

THE EVOLUTION OF DIGITAL LEVELLING TECHNIQUES – LIMITATIONS AND NEW SOLUTIONS

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Forerunners

The development of Prof. Zetsche at Bonn [1966] can be considered as a forerunner of all digital levels. The image of the rod pattern was compared with a scaled-down rod pattern on a ruler at the focal plane. Due to the lack of adequate electronics there was no further progress in this direction until the appearance of CCD-sensors in the early eighties, and an improvement of the microprocessor performance opened the way to powerful image processing.

Besides the development made by Leica, it is also necessary to refer to the research work of the Technical University Dresden in collaboration with Carl Zeiss, Jena (Germany). A development instrumentally based on the Zeiss Ni002 and using a linear CCD-array with 1024 elements (pixels), had been started in 1982 and stopped in 1988 in benefit of other projects. These experiences are certainly the base for the actual development of Zeiss digital levels. In 1987 the development of a digital level at the Neues Technikum Buchs (NTB) (Switzerland) was published. Despite of a sophisticated zoom optic its measuring range was restricted to distances between 20 and 30 meters.

The Fundamental Information and Image Technologies in Digital Levelling

Most of the geodetic measurement methods as electronic terrestrial or spatial distance determination (EDM, GPS, GLONASS) can be characterised as an information transfer between two positions. Transferred to the levelling process it is the determination of a position at a vertical scale represented by a coded staff.

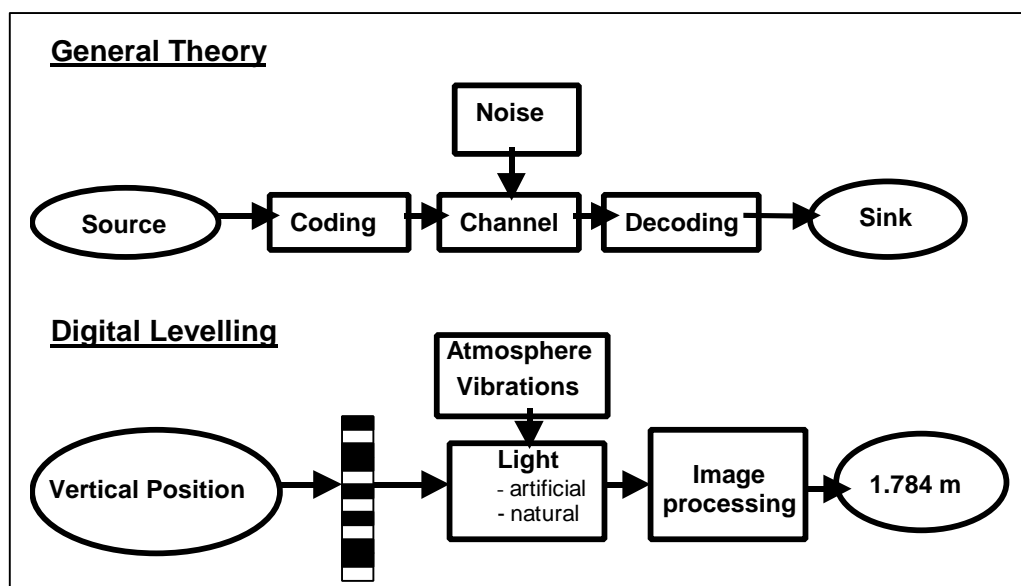


Fig. 1: The information transfer of digital levelling

According to other geodetic measurement techniques the same principles in coding and demodulation can be found in EDM- and GPS-technologies. As all digital levels normally operate with natural light, the sun light, various influences – in the language of information-transfer it is called NOISE- have to be covered and suppressed by the digital levelling process. These influences are listed in the following table 1.

Illumination	Atmospheric influences	Mechanical influences	Instrumental behaviour
Various light intensity of natural light (SNR)	Turbulences (blurred image, higher SNR)	Vibrations (deviation of the line of sight)	Thermal effects (deviation of the line of sight)
Inhomogeneous light intensity by shadows at the staff	Refraction (deviation of the line of sight)	Settlement of the instrument and staff	Interference of code-element size and pixels (wrong results at certain distances)
Spectrum of the light source		Staff centring and inclination of the staff	Compensator function (eigenfrequency)

Table 1: The different noise effects in the digital-levelling process

The Various Codes in Digital Levelling

The efficiency and the reliability of the information transfer is mainly a question of the appropriate code (modulation) of the information. In addition to the basic requirements of the information transfer, several geometric requirements of a code as pseudo-random characteristic, good contrast at the edges and unambiguity within a staff length of four meters and the distance range up to 100 m have to be covered. For patent reasons every manufacturer developed his own code and processing method. The Bonner and the NTB developments have shown that normally tuning of the scale by a zoom optic is required. The manufacturers were forced to develop special codes for the digital-levelling system, giving a clear projection without extensive optics. The code of all the manufacturers is set up in a way to convert the image via a linear CCD-array into a digital intensity- and position-information. Therefore, all codes use the black-white transition at the edge of the code-bars.

