# DEVELOPMENT OF A CCD CAMERA BASED REFLEX GONIOMETER

M. Fuhrland

Institute of Geodesy, Technical University Dresden, Helmholtzstraße 10, 1062 Dresden, Germany - Matthias.Fuhrland@tu-dresden.de

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**ABSTRACT:**

The article describes the development of a reflex goniometer for biaxial angle measurement of a gimbal mounted mirror by means of a CCD camera. After the state of the art the measurement principle and the optical setup are explained. Investigations concerning the accuracy of a laserspot detection using a CCD and the results of temperature calibration are shown. Several centroid computation methods and correlation methods are compared to determine the beam position on a CCD. Standard deviations below 10 nm were achieved for the 2D spot position by averaging over 30s measurement duration using a 3D gaussian fit.

**KURZFASSUNG:**

Der Beitrag beschreibt die Entwicklung eines Reflexgoniometers zur zweiachsigen Winkelmessung eines kardanisch aufgehängten Spiegels. Nach dem Stand der Technik werden das Messprinzip und der Versuchsaufbau erläutert. Untersuchungen zur Genauigkeit der Detektion eines Laserspots mit einer CCD und Ergebnisse der Temperaturkalibrierung werden vorgestellt. Verschiedene Methoden der Centroid-Berechnung und Korrelationsmethoden zur Berechnung der Strahlposition auf der CCD werden verglichen. Für die zweidimensionale Lage des Laserspots wurden durch Mittelung über 30s Messzeit Standardabweichungen unter 10 nm erreicht.

## 1. THE TASK

One aim of the project "Ultra precise 3D Positioning with indirect sight" sponsored by the DFG was the development of a reflex goniometer for biaxial angle measurement of a gimbal mounted mirror (see Fig. 1). The mirror is used for defined deviation of a ranging laser which runs coaxial with the pivoting axis of the gimbal. A high precision measurement of the tilt angle $\Phi$ and the pivoting angle $\vartheta$ of the deflected beam within the coordinate system xyz was the task to solve. The main goal of the project was to measure hidden points directly by ranging around the corner. Possible applications can be plumbing and vertical direction transfer in deep shafts or industrial positioning tasks. The research was done by the Geodetic Institute and the Institute for Applied Photophysics at the University of Technology Dresden.

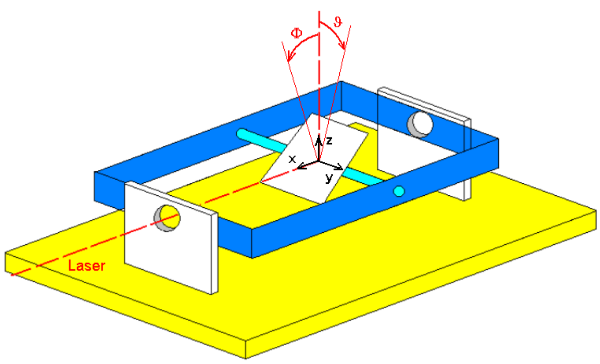


Figure 1. Measurement of $\Phi$ and $\vartheta$ within the gimbal

## 2. STATE OF THE ART FOR BIAXIAL ANGLE MEASUREMENTS

For the biaxial angle measurement there are miscellaneous solutions in geodesy, photo physics and metrology. A roundup of technologies was published by (Schwarz, 1995). Precision inclinometers based on electrolyte levels, liquid horizon, pendular systems or acceleration sensors, but also systems with piezo actuators or voice coil actuators yield measuring results with high precision but only for small or very small angular ranges.

To use the whole angular range of 360° in both rotation axes precise graduated circles became widely accepted like they are used in theodolites, Total stations or in CNC-machines. Here a measurement happens directly at the axis. It is based on a photoelectric relay which samples the circle that is joined with the axis. Another method for direct sampling of the axis is the InductoSyn technique. It measures the change of an induced current while turning the axis. Capacitive angle sensors reach a sampling rate of 10 kHz with a resolution of 0,1° and therefore they are often used in industrial and automotive applications (Brasseur/Brandstatter/Zangl, 2003).

