

# HIGH-PRECISION OBJECT MONITORING WITH IMAGE ASSISTED THEODOLITES - STATE OF THE ART <sup>1</sup>

*Kahmen Heribert and Reiterer Alexander*

*Institute of Geodesy and Geophysics, Engineering Geodesy, Vienna University of Technology*

*heribert.kahmen@tuwien.ac.at, alexander.reiterer@tuwien.ac.at*

## **Abstract:**

In the past, high-precision online 3-D measuring required artificial targets defining the points on the objects to be monitored. For many tasks like monitoring of displacements of buildings, artificial targets are not desired. Today's image assisted theodolite systems can perform their measurements even without targeting. Such systems use the texture on the surface of the object to find "interesting points" which can replace the artificial targets. However, well-trained "measurement experts" are required to operate such a measurement system. In order to make such systems easy to use even for non-experts, it can be extended by an appropriate decision system which supports the operator. We report on the state of the art of such image assisted theodolite measurement systems and on the potential of future developments. Mainly, research work carried out at the Vienna University of Technology and Leica Geosystems (Heerbrugg) will be described here.

## **1. INTRODUCTION**

In science and industry increasingly 3-D representations of objects in the built environment are needed with high accuracy. Meanwhile a greater number of optical 3-D measurement techniques is available: laser scanners, photogrammetric systems, measurement robots, theodolite measurement systems [3]. In comparison with laser scanners and measurement robots theodolite measurement systems measure objects with higher accuracy, compared with photogrammetric systems in many cases they can easier be used for on-line measurement processes. This will especially be the case, if the theodolite measurements can be performed with a high degree of automation.

Today theodolites measure directions automatically with electronic sensors. The axes are driven by motors controlled by a computer, automatic pointing is possible if especial cooperative targets or active targets are used, and data can be captured, stored, and evaluated without human interaction. A higher degree of flexibility and automation, however, will be possible, if no longer special targets must be fixed on the objects to be monitored.

This will be possible, if image assisted theodolites are used. This kind of theodolite has a CCD camera in its optical path. The images of the telescope's visual field are projected onto the camera's CCD chip. The camera is capable of capturing mosaic panoramic images through camera rotation, if the axes of the theodolite are driven by computer controlled motors. With

---

<sup>1</sup> This work is supported by the Austrian Science Fund (FWF) Project P14664.

appropriate calibration these images are accurately georeferenced and oriented as the horizontal and vertical angles of rotation are continuously measured and fed into the computer. The oriented images can then directly be used for direction measurements with no need for object control points or photogrammetric orientation processes.

In such a system viewing angles must be addressed to CCD pixels inside the optical field of view. That means, especial calibration methodes have to be used for the theodolites, an autofocus unit has to be added to the optical path, and special digital image processing procedures have to be used to detect the points of interest on the objects to be measured. As will be shown, such systems are very sophisticated, and therefore highly qualified experts are used to handle them. This, however, can be overcome, if the instrument is supported by tools of artificial intelligence.

## **2. THE OPTICAL SYSTEM**

An optical system for an image assisted theodolite was developed by Leica [16]. It is reduced to a two-lens system consisting of the front and the focus lens. Instead of an eyepiece a CCD sensor is placed in the intermediate focus plane of the objective lens. The image data from the CCD sensor are fed into a computer using a synchronized frame grabber. For the transformation of the measured image points into the object space the camera constant must be known. In an optical system with a focus lens the camera constant, however, changes with the distance of the object. The camera constant can be derived from the focal length. This can be performed automatically if an encoder measures the focus lens position relative to an origin, which is chosen when focusing to infinity. Now the optical mapping model includes not only the theodolite's axis errors and the vertical index error, but also errors resulting from a displacement of the projection center from the intersection of the theodolites axes and from the optical distortions for field points. Consequently calibration of an images assisted theodolite has to comprise all these errors [16].

## **3. IMAGE ASSISTED THEODOLITE FOR VISUAL POINTING**

The key element of a semi automatic system (developed at the Vienna University of Technology) is a vision software that supports the operator to identify "natural targets" on the surface, which he can intuitively reduce to features of simple geometrical forms. The main goal of the measurements is, to find points of interest with such a distribution and density that the geometrical interpretation of the object's surface is possible.

The work-flow of the vision software is shown in Figure 1. The main steps are image formation, image preprocessing, iconical image processing, image feature extraction, image interpretation, and image analysis [13, 6].