The **Leica** code represents an aperiodic pseudostochastic binary code. The complete bar code over the full 4050 mm length of the staff has 2000 elements, i.e., each code element has a 2.025 mm dimension. The so-called **Zeiss** bi-phase-code or more exactly the modulation of the code is based on an alternation of brightness within each bit of 2 cm width, that means whether a certain code element is either black or white, or consists of a black and a white bar. This pattern has an optimum distribution over the whole visual field so that at least 15 black-white-transitions can be detected within a field of view (FOV) of 30 cm. This grants sufficient oversampling and hence a high accuracy for the fine measurement. Only at very close range, below 6 m, additional 2 mm wide black or white lines are required.

The **Topcon** staff carries a code with three overlapping single patterns. A constant bar-triplet R as reference pattern and two further bars A and B coded in the adjoining bars. The bar width of the A and B pattern changes according to a sinus function from 2 to 10 mm and a wave length of

600 mm and 570 mm, respectively. The distance p between the bar-centres is 10 mm and constant. The two sinus signals have a phase shift of $\pm \pi/2$ at the beginning of the rod, so that there is always an unambiguous phase difference of the two signals A and B within the height range of 4 m. Distance and height are derived from the frequency and the phase position of the image of the three related codes using FFT.

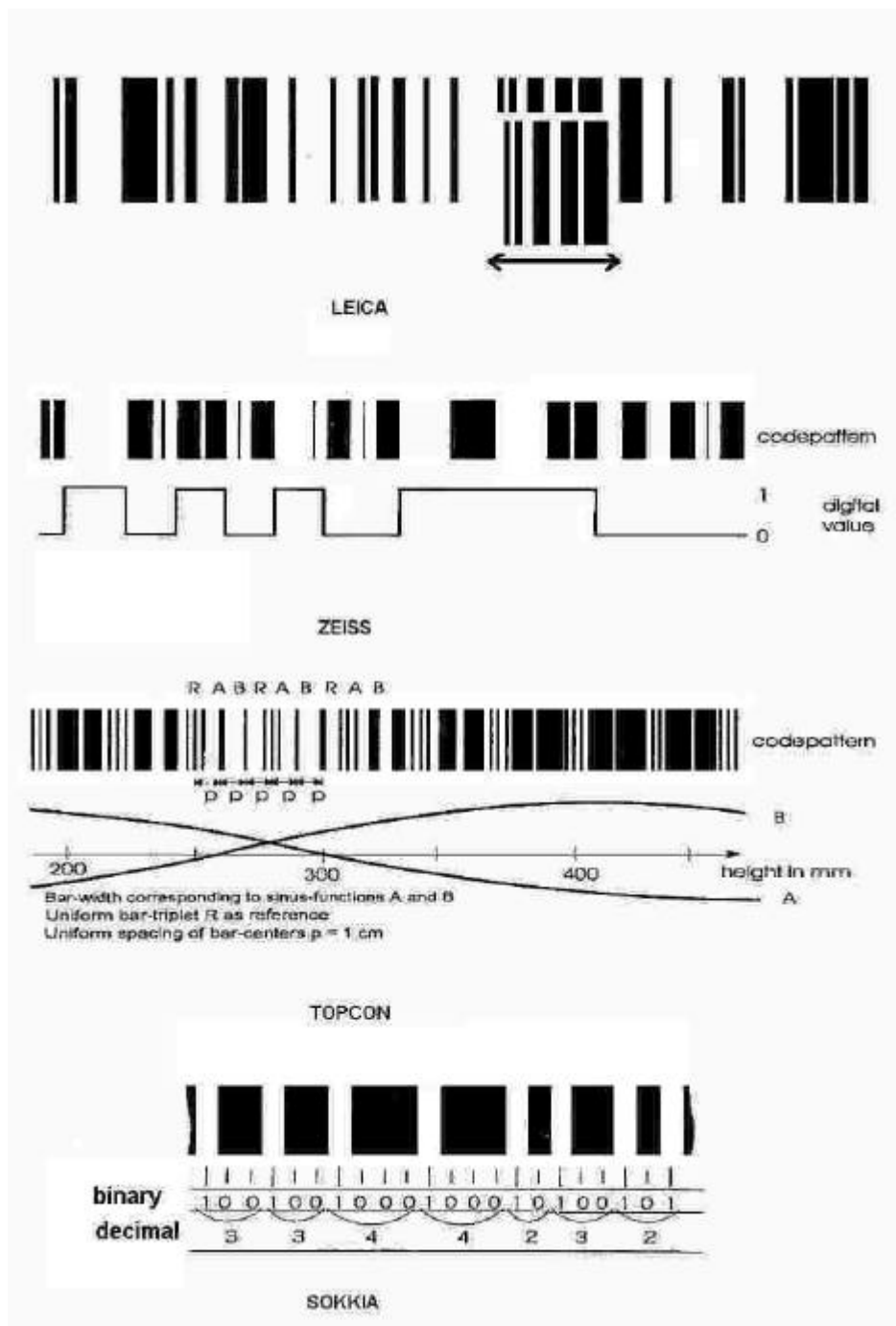


Fig. 2: The various codes of the actual digital levels