A 3D tracking system with dynamic biaxial angle measurement is offered by the american company Arc Second under the name „Indoor GPS“. For its positioning the receiver measures the time delay of two laser pulses which are generated by rotation of two laser planes. The planes are inclined to each other and come from a rotating transmitter. With knowledge of the inclination angles and the horizontal angle delay of the planes, the rotation speed of the transmitter and using an additional time mark (strobe LED) the horizontal and vertical angle to the receiver can be measured. Measuring the signals of at least two transmitters with known coordinates the 3D position of the receiver can be determined with an accuracy between 0,1 mm and 0,3mm over ranges up to 30m (ArcSecond, 2002).

The approach described here offers possibilities for a biaxial measurement by a universally applicable system which is independent from the axes.

## 3. PRINCIPLE OF THE REFLEX GONIOMETER

The innovative approach consists of placing an optical deviation device coplanar to the gimbal mounted mirror and tilting and pivoting it together with the mirror. This deviation device can be plane parallel plate or preferably an etalon. It is used to shift a laser 2, which runs parallel to the ranging laser 1, depending on the tilt angle Φ and the pivoting angle ϑ parallel in two dimensions. The two-dimensional shift of the laser has to be measured highly precise by means of a position detector.

The plane parallel plate is often used as a deviation device in geodetic instruments. The plane parallel shift happens here by means of the refraction effect. But by use of a laser some problems occur because the transversal beam profile and the power of the laser are altered due to multiple reflections, dispersion, absorption and polarisation splitting depending on the tilt angle.

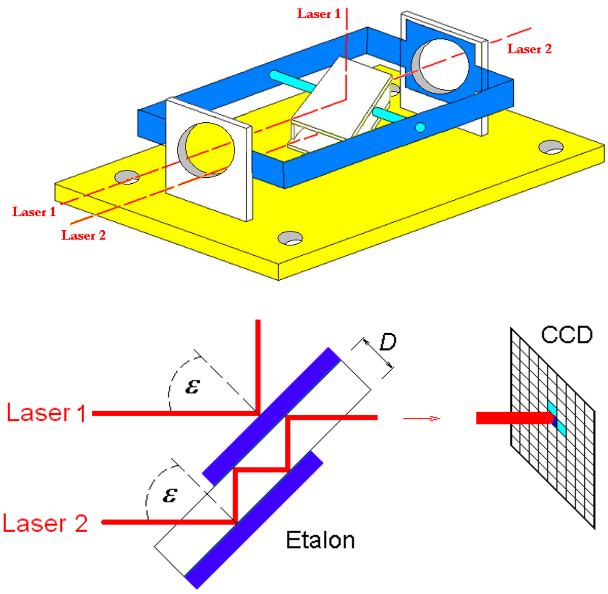


Figure 2. Principle of the reflex goniometer with etalon

The smartest way to avoid the problems occurring by use of a plane parallel plate is to use the effect of reflection instead of refraction for the parallel beam shift. Instead of the plate a so called etalon has to be placed into the gimbal (see Fig. 2). The etalon consists of two plane parallel plates with fully mirrored surfaces. Between the inner mirror planes the laser is parallel shifted by reflection. The resolution of the tilt angle is much higher than by use of the plate. It can be increased at will by means of multiple reflections but the angular range is reduced to the same degree. The effects of dispersion, absorption and polarisation splitting, which are relevant using the plane parallel plate, do not occur here. The determination of the refractive index of the plate can be omitted and stringent monochromasia of the laser is not necessary.

