D vision system.



a) Before

b) after

Fig. 6. Range image of a screw tip before and after hole filling

4.4 Hole filling algorithm

Regardless of the type of 3D sensor, range image measurements are affected by noise. As a result, acquired images have values of limited confidence and may also comprise data with no confidence at all, i.e. invalid data points. Based on assumptions relative to noise and continuity properties of the measured object, measurements can be improved by software tools. This example concerns a hole filling algorithm, a method that allows recovering from invalid data or from data with low confidence. In presence of a data point of very low confidence, the algorithm applies the hypothesis of surface continuity and consolidates the point as a function of its neighbors with high confidence.

The hole filling algorithm presented in[14] works according to this principle and performs the consolidation process in an adaptive way in order to reach maximal confidence. An example is illustrated in figure 6 on previous page.

5. CONCLUSION

The authors hope that the presented considerations relative to the application of 3D vision methods and the discussed selected examples help others to develop innovative applications in this field.

ACNOWLEDMENTS

We acknowledge the collaboration with HES-SO in Yverdon, and CSEM SA in Alpnach and Zurich, all in Switzerland, for some of the described activities.

REFERENCES

1. J-A. Beraldin, F. Blais, L. Cournoyer, G. Godin and M. Rioux, Active 3D sensing, Scuola normale superiore Pisa, Quaderni 10, 2000, http://www1.cs.columbia.edu/~allen/PHOTOPAPERS/beraldin.pdf
2. P. Seitz, Unified analysis of the performance and physical limitations of optical range-imaging techniques, Proc. First Range Image Research Day, Zurich, 2005.
3. Thierry Zamofing & Heinz Hügli, " Applied multifocus 3D microscopy", Proc. SPIE, Vol 5265, pp, Oct. 2003
4. Nykon, Introduction to stereomicroscopy, 2004, http://www.microscopyu.com/articles/stereomicroscopy/stereointro.html.
5. Gaudenz Danuzer. Quantitative stereo vision for the stereo light microscope : an attempt to provide control feedback for a nanorobot system. PhD thesis, ETH Zurich, 1997
6. Joaquim Salvi, Jordi Pagès, Joan Batlle, Pattern codification strategies in structured light systems, http://eia.udg.es/~jpages/coded_light/index.html
7. L.-S. Bieri and J. Jacot. Three dimensionnal vision using structured light applied to quality control in production line. Proc. SPIE , vol. 5457, pp 463–471, Sept. 2004
8. M. Fleischer, R. Windecker, H.J. Tiziani, "Fast algorithms for data reduction in modern optical three-dimensional profile measurement systems with MMX technology", Applied Optics, Vol. 39, No. 8, S. 1290-1297 (2000)
9. Tiziani H. J., Wegner M., Steudle D.; "Confocal principle for macro- and microscopic surface and defect analysis", Opt. Eng. 39 (1), 32-39 (2000)
10. Bumblebee, http://www.ptgrey.com/products/stereo.asp
11. SwissRanger, http://www.swissranger.ch/
12. Heliotis AG, http://www.heliotis.ch/.
13. T. Zamofing & H. Hügli, "Fast stamping side detection", Proc. EOS Conference on Industrial Imaging and Machine Vision, 13-15 June 2005, pp 127-128, Ed. EOS, Hannover, 2005
14. T. Zamofing & H. Hügli, "Range Image Filtering Using Reliability Information", Proc. SPIE Vol. 5606-16, 2004