Image formation involves the light source and the object reflecting the light. The real scene is transformed into a two dimensional function of the object and stored as a matrix of grey values. The hardware contains amplifiers, A/D converters, frame grabbers, and additional devices. The preprocessing software enables improvement of the radiometric quality of the images and enhancement. The radiometric quality is influenced by different handling of the grey value diagrams and enhancement includes improvement of the geometric quality of the image

and data reduction by applying digital filtering. The result is an inconical image which is now more suitable for feature extraction and detection of interest points.

Iconical image processing is used to create new images, finally resulting in sets, containing the desired information. Image feature extraction (segmentation) comprises searching the objects of interest from the rest of the scene with the aim of partitioning the image into various clusters. Thresholding is a special method for that. Figure 2 shows a result, taken from a facade. Finally the operator has to extract feature information from the enhanced and segmented images and analyze whether it can be identified targets. As mentioned in Chapter 2, there is no standard telescope reticule in the telescope's visual field. Therefore, for visual pointing a reticule has to be added to the optical system by special image processing software. This reticule then can be used for the alignment of the extracted targets (features) on the object. For the alignment procedures a display is used.

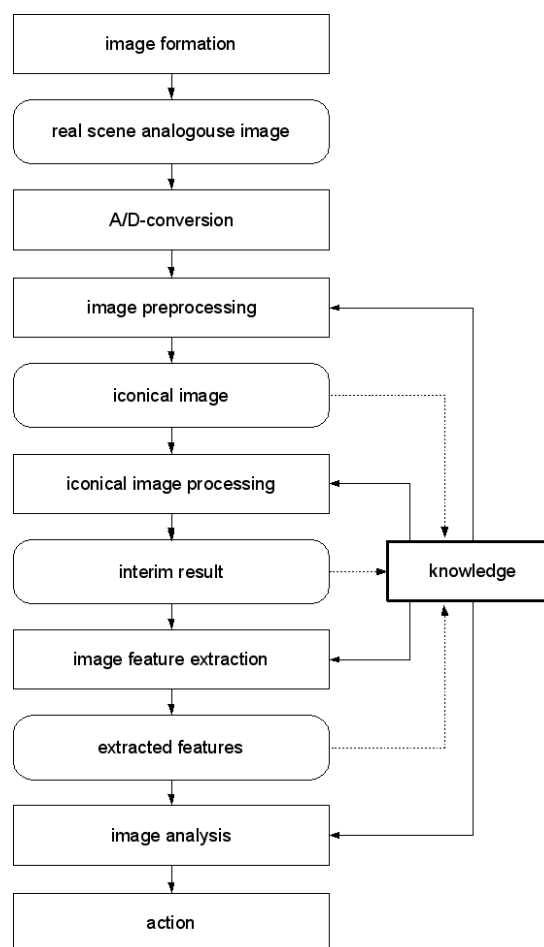


Figure 1: Work-flow of the theodolites vision software [13, 6].

To test the measurement sytem, a facade was monitored. About twenty selected edges were monitored. To enhance the edges a Sobel operator was used with histogram equalization and thresholding (Figure 2). Finally the edges could be measured with an accuracy of 2 mm ( $1\ \delta$ ). The accuracy was only limited by the roughness of the surface. In addition very accurately

defined industrial objects were measured. It could be shown that accuracies of about 0,1 mm ( $1\delta$ ) are possible [13].



Figure 2: A building facade after histogram equalization, edge detection and thresholding was applied [13].

#### 4. AN AUTOMATIC 3-D POINT DETECTION SYSTEM

The main goal of an automatic system (as developed at the Vienna University of Technology) is, to detect points of interest on the surface of the objects with a minimum of human interaction. Then two or more theodolites are used in a master and slave mode. If two theodolites are used, one (master) scans the object while the other one (slave) tracks it.

Scanning means that points of interest have to be detected, which finally can describe the 3D surface of the object. The procedure is described in Figure 3 [7]. Points of interest can be identified with interest operators (IOPs). We decided to take the Förstner operator [2], the Harris operator [5] and the Hierarchical Feature Vector Matching (HFVM) operator [9].