In case of double reflection the beam shift $v$ can be computed in dependence on the angle of incidence $\varepsilon$ at the mirror plane by

$$v = 4 \cdot D \cdot \sin(\varepsilon) \tag{1}$$

D denotes to the distance between the inner mirror planes, which is 10 mm for the prototype. The geometric resolution increases with the angle of incidence. The placement of the position detector determines not only the measuring range but also the attainable accuracy. For biaxial angle measurement, i.e. tilting and pivoting the etalon, a vectorial splitting of the shift amount into $v_y$ and $v_z$ results with

$$v = \sqrt{v_y^2 + v_z^2} \tag{2}$$

The coherence to the tilt angle Φ and the pivoting angle ϑ follows up by

$$\Phi = 100\,gon - 2\varepsilon \tag{3}$$

$$\vartheta = \arctan \frac{v_y}{v_z} \tag{4}$$

$v_y$ and $v_z$ are the really measured values which have to be recorded by means of the position detector. Tilting and pivoting of the plane parallel plate or the etalon cause a parallel shift of the beam without a rotation of the beam profile. That means only translations occur between the internal 2D coordinate system (beam profile matrix) of a not rotation-symmetric laserspot and the 2D coordinate system of the position detector. For an easy computation of these translations it is useful if both coordinate systems stay parallel. The latter condition is omitted if the beam is rotation-symmetric.

## 4. EXPERIMENTAL SETUP

Based on these considerations the following optical and mechanical breadboard construction was realized in the lab (see Fig.3). By means of a convex lens a laser is focussed on a CCD chip over a length of nearly 50cm. To get the optimum beam quality the laser is first coupled into a single mode fiber. The fiber core with approx. 5µm diameter is surrounded by a 125µm cladding, which is again covered by a 250µm acrylic jacket. The light coupled into the fiber propagates along the core and partially in the cladding. It is coupled out at the free end of the fiber. The beam coming out of the fiber possesses only one transversal mode which is perfectly gaussian. The free end of the fiber is threaded into a cannula which is mounted on an adjustable fiber positioner with a lens holder made of invar. This special construction has to keep positions of light source and focussing lens stable independently from the temperature. Before the beam meets the CCD it passes the gimbal mounted etalon and a neutral grey filter mounted at the camera housing instead of a lens to prevent irradiation of the CCD.

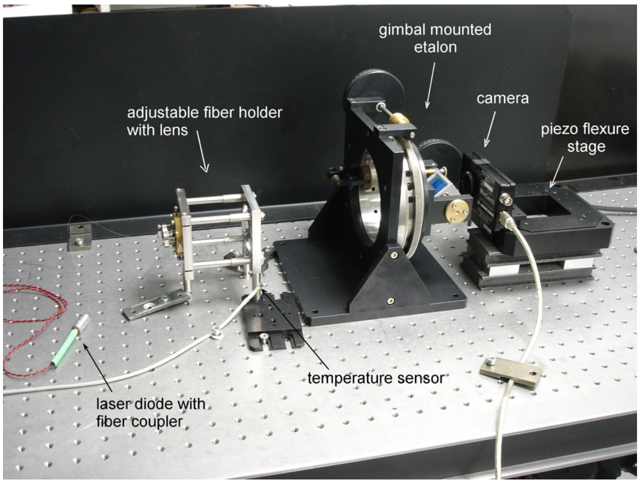


Figure 3. breadboard construction

The tested camera system WinCamD from the american company DataRay was designed for laser beam analysis. It works with interline transfer, has got an automated exposure time control and can measure 4 full frames per second. By means of software the size of captured window can be decreased. Thus higher frame rates are possible. The CCD sensor used is an ICX205 AL from Sony with 1360x1024 active quadratic pixels and pixel size 4,65 µm.

