A CIRCLELESS „2D/3D TOTAL STATION“

A LOW COST INSTRUMENT FOR SURVEYING, RECORDING POINT CLOUDS, DOCUMENTATION, IMAGE ACQUISITION AND VISUALISATION

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ABSTRACT:

Hardware and software of the universally applicable instrument - referred to as a 2D/3D total station - are described here, as well as its practical use. At its core it consists of a 3D camera - often also called a ToF camera, a pmd camera or a RIM-camera – combined with a common industrial 2D camera. The cameras are rigidly coupled with their optical axes in parallel. A new type of instrument was created mounting this 2D/3D system on a tripod in a specific way. Because of it sharing certain characteristics with a total station and a tacheometer, respectively, the new device was called a 2D/3D total station. It may effectively replace a common total station or a laser scanner in some respects. After a brief overview of the prototype's features this paper then focuses on the methodological characteristics for practical application. Its usability as a universally applicable stand-alone instrument is demonstrated for surveying, recording RGB-coloured point clouds as well as delivering images for documentation and visualisation.

Because of its limited range (10m without reflector and 150 m to reflector prisms) and low range accuracy (ca. 2 cm to 3 cm) compared to present-day total stations and laser scanners, the practical usage of the 2D/3D total station is currently limited to acquisition of accidents, forensic purpuses, speleology or facility management, as well as architectural recordings with low requirements regarding accuracy. However, the author is convinced that in the near future advancements in 3D camera technology will allow this type of comparatively low cost instrument to replace the total station as well as the laser scanner in an increasing number of areas.

1. INTRODUCTION

1.1 Motivation

The idea for the device presented here came from working with a polar coordinates generating 3D camera, which makes use of the pmd principle. To begin with the viability of utilizing a low-range camera - ca. 10 m range - for the task of recording buildings, as well as for more general surveying tasks had to be determined. The question to be answered was if there would be a benefit to the use of a pmd camera over traditional area recording techniques like laserscanning, photogrammetry or point-gathering via a total station. It had to be taken into consideration that - compared to established methods of recording - the 3D camera technology itself is still at an early stage of its development. Consequently, the focus was on solely demonstrating the innovative possibilities offered by the new technology. Two different processes and corresponding types of instruments were developed, one of which is the 2D/3D total station this paper centers on.

1.2 The pmd camera

The 3D pmd camera captures a point cloud representing the entire three dimensional geometry of its surroundings at a single click. In a similar manner, a modern 2D digital camera provides colour, as well as the direction to object points.

The pmd camera is a type of device often alternatively named ToF-camera (time of flight), RIM-camera (range imaging) or simply 3D camera. In this paper, use of the term pmd camera (photonic mixer device) will be maintained, not only because the name denotes the underlying principle of the camera that is actually used, but also because virtually all of the differently labeled cameras utilize the pmd method for distance measuring. Each pixel of the pmd sensor carries its own miniaturized electronic distance measuring unit. An optical signal generated by the camera and reflected back by an object is detected by the pmd sensor, where it is then overlayed (mixed) with an internal reference signal. Thus the technology is named photonic mixer device (pmd).

Each individual pixel's location on the sensor is utilized to calculate two directions, analog to the approach in photogrammetry. In conjunction with the measured distance the position of an object point is determined, and then expressed by polar coordinates within the local coordinate system of the camera.

The maximum resolution by pixel of current 3D cameras is generally low compared to standard 2D cameras. At 204x204 pixels (ca. 41 k) the camera employed here, a CamCube 2.0 manufactured by PMDTechnologies (PMDTechnologies 2013), represents the present state of the art in terms of pmd sensors. However, 3D cameras offering 512x480 pixel resolution (BrainVision 2012) are already being planned.

1.3 The combination of a 2D camera with a 3D camera

In order to achieve more reliable and precise modeling, a synergistic measuring system combining a 3D camera for the coordinates with a 2D camera supplying colour was constructed: Both cameras provide a central perspective, with the pmd camera supplying 3D coordinates at a rather limited resolution, and the 2D camera supplying colour information and delivering superior point resolution (see below).

A 2D camera, 5 megapixel, 17fps max., manufactured by Basler (Basler AD datasheet, 2012) was rigidly coupled to the pmd camera, with both camera's optical axes in parallel to each other. This 2D camera provides the RGB colour values used for colouring the 3D point clouds; it also serves to enhance 3D point density (Lipkowski, Scherer 2013). Synchronous triggering is achieved via electrical signals utilizing a custom-built hardware trigger box. Two sensors provide temperature monitoring, a central notebook computer controls data acquisition as well as data storage.