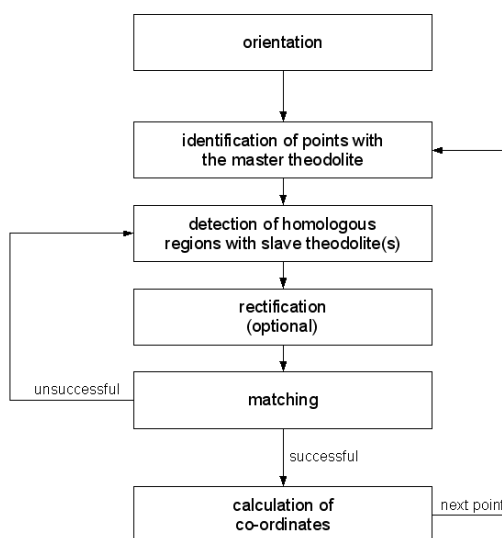


Figure 3: Work-flow of the semi-automatic measurement system [7].

With interest operators a wide field of different points can be located with subpixel accuracy: points on lines or edges, centres of symmetrical figures, intersections of lines, edges.

While the master theodolite is scanning the object, the slave has to track it in order to find homologous regions and finally, homologous points.

A fast tracking algorithm has been developed by making use of the epipolar line geometry. An epipolar line is given by the intersection of two plains. Here one plane is defined by the collimation axes of the two theodolites when pointing at a point of interest, given by approximate coordinates. The other plain is given by the CCD array of the slave. Approximate coordinates of the interest point we get from measurements of the master while scanning the object: horizontal and vertical angles from the encoders and an approximate distance from an autofocus system [7]. Figure 4 shows how intersections of the epipolar line and the frame of the CCD array can be used to control the slave theodolite. After the coordinates of the intersections are determined with respect to the theodolite coordinate system correction angles can be calculated by which the collimation axis of the slave can be moved along the epipolar line. Simultaneous with this tracking procedure, a matching algorithm is used to detect homologous regions and points with respect to the master theodolite.

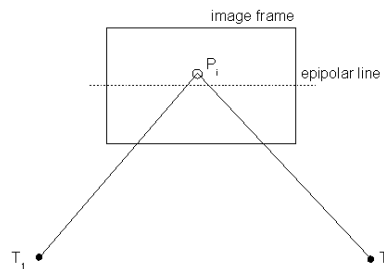


Figure 4: The tracking procedure by using epipolar line.

A seconde semi-automatic system was developed at the Technical University of Munich. It can measure horizontal directions without human interaction if the targets are symmetrical figures, like church towers or flag staffs [17].

At the Vienna University of Technology a measurement method was developed that furnishes an approach to copy human visual perceptivity. Individual objects are extracted and their deformation analysed. Different colours represent the starting point for distinction of objects in the captured image. A semantic statement about the occurrence of deformation is the result [8].

## 5. AN AUTOMATIC MEASUREMENT SYSTEM

In a complex measurement system, as developed at the Vienna University of Technology [13, 7, 6], with many algorithms (e.g. for image processing or for point detection), the selection of suitable algorithms, their order of application, and the choice of necessary input parameters is a highly non-trivial task.

The main goal of this current development step is the integration of a suitable decision system. A decision systems is a specific class of a computerized information system that supports engineering, business or organizational decision-making activities. A properly designed decision systems is an interactive software-based system intended to help decision makers to

solve problems and to make decisions. Such a system consists in its plainest form of three main components: an input component, decision algorithm(s) and an output component (Figure 5).

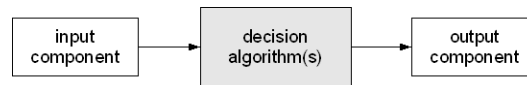


Figure 5: Decision system.

In image-based measurement systems all decisions have to be done on the basis of the captured image or on values which represent this image. Using the whole image as input is, because of processing time, not suited for an on-line measurement system. For this reason appropriate values as input for the decision system have to be used.

Extensive experimentation [11] showed that the algorithms for image preprocessing and interest operators can be chosen on the basis of parameters extracted from the image (low-level feature extraction). This is done by calculating two types of image features, namely *histogram features* (mean, s.d. and skew) and Haralick features<sup>2</sup>.

To provide automated support, a knowledge-based approach has been chosen for representing the knowledge necessary for decision-making, allowing for a declarative and modular representation of a decision policy together with easy extendibility. Knowledge-based systems (KBS) emulate human expertise in well defined problem domain [15]. They are the results of research in the area of artificial intelligence. The availability of knowledge-based system tools, such as CLIPS [1] or ILOG [5], has simplified the development of knowledge-based systems.