According to production depending conditions of the english company SLS Optics the gimbal mounted etalon was designed so that a measurement from both sides of the etalon is possible and the angular range $\Phi = \pm 20$ gon due to double reflection of a laser with 2,5 mm radius can be used. The angular range for the pivoting angle amounts $\vartheta = \pm 23$ gon for $\Phi = + 20$ gon and $\vartheta = \pm 20{,}5$ gon for $\Phi = - 20$ gon. The distance *D* between the inner mirror planes amounts 10 mm. According to manufacturer information the surface flatness of the etalon planes is approx. 6nm $(^{\lambda}/_{100})$. That means, the deviation of parallelism of the etalon planes shouldn't be more than 0,015 mgon. The etalon is mounted in an aluminium frame which again is mounted in the tilt axis of the gimbal. The gimbal was constructed by the Freiberger Präzisionsmechanik company. At both gimbal axes a fine tuning screw is mounted with a scale and a small drive ratio. The scale resolution is 0,56 mgon for the tilt angle and 2,73 mgon for the pivoting angle.

To investigate the functionality and accuracy of the system the camera was mounted on a three-dimensional piezo flexure stage P517.3CL from Physics Instruments. The piezo flexure stage has got a travel range of 100 µm for the horizontal axes with an accuracy of 1nm in closed loop mode. In the vertical axis the stage has got a travel range of 20 µm with an accuracy of 0,5 nm in closed loop mode. The latter means that the actual position is checked and readjusted by means of capacitive sensors. Thereby the drift of the piezos can be compensated. The large scanning range is realized by piezostacks, the extremely high parallelism is reached with a parallelogram suspension. The piezos are driven by means of a controller, which again can be controlled via RS232- or IEEE-port by a PC. For the common control of flexure stage and camera a software was developed. Several methods of beam positioning were integrated into this software.

## 5. INVESTIGATIONS CONCERNING THE ACCURACY OF BEAM POSITIONING USING A CCD

There are several methods to determine the beam position on a CCD. As static methods, i.e. without moving the camera, possible solutions are the computing of the peak position, the computing of the centroid or the geometric centroid, the correlation with a measured beam profile or a model profile (e.g. gauss fit) or the Fourier-Method (Weißhaar et al., 2003). The WinCamD offers some of them in its standard software. As kinematic method the Pixelscanning was developed. Below the tested static approaches to determine the position of a laserspot with a diameter of 15 up to 30µm are discussed. The diameter is defined here by the full width half maximum (FWHM) of the transversal beam profile.

The c*entroid method without a cliplevel* and with cliplevel equal to zero respectively has got the advantage of independence from laserpower and its fluctuations. The three-dimensional centroid of the whole picture figure is computed. Nevertheless the result can be distorted if the pixel values around the small laser spot are not zero, but influenced by noise or adventitious light. Depending on the window size and the position of the laserspot within the window the error can amount up to some µm.

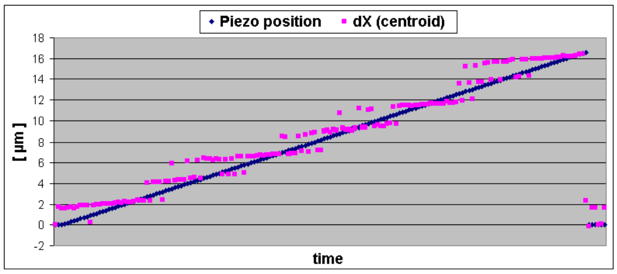


Fig. 4 : resolution of the centroid method

The c*entroid method with a fixed cliplevel* (fixed grey tone) includes only pixels with a grey tone above the cliplevel to compute the centroid. The method shows fluctuations in positioning between 0,1 up to 1,3 µm (see Fig.4). Particularly for very small laserspots this can be explained by the extreme influence of fluctuations in power or direction of the laser in the regions of the profile edge. The figure shows the comparison between the spot position changes measured within the picture and the position changes of the piezo flexure stage where the camera was mounted on. The centroid method with a dynamic cliplevel (percentage of the actual maximum grey tone) doesn't show much better results because of the small changes in the peak level.

The same can be stated for computing the g*eometric centroid*. It means the centroid of the intersection area making a horizontal cut across the picture figure in the height of the cliplevel. Also this method shows jumping position changes in the µm-range depending on pixel- and spotsize.