The **Sokkia** Random Bidirectional Code (RAB) covers a width variation of 6 codes, where each code is defined in relation to the basic code-element dimension of 16 mm. Each code can be recognised by the following relations: 1 = 4:12, 2 = 6:10, 3 = 8:8, 4 = 10:6 and 5 =12:4. The 0 code is required for short range measurements and is integrated in the form of white lines in the black bars [Nagao, Kanagawa].

Manufacturer	Properties	Near-farfield code	Distance/ scale required	Dimension of one code element
Leica	Pseudostochastic	Yes	Yes	2.025 mm
Sokkia	Random bidirectional Digital width relation	Yes	No	16 mm
Topcon	Analog width variation	No	No	10 mm
Zeiss	Biphase	Yes	No	20 mm

Table 2: Code properties

General Features of the Receiving Units

Optical layout

Digital levels can be regarded as a fusion of a digital camera and automatic level. It has a telescope with upright image and a compensator to stabilise the line-of-sight. Additionally a position sensor coupled with the focus lens supplies a rough distance information. This refers to the Leica instruments only, the others operate without information of the focus-position. A tilt-sensor observes the compensator position and a beam-splitter guides part of the light to the CCD-sensor.

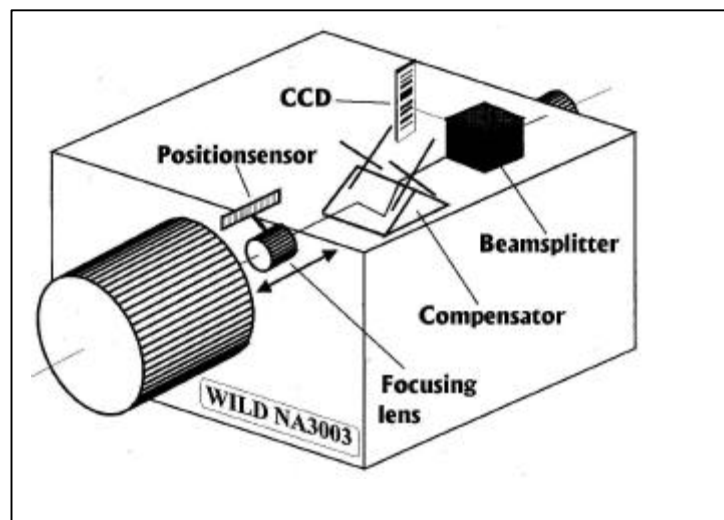


Fig. 3: Basic optical design of today's digital levels Leica NA3003

Electronics

The processor system is based on a microprocessor. For the complex computations needed for the correlation and reference functions, it is supported by a gate array (LEICA). The detector-diode array converts the bar-code image into an analog video signal of 256 intensity values.

Signal Analysis and Image Processing Methods of Digital Levels

The determination of the position by image processing is a combination of a radiometric processing and the detection of the edges, i.e., the black-white transition of the code elements.