The advantages of knowledge-based systems in comparison with conventional programming languages, such as Delphi, Fortran and C++ are:

- the knowledge about the problem domain is separated from general problem-solving knowledge (makes it easier for the knowledge engineer to manipulate this knowledge);
- not only “hard” knowledge can be represented, but also “loose” knowledge (useful and potentially very profitable);
- experts-knowledge, existing very often in form of rules, can be captured in this form without converting into forests of data definitions and procedures.

An other advantage of a knowledge-based approach is that some tools make it very simple to deal with uncertainty. Uncertainty occurs if one is not absolutely certain about a piece of information. Uncertainty is represented by a crisp numerical value (from 0 to 1), where a factor

---

<sup>2</sup> Haralick [4] proposed 13 measures of textural features which are derived from the co-occurrence matrices, a well-known statistical technique for texture feature extraction. The grey-level co-occurrence matrix is the two dimensional matrix of joint probabilities between pairs of pixels, separated by a distance in a given direction. It is popular in texture description and is based on the repeated occurrence of some grey level configuration in the texture.

of 1 indicates that the user/system is very certain that the information is true, and a factor of 0 indicates that is very uncertain that the information is true.

There exist various schemes for knowledge representation, e.g. rules, frames, semantic nets and others. Each has its peculiar strengths and weaknesses. The structure of a rule-based approach is very similar to the way how people solve problems. Human experts find it convenient to express their knowledge in form of rules (situation-action pairs). Further rules are a way to represent knowledge without complex programming constructs. For these reasons a rule-based approach should be used to implement the relevant knowledge.

The development carried out at the Vienna University of Technology [11] supports the operator when making the following decisions: (1) selection of suitable image preprocessing and image enhancement algorithms, (2) selection of suitable interest operators, (3) selection of points which are convenient for deformation analysis / object reconstruction. The work-flow of our system is shown in Figure 6.

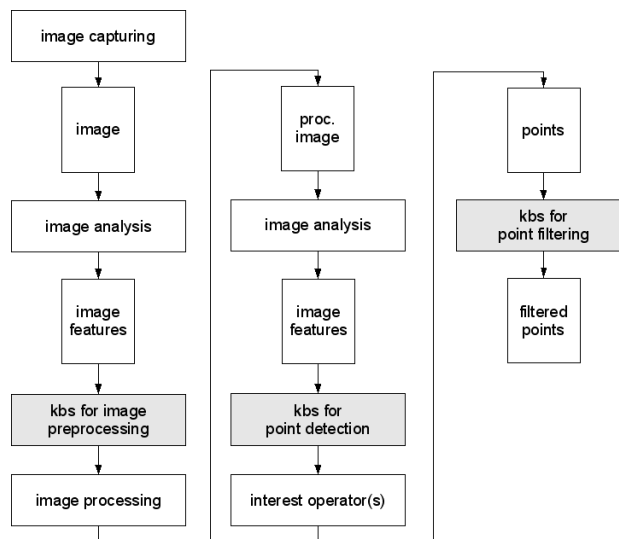


Figure 6. The work-flow of the developed system [11].

### 5.1. Knowledge-based image pre-processing

As mentioned above a necessary precondition for the successful application of algorithms for finding interesting points is the “quality” of the image. It is often required to improve the visual appearance of an image. This can be done by image pre-processing and enhancement processes. Furthermore, flexible image processing makes the measurement system more independent of variable illumination in the course of image capturing.

We have implemented the following image processing algorithms: histogram equalization, grey-level scaling (image brightening/darkening), median and gauss filtering, edge detection (Sobel-, Prewitt-, Laplace operator) and thresholding. The implementation of further algorithms for image pre-processing and enhancement is envisaged.

The aim of the developed knowledge-based image processing system is to select, suitable image processing algorithms, on the basis of extracted image features. This is done by three processing steps:

- Image analysis: after the image is captured, image analysis is carried out. Finally, image features will be stored in a file in a suitable form.
- Choice of image processing algorithms: based on the extracted image features, the knowledge-based system chooses a single algorithm or a combination of algorithms for image pre-processing and enhancement in order to improve the image for the subsequent application of interest operators. At critical processing steps (e.g., edge detection, median filtering) the user has the possibility to overrule the system decision.
- Image processing: the last step in the processing chain is the application of chosen processing steps. The result is an improved image.