Using c*orrelation methods*, e.g. the least squares matching, a resolution of 1/50 pixel can be reached (Maas, 1992). A correlation of the CCD picture with a gaussian curve makes sense because of the gaussian transversal profile of the laserspot. The Gauss fit conforms an equalizing normal distribution curve. A two-dimensional Gauss fit of the laserspot each in Y- and Z-direction was done by computing a normal distribution curve as equalizing function for the pixel values of the line and column that contain the peak pixel. The mean values of both curves define the spot position. As it can be seen below this method shows better results than the centroid method.

A three-dimensional Gauss fit was used among others by (Langhans, 2005) to detect positions of stars and planets within a CCD picture. It is ideally suited to detect a laserspot position. The applied mathematical algorithm was the computation of a bivariate normal distribution as equalizing function for the pixel values of an 11x11-Pixel-Matrix around the peak pixel. The matrix is to dimension according to the spotsize and the spacing of further airy rings. Because of the higher redundancy the graduation delivers a more accurate result than the two-dimensional Gauss fit which could be approved experimentally. The resolution achieved lies in the range of several nm for a spotsize of approx. 15µm.

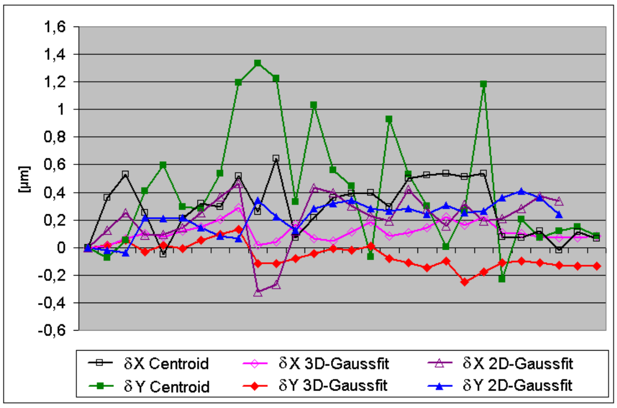


Fig. 5: differences to the reference position

The listed methods have been integrated into the software and tested in comparison. To minimize the impact of other disturbing factors for this measurements the focal length and the exposure time were set up very short. Fig. 5 shows the single shot accuracy of three methods in comparison in terms of differences to the reference position. Using the piezo flexure stage a range of 10µm in y- and 10µm in z-direction with a step width of 1µm was scanned. It is clearly visible that the three-dimensional Gauss fit yields the smallest residuals. Further investigations showed at each method a larger spread in one pixel intervals. This effect can be traced back to the sensor architecture. The fill factor of the interline CCD amounts only approx. 70%. So for small laserspots an important part of the light shines on the nonsensitive areas between the microlenses. Already slight fluctuations of the beam direction cause jumping changes of the computed spot position if the power maximum lies in this area. By use of a fullframe or frame transfer CCD this effect should not occur. But using this one would have to work with a mechanical shutter which had to be synchronized with the laser. The laser should be switched on shortly after opening the shutter and switched off shortly before closing it, otherwise the beam profile in the picture is falsified.

Stochastic errors, like the noise of the CCD or fluctuations of the beam direction caused by air trouble or mechanical vibrations, can not be minimized by a single shot. Air trouble can arise from spatial density fluctuations and resulting changes of the refractive index (refraction). It can be caused by air turbulences and temperature gradients crosswise to the laser beam. Resulting fluctuations of the beam direction can amount up to 10 µm/m under normal conditions (Schüssler, 1971). Retaliatory actions are encapsulation of the optical path and a low-pass filtering of the measured data. I.e. to reach higher accuracies for the spot position an averaging over several measuring epochs has to be done. For this the window size was decreased to achieve a higher frame rate. By averaging over e.g. 100 measuring epochs much higher accuracies could be reached statistically in a maintainable measurement duration. But first the higher amounted systematic error arising from the temperature dependence of the mechanical and optical setup has to be calculated.