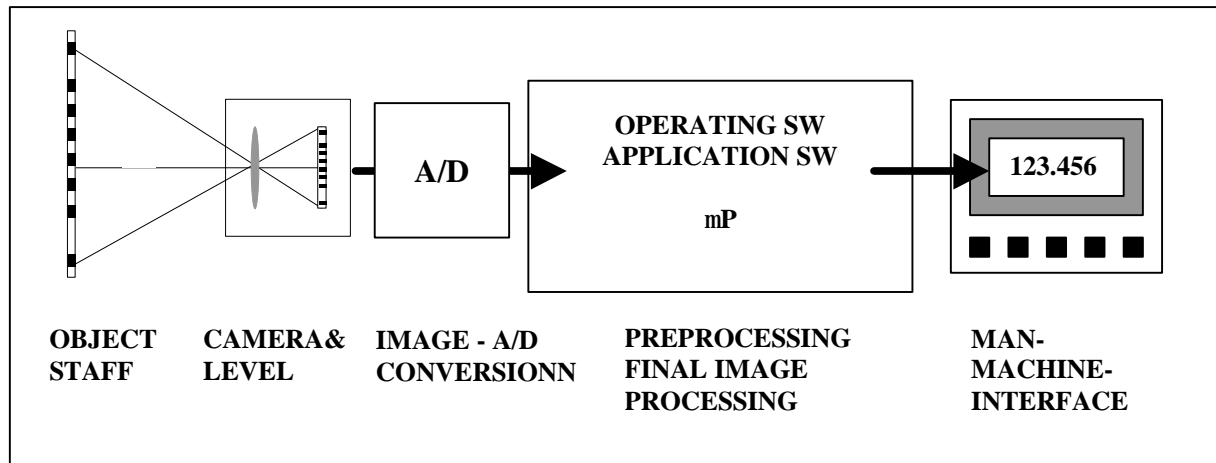


Fig. 4: Data capture and processing

Radiometric aspects of the image capture

The radiometric process must also take into account that each CCD-pixel exhibits a Gaussian sensitivity. This can be compensated by the convolution of the image with a trapezoidal detector-sensitivity function. In addition to the aforementioned detector sensitivity an inhomogeneous intensity variation (see Fig.5) of a partly shaded staff has to be covered by the image analysing and compensating process.

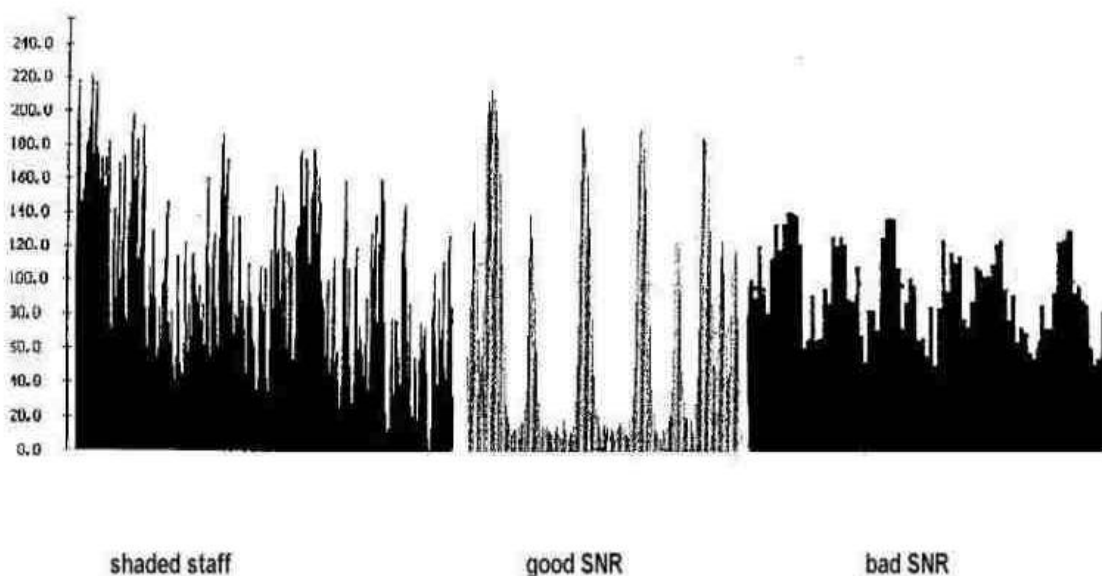


Fig. 5: Radiometry of rod images

Except the Leica system all other digital levels have at 100 m distance an oversampling of a minimum of 4 pixels with an average focal length of 250 mm and a pixel size of 10 μ and a code element of 1 - 2 cm. With Leica instruments having the aforementioned focal length at about 25 m staff distance there may occur interferences between the code element size (2.025 mm) and the pixel size [Schauerte]. In the mean time this effect is reduced by new image processing software.