2. THE 2D/3D CAMERA SYSTEM IN THE CONTEXT OF OBJECT-MEASURING SENSOR SYSTEMS

Today, surveying is predominantly carried out via tacheometry and GNSS. Object recording is done via architectural photogrammetry, terrestrial laser scanning (TLS) or pattern projection, which includes the Kinect camera used for video games. See table 1 for a summary of the typical characteristics of these recording methods.

method	central criterion	instrument / sensor
	direct acquisition (polar coordinates)	
tacheometry,	individual single point	total station
terrestrial laser scanning (TLS)	sequential capturing of masses of single points	camera scanner, panorama scanner or hybrid scanner
	indirect acquisition (intersection of directions)	
photogrammetry	directions from images	2D-camera; bundle adjustment, structure from motion
pattern projection	parallactic angle, projection of stripes and arrays	instruments of high precision and Kinect

Table 1 Recording methods and their characteristics

Photogrammetry and pattern projection are both based on the principle of intersection of directions. In order to locate coordinates, at least two directions are needed, taken from two images recorded from different perspectives. Accuracy depends on base line length relative to the distance to the object point. This can pose difficulties in problematic recording conditions, like e.g. indoors. At low parallactic angles between the directions depth precision declines steeply as distance increases.

Polar coordinates are the primary measured variables for the tacheometer, for the laser scanner as well as for the 3D camera. Methods using direct polar acquisition are at an advantage over those based on the principle of intersection of directions, insofar as they exhibit a more uniform accuracy of distance measurements even at increasing distances. Tacheometry provides single point coordinates. The same holds true for TLS, here point acquisition occurs in rapid succession, usually in vertical plains at a given direction.

In contrast to these **sequentially** operating recording methods, the pmd camera allows for a three dimensional **snapshot** recording; **all** object points are captured in parallel - **simultaneously** – by the sensor. Simultaneous recording of all object points by a snap-reading method is **the** distinguishing unique feature of the pmd camera. It is this capability to perform direct **simultaneous** mass recordings of polar coordinates that sets the pmd camera apart from all other recording methods. Moreover, 3D snapshots can be executed in rapid succession, e.g. at 10fps, resulting in a coordinate film.

Thus, the question to be answered was how these unique capacities (i.e. the added benefit) be utilized for surveying and recording. The fact that the pmd camera is not yet technically mature had to be taken into consideration. Improvements have yet to be made in terms of reliability (object acquisition without significant gaps within the point cloud), in terms of accuracy (under various exterior conditions), in terms of general density of points as well as in terms of achieving more adequate maximum range.

As far as point density and directional accuracy are concerned, improvements were already made by the addition of the 2D camera (see below); it allows for the allocation of RGB values to the 3D coordinates. Data analysis is then followed by the calculation of three dimensional RGB-coloured point clouds as a basis for virtual models, intersections or dimensioned drawings. Software packages designated for the processing of TLS data may be used, thus eliminating the need for specialized software in order to make use of these 3D generated point clouds.

Therefore, this paper is primarily focused on the device's hardware, as well as on the peculiarities of the instrumentation and the resulting new possibilities regarding the methodology of object acquisition.

3. OBJECT RECORDING AND SURVEYING VIA THE 2D/3D CAMERA SYSTEM

What sets the pmd camera apart is its ability to record a large amount of coordinate data at a single shot, with the additional capability of recording shots in quick succession (>10 fps coordinate film). These unique features allowed for the exploration of new and innovative methods of measuring. Different modes of operation in terms of movement of the system itself may be distinguished, and distinctions may also be made between static objects and moving objects. Respective combinations between system application and object status allow for a diverse range of operating modes (see table 2).

system-status	object-status
A) rigidly directed	static (plus moved)
B) stationary usage: rotation about two axes; shots when rotating	static
C) dynamic usage: free motion in space, automatic shots	static
D) combination of A) and B)	static and moved

Table 2 Operating modes of the 2D/3D- camera system

Mode A has the pmd camera mounted rigidly, as it is applicable in process engineering, as well as in object monitoring and in the field of personal surveillance (e.g. to monitor conduct of car drivers).

Operation, as well as the respective applications, are very different for stationary usage as per B), which has the system fixed to one place with motion restricted to pivoting, and C), dynamic free-hand movement usage in space. The 2D/3D camera system and both its mounting options are shown in figure 1. Both modes of operation have been studied to varying degrees (see Scherer, M., Lipkowski, S., 2013).

Figure 1 Dynamic usage of the 2/3D camera system (for recording) and stationary usage (for surveying and recording)

In order to allow for free movement in space (tab. 2, C), the 2D/3D camera system was mounted to a Steadicam (stabilizing mount) as used for the filming of motion pictures. For this mode of operation, the battery, the hardware trigger as well as the main computer are currently stored in the operator's backpack. Both control of the recording perspective and the entire system itself are carried out via a touchscreen fixed to the Steadicam's stand, allowing for highly flexible operation by a single person. The dynamic system is easy to use and ideally suited for the recording of - even rather complex - objects, its primary application. The resulting RGB-coloured point clouds are then matched for subsequent processing, similar to TLS.

Since the dynamic recording technology utilizing the Steadicam-based system is already depicted elsewhere (Lipkowski 2013), this paper instead focuses on the hardware and software of stationary recording. The practical advantages of this technology specifically for surveying as well as recording of RGB-coloured point clouds will be demonstrated.