## 6. TEMPERATURE CALIBRATION

During the design process for the mounting of the optically operative components the highest thermal stability was minded. The etalon is made of Zerodur. The fiber positioner with included lens holder is made of invar. The fiber was pasted into a cannula and this again was fixed by means of thermally stable glue inside the positioner. The remaining dependence of the mechanical and optical setup on the temperature was investigated with a fixed position of the piezo flexure stage. Synchronously to the picture capture the sampling of an analogue temperature sensor via a 16bit A-D converter card was programmed. By averaging over several measuring epochs its accuracy was statistically increased to 0,02K. The placement of the temperature sensor at different parts of the mechanical setup showed, that the temperature inside the camera itself has got the highest correlation with the measured spot positions. While measuring the temperature at the fiber holder, at the gimbal, at the breadboard or at the flexure stage the autocorrelation of the curves only after approx. 1 hour reached a maximum. The placement of the sensors inside the camera housing yielded an autocorrelation maximum of 95% after 2 minutes already. The attempt to stabilize the housing temperature using a controlled peltier cooling didn't show the desired results. Therefore a calibration is necessary. The used CCD did not only show a vertical drift of 2,7 µm/K but also a horizontal thermal drift of approx. 4 µm/K. The correlation with temperature was much better in the vertical than in horizontal direction (see Fig. 6).

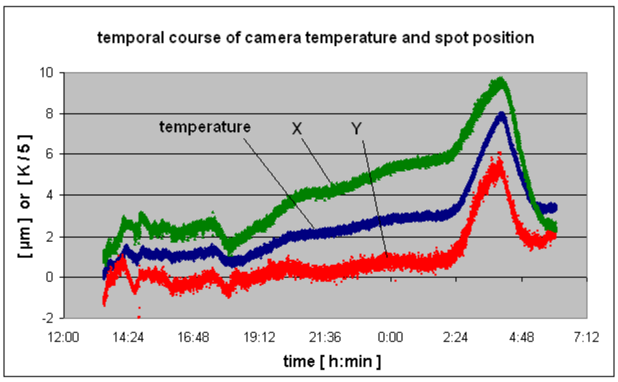


Fig. 6: temporal course of camera temperature and spot position

The problem of nonlinearity visible especially in the right part of the figure depends on the horizontal adjustment of the fiber optics. This could be ascertained by a measurement using the camera turned by 90°, where the correlation was quite good in the horizontal direction but not in the vertical direction of the picture. The different drift amounts could be traced back to the mounting of the board inside the camera housing. Opening the housing revealed that the board was only screwed on the left end, so that the thermal expansion of the board mainly causes a horizontal drift. Moreover the FireWire socket was at the right (free) end, so that also the stiffness of the cable could cause deviations from linearity. Unfortunately this mounting problems couldn't be solved with the used camera. But with better mounted CCD sensors the calibration should yield good results in both axes. During measurements, where the thermal drift was linear, the standard deviation of a 2 second measurement (average of 20 pictures) in one axis is less than 100nm after drift correction. Encapsulation of the optical path decreases the standard deviation by a factor of 2. So for the 2D spot position a standard deviation of 20nm was achieved for the average of 600 single shots (1 minute measurement duration) with a focal length of the laser of 0,5m (see Fig.7). With shorter focal

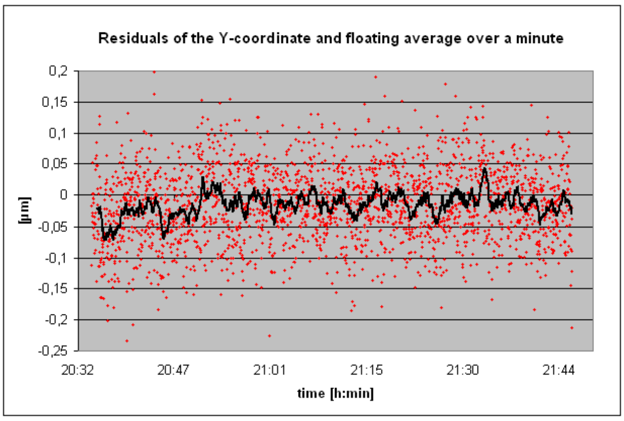


Fig. 7: Residuals after linear temperature correction

lengths, i.e. a shorter distance between lens and camera, the positioning noise of the laserspot was obviously smaller and standard deviations below 10nm were reached with averaging over 30s measurement duration. Nevertheless these values are not to interpret as absolute accuracies considering the background of nonlinear thermal effects and the influence of the nonsensitive areas between the pixels.