Position Determination by Image Processing

The **Leica** digital level applies a two step and two-dimensional correlation method similar to GPS pseudo-range determination. The code is correlated with the image of the rod projected to the CCD-array. As the image varies not only in height but also in scale, according to the distance of the rod, it is necessary to optimise both parameters. With a range of 0 to 4.05 m in height and 1.8 to 100 m in distance and the respective increments of some millimetres in height and some meters in distance this would lead to 50 000 correlation coefficients to be computed with 8-bit accuracy. To speed up the evaluation process it is divided into three steps.

In a first step a rough distance information is derived from the position of the focus lens beforehand. The second step is coarse correlation. Using a threshold value according to the average intensity of the signal, its 8-bit dynamic is reduced to 1-bit. This permits the use of an EXNOR logic function instead of multiplication. The last step is a fine correlation with full 8-bit intensity-signal-accuracy in a very restricted area around the solution of the coarse correlation. Typical computation time is about 2 seconds.

The procedure of **Zeiss** can be described as geometric positioning method. A minimum FOV only 30 cm is sufficient to derive height and distance in the whole range up to 100 m. It uses the code for coarse positioning only and performs fine positioning by detecting and averaging several dark-light-transitions of the code-elements.

Topcon uses a phase-measuring method quite similar to the method known from electronic range-finders. The frequency and the phase position of the three signals can be gained by fast Fourier transformation (FFT). Besides linear combinations of the 3 codes A, B and R for accuracy augmentation are imaginable.

The **Sokkia** image processing method is quite similar to the Zeiss method. Intensive investigations at the Institute for Geodesy and Photogrammetry of the ETHZ have shown that this method is able to work with a minimum of 8 cm code.

Instrument	TOPCON	WILD	SOKKIA	ZEISS
Feature	DL102	NA3003	SDL30	DiNi10
Accuracy mm/km Double levelling	0.4 mm Invarstaff	0.4 mm Invarstaff	1.0 mm (0.7 mm ETHZ) Fibreglass Staff	0.3 mm Invarstaff
Distance (Resolution)	1 cm	1 cm	0.1% x D	1 cm
Compensator				
- Type	Pendulum	Pendulum	Pendulum	Pendulum
- Accuracy	0.3"	0.3"	-	0.2"
- working range	± 15'	± 15'	> ± 15'	± 15'
Measurement time	4 s	4 s	> 3 s	4 s
Range	2-60 m Invarstaff	1.5 - 60 m Invarstaff	1.6 – 100 m Standard-staff	1.5- 100 m Invarstaff
Man-Machine-Interface (MMI)	Menu	Menu with function keys	Menu	Menu with function keys
Display	2 lines	2 lines	2 lines	4 lines
Operation time/ battery	10 hours	8 hours	> 7 hours	1 day
Weight including battery	2.8 kg	2.5 kg	2.4 kg	3.0 kg
Field of view (FOV)	No Information	2°	1°20'	Minimum 30 cm
Data storage capacity	2400	500	-	2000