The knowledge which was required to be included in this part of the knowledge base was obtained in different ways: from technical literature [10], other projects [13, 7] and from extensive experiments [11]. Due to the moderate number of implemented image preprocessing and image enhancement algorithms, the knowledge base could be kept compact and thus easily modifiable and extensible.

## **5.2. Knowledge-based point detection**

The second component of our system is the knowledge-based point detection by means of interest operators. As mentioned above there exist many IOPs [2, 5, 9]; however, no IOP is suitable to find all desired points. The choice of a suitable algorithm and its parameters is made by the KBS. Like image pre-processing algorithms in the previous section, a suitable IOP is selected together with its parameters. This process is based on image features, too.

The knowledge for the selection of suitable interest operators was obtained by theoretical considerations and extensive experiments. The problem of existing “interest operator comparing methods” is that most of them are based on human visual inspection or ground-truth verification. These rely on human symbolic interpretation of the image and are therefore subjective. Furthermore, human interpretation limits the complexity of the image used for evaluation [14]. For these reasons we use several methods for the evaluation of interest operators including a new development, which is based on measuring the distance between sets of interest points [11]. Additionally to these evaluation we have inspected the runtimes of the interest operators used. This information can be used to choose a suitable operator if more than one is qualified for the same situation.

## **5.3. Knowledge-based point filtering**

Point reduction is necessary since, in spite of choosing suitable algorithms for image pre-processing and for interest operators, many undesirable points are detected. The application of the developed measurement system is currently focused on monitoring of building facades. Point detection has to be done in such a way, that the extracted points characterize the object. In case



of facades the elementary structure can be represented by a simple line geometry. Points detected apart from this line structure (e.g. points inside glass windows) are undesirable and not useful for subsequent process steps, like object reconstruction or deformation analysis. The filtering process (which is not an erasing, but a weighting process) can be done by means of two methods: (1) point filtering on basis of defined rules and (2) inter-active point filtering.

For the first method several criterions will be used for weighting each point, which can be summarized as follows: (a) how many interest operators detect the same point and (b) which “property-parameters”, obtained from the corresponding interest operator, has the point. The first criterion is very simple but effective. The point filter scans all point lists (one point list for each applied interest operator) and weights each point in correspondence with the number of interest operators, from which this point has been detected. In practice this is a search routine which finds points with the same co-ordinates in different point lists. The weights are fixed on the basis of this simple coherence. The second criterion is based on “property-parameters” obtained from the corresponding interest operator for each point. On the basis of these returned values we can formulate several rules for point filtering. In the simplest case threshold values will be used. Points with returned values less than the threshold values get a different weight from points with returned values greater than or equal to the thresholds. Following, points with low weight can be removed.



Figure 7: (a) Extracted points by the Förstner operator before and (b) after filtering.

The second method (interactive point filter) allows the user to choose the points or point clouds to be removed. This selection process is realised by means of a graphical user interaction (the user has to draw a rectangular window in the graphical output - points inside these selected windows will be removed).

In Figure 7a points detected by a single interest operator, the Förstner operator, are shown. It can be seen that the result is of average quality. A few of the interest points are suitable for subsequent analysis (e.g. deformation analysis, reconstruction, and others), but many of them represent isolated points on the masonry or on the window-areas. This effect results from high local grey value variations present in this area, which could not be discerned with the developed image analysis.



Figure 8: (a) User-graphic interaction for point filtering and (b) points after interactive filtering.

A intuitively better result (points which represent the elementary building facades elements, like edges, windows, beams) can be obtained after point filtering (Figure 7b). Most of the isolated points on the masonry have been filtered, even though some undesirable interest points remained (e.g. the window-areas on the bottom right). Figure 8a shows the user-graphic interaction and Figure 8b the final point cloud. This method enables the user to adjust the interest points to a best qualification for all sorts of subsequent applications.

## 6. FUTURE

For the future there are still many possibilities to improve the operability of image assisted theodolite measurement systems; beside the improvement of existing system components, the degree of automation for the whole system should be increased by integrating other sensors in the measurement process. A suggestive extension could be the integration of a 3D laser scanner. The data of the different sensors have then to be merged by a special data fusion process, which could be knowledge-based.