## 7. OUTLOOK

Fullframe sensors are available with very large size (actually up to 4cm x 5cm), which enables a large angular range with very high accuracy. In the present configuration the intersection angle could theoretically amount $0 \leq \varepsilon < 90°$. For $\Phi$ this would enable a range of $-90 \leq \Phi < 90°$. A high linearity and calibration accuracy can be expected with a fill factor of 100% and thermally stable mounting of the CCD.

According to the DFG project possible applications of the technology can arise from a combination with a measurement of pseudo ranges using a pulsed laser. The method is called 3D-Positioning with indirect sight (Fuhrland/Eng/Möser, 2004). The reflex goniometer can also be used to deflect the ray of sight or the laser of a Total station. Therewith the Total station could be used e.g. for oblique plumbing down in all kinds of shafts. Contrary to other instruments the reflex goniometer can work headfirst. With a corresponding design of the etalon the reflex goniometer can also serve as biaxial inclinometer.

The principle of laserspot positioning can also be used in a dispersometer. While (Böckem, 2001) used a modified 4-quadrant-diode and the gap area between the quadrants for laserspot positioning, the principle could be realized with CCD too. By means of the three-dimensional Gauss fit as shown above accuracies can be reached like (Schwarz, 1999) arrogated for positioning within a dispersometer.

**References**:

ArcSecond, 2002: *Constellation 3D-i Error budget and specifications*, White paper 063102 Arc Second Inc., http://www.indoorgps.com (accessed 10 Apr. 2006)

Böckem, B., 2001. *Development of a Dispersometer for the Implementation into Geodetic High-Accuracy Direction Measurement Systems*, Dissertation ETH Zürich, IGP notes no. 73

Brasseur, G., Brandstatter, B., Zangl, H., 2003. *State of the art of robust capacitive sensors*, ROSE' 03 1st IEEE International Workshop on Robotic Sensing 2003 : sensing and perception in 21st century robotics, Örebro University, Sweden, http://ieeexplore.ieee.org/xpl/tocresult.jsp?isNumber=27394 (accessed 10 Apr. 2006)

Fuhrland, M., Eng, L., Möser, M., 2004. 3D-Positionierung mit indirektem Sichtkontakt, *Ingenieurvermessung 2004, 14th International Course on Engineering Surveying*, ETH Zürich, pp. 349-354

Langhans, R., 2002. A universal computer program for high precision position determination of minor planets on CCD-frames. In: *Proc. JOURNÉES 2002*, Bukarest, Romania

Maas, H.-G., 1992. Robust automatic surface reconstruction with structured light, *International Archives of Photogrammetry and Remote Sensing*, Vol. 29 (1992), Part B5, pp. 709-713

Schüßler, H.H. : Die Eignung von Laser-Strahl und photoelektrischen Detektoren zur Messung der Abweichung von Geradlinigkeit und Ebenheit im Maschinenbau, Dissertation RWTH Aachen, 1971

Schwarz, W., 1995. *Vermessungsverfahren im Maschinen- und Anlagenbau*, DVW Schriftenreihe no. 13, pp. 97-156

Schwarz, W., 1999. Neuere Entwicklungen in der Ingenieurgeodäsie, *Vermessung und Raumordnung* Vol. 61 (4+5), pp. 251-257

Weißhaar, E., Küveler, G., Bianda, M., 2003. Schnelle und genaue Methode zur Schwerpunktfindung in Messreihen, *Photonik* 1/2003