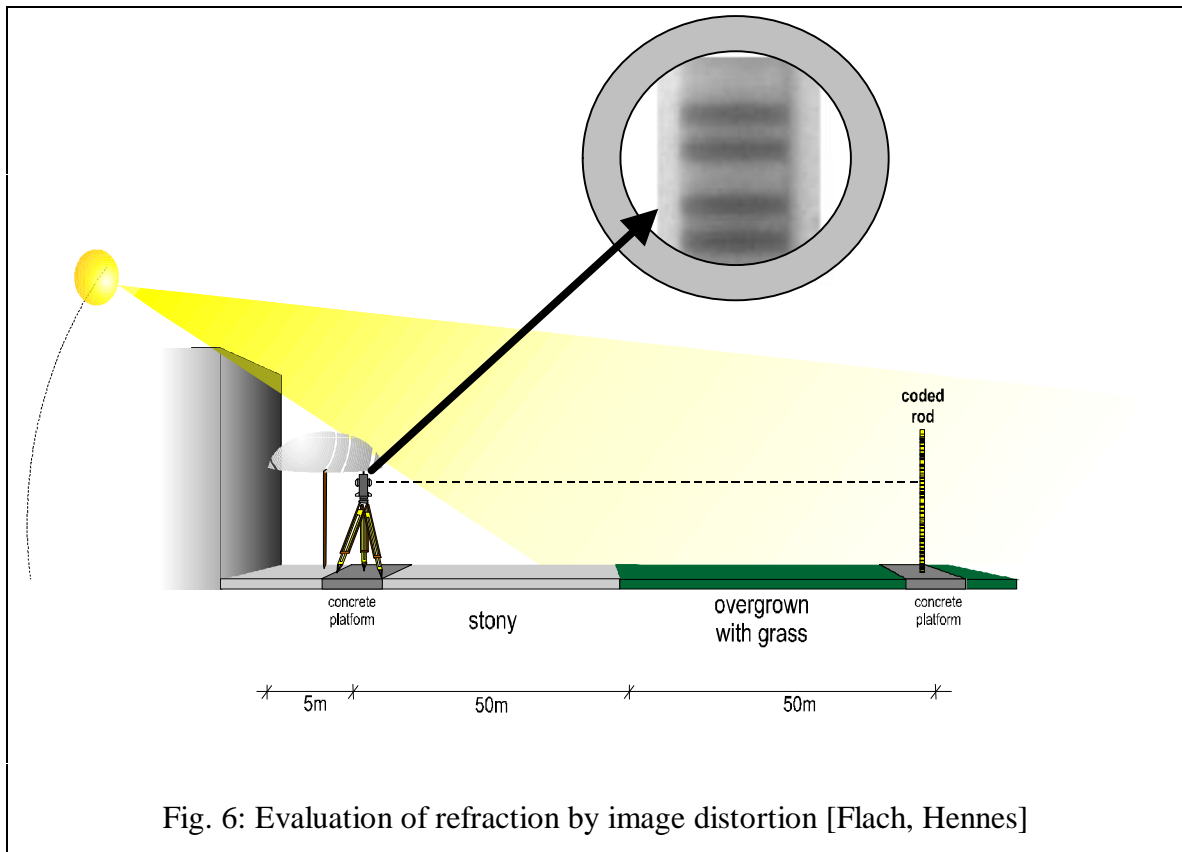
Table 3: Performances of the actual digital levels

Technical Improvements of Digital Levels

Although it is one of the most frequently asked questions in connection with digital levels, implementation of an autofocus has not been realised up to now in order to keep cost low.

Modern digital levels realise a height precision of some 1/100 mm. For typical levelling distances of about 30 m this is well below the influence of the atmospheric refraction. If we want to improve the reliability of height measurements, we must manage to determine the systematic influence of the atmosphere.

At the ETH Zurich there are promising results to evaluate refraction from image distortion [Flach, Hennes]. The realisation is asking for higher resolution, a rather large FOV, and a higher computational power. Another step in the development of digital levels can be the implementation of inclination sensors to enable inclined trigonometric observations with digital levels.



New Applications with Digital Levels

Besides the standard levelling application, digital levels have opened a new dimension in geometric levelling. But they have a potential to solve further problems that is just starting to be used:

- permanent monitoring with motorization
- improved motorised levelling
- plumbing
- tracking of construction machines

The frequent need for observation of buildings under construction has been leading to the idea of a digital level with motorised focus- and azimuth-drive to observe several targets permanently and automatically. Including reference-targets into the measuring cycle confirms the stability of the station. This system has been developed by Solexperts AG, Schwerzenbach (Switzerland), together with the Institute of Geodesy and Photogrammetry of the ETH Zurich. The first system, based on the NA3003, operated 1995/1996 at a building sites at Zurich. Meanwhile other monitoring systems, based on the Zeiss instrument, had been installed successfully [Keppler et al]. Beside the levelling task zenith and nadir plumbing can be realised with a pentaprism mounted to the front lens tubus and allow a monitoring of horizontal movements.

Outlook

Nowadays digital levels are used in all levelling procedures including motorised levelling. With the integrated horizontal circle the Zeiss DiNi has the capability of a levelling tachometer. An implementation of area CCD's could give the performance of x-y-positioning and height tracking for construction machines and will improve the efficiency of motorised levelling in the future. It can be foreseen that high resolution CCD's and the adequate processing power will enable a correction of influences of refraction and turbulences. Basing on this the distance range of precise levelling and machine navigation with digital levels can be extended.

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