Such a system provides an immense number of 3D data, both from the theodolite system and from the laser scanner. This point cloud can not be reduced very effectively by filtering. A new approach could be based on cognitive vision and work in a two step mode:

- The captured data (image and laser scanner data) must be used to produce a description of the image. This can be done by recognizing and assigning different objects to proper categories together with information about the object and relevant parameters. This process results in a special kind of information system.
- The yield information is then used to produce actions into the physical world, like measuring only a special part of the object.

Such a new measurement system would benefit from the efficiency of the 3D laser scanner, from the image information captured by the theodolites, and from the automation of decision processes basing on cognitive vision. The result would be a (semi) automated measurement system which is able to act and react in a known environment to unknown situations.

## References

- [1] CLIPS: <http://www.ghg.net/clips/CLIPS.html>, 2004.
- [2] Förstner, Wolfgang: Statistische Verfahren für die automatische Bildanalyse und ihre Bewertung bei der Objekterkennung und -vermessung, DGK, vol. C, no. 370, München, 1991.
- [3] Grün, Armin / Kahmen, Heribert (eds.): Optical 3-D Measurement Techniques VI, Volume I and II, ETH Zürich, 2003.
- [4] Haralick, Robert M. / Shapiro, Linda G.: Computer and Robot Vision, 1st Edition, Addison-Wesley, New York, 1993.
- [5] Harris, Chris / Stephens, Mike: A combined corner and edge detector. In: Proceedings of the 4th ALVEY vision conference, Matthews (ed.), University of Manchester, 1988.
- [5] ILOG - White Paper: <http://www.ilog.com>, 2004.
- [6] Kahmen, Heribert / Niessner, Anton / De Seixas, Andrea: 3D Object Sensing Using Rotating CCD Cameras. In: Kropatsch / Bischof (eds.), Digital Image Analysis, 1st Edition, Springer, Berlin/Heidelberg/New York, 2001.
- [7] Mischke, Alfred / Kahmen, Heribert: A New Kind of Measurement Robot System for Surveying of non Signalized Targets. In: Optical 3-D Measurement Techniques IV, Grün and Kahmen (eds.), Herbert Wichmann, Karlsruhe, 1997.
- [8] Niessner, Anton: Qualitative Deformationsanalyse unter Ausnützung der Farbinformation. PhD Thesis, Vienna University of Technology, 2002.
- [9] Paar, Gerhard / Rottensteiner, Franz / Pötzleitner, Wolfgang: Image Matching Strategies. In: Kropatsch / Bischof (eds.), Digital Image Analysis, 1st Edition, Springer, Berlin/Heidelberg/New York, 2001.
- [10] Pratt, William K.: Digital Image Processing, 1st Edition, John Wiley and Sons, New York/Chichester/Brisbane/Toronto, 1978.
- [11] Reiterer, Alexander: A Knowledge-Based Decision System for an On-line Videotheodolite-based Multisensor System. PhD thesis, Vienna University of Technology, 2004.
- [12] Reiterer, Alexander / Kahmen, Heribert / Egly, Uwe / Eiter, Thomas: Knowledge-Based Image Preprocessing for a Theodolit Measurement System, In: Optical 3-D Measurement Techniques VI - Volume I, pp. 183-190, Grün and Kahmen (eds.), Zürich 2003.
- [13] Roic, Miodrag: Erfassung von nicht signalisierten 3D-Strukturen mit Videotheodoliten. PhD thesis, Vienna University of Technology, 1996.
- [14] Schmid, Cordelia / Mohr, Roger / Bauckhage, Christian: Evaluation of Interest Point Detectors. In: International Journal of Computer Vision, Volume 37/2, pp. 151-172, 2000.
- [15] Stefik, Mark: Introduction to knowledge systems, 2nd Edition, Kaufmann, San Francisco, 1998.
- [16] Walser, Bernd / Braunecker, Bernhard: Automation of Surveying Systems through Integration of Image Analysis Methods. In: Optical 3-D Measurement Techniques VI - Volume I, pp. 191-198, Grün and Kahmen (eds.), Zürich 2003.
- [17] Wasmeier, Peter: The Potential of Object Recognition Using a Servo-tacheometer TCA2003. In: Optical 3-D Measurement Techniques VI - Volume II, pp. 48-54, Grün and Kahmen (eds.), Zürich 2003.