As far as objects to be recorded are concerned, the primary targets are architecture and facility management applications, but also documentation of accidents and indoor recording for forensic or speleological applications - that is applications with an operating range of ca. 10 m at marginally acceptable median coordinate accuracy. Currently, absolute accuracy is estimated at 0.7 cm + 2.4 cm / 10m (see below). So the focus was on developing novel system specific recording methods, rather than exerting all efforts towards calibration and maximum geometric accuracy.

4. THE CIRCLELESS 2D/3D TOTAL STATION

In mode B) the system is fixed to a tripod. Like the telescope of a tacheometer it may be rotated about both a horizontal and a vertical axis (figure 2). The Camcube gathers data analog to the polar primary data attained by tacheometric recording – horizontal direction, zenith angle and distance – but as a snap-shot of more than 41,000 polar coordinates within the field of view (dihedral angle ca. 40 gon), with the 2D camera providing the relevant image.

The merging of larger overlapping areas after rotating the

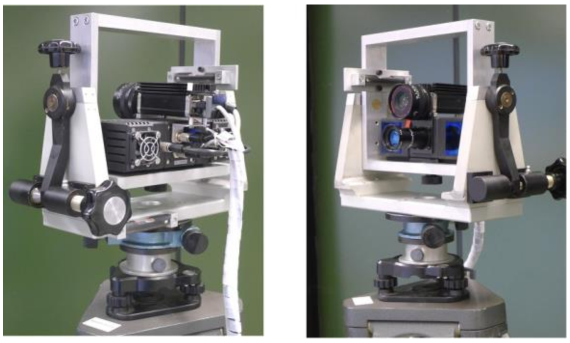

Figure 2 Prototype of the 2D/3D camera total station

system around an axis allows for angle determination as results from the reading of a circle with a tacheometer. However, the 2D/3D total station does not require circles, since the magnitude of rotation is derived via redundant procedures. The employment of the appropriate method for the respective application is mandatory (table 3).

measuring device	method of angle measurement	measuring element/ indicator
2D camera	producing panoramas	position of the pixel
3D camera	coordinate transformation	distance above all
2D-/3D camera	detection of outliers and breaks	structure of the object
3D camera	reflectivity	flag

Table 3 methods for angle determination

A commonly shared characteristic between all of the aforementioned methods is their utilization of large numbers of single measurements from a 2D/3D snap-shot for determining the angle between recordings. Instead of using a device's internal high-precision (small) circle - as is the case with a tacheometer – the camera's respective pixels are employed for this task. Thousands of points are averaged utilizing a variety of very different methods, see below for the most important ones:

1. Direction determination via spherical panoramas

Panoramas are generated exclusively from images shot by the 2D camera with the nodal point of the camera positioned at the intersection of the horizontal and the vertical instrument axes. Efficacy of the well-established method of generating panoramas relies on complex and diversely-coloured textures being present in the overlapping images. Overlapping areas provide stitching in order to ensure that lateral differences between pixels assigned to identical object points are minimized. For an easily accessible example of measuring directions using panoramas see Labonde (2012). A panorama augmented by the distances measured with the pmd camera can then be clicked upon to display three dimensional polar object coordinates corresponding to each pixel.

Fixed horizontal positions and/or zenith angles help to minimize overlap. The 2D camera used here allows for an angular – single point - resolution of 0.02 gon corresponding to 3 mm of lateral deviation at a distance of 10 m (in order to raise coordinate accuracy, see (Lipkowsi, Scherer2013)).

2. Direction determination via coordinate matching

Images on their one are usually insufficient to allow for reliable stitching. Thus, an additional procedure independent

of texture and object shape is necessary, as stitching will malfunction in low-contrast environments like, e.g., a room painted all in white. However, under these conditions the 3D camera continues to supply coordinates, since it actively transmits the infrared signal.
In order to calculate the angle solely from a set of two coordinate measurements it is not at all necessary for the object to offer a structured surface: Even when recording a flat white wall the rotation angle α between the local coordinates taken via two shots can be calculated precisely from the overlay of both the local coordinate systems.

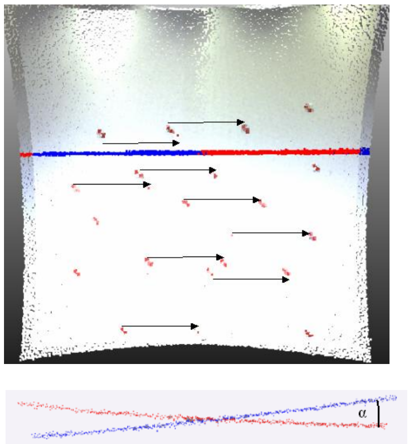

Figure 3 Recording a white wall (RGB-coloured pixel of coordinates)

Upper part of figure 3 demonstrates overlaid pixel images of two local coordinate systems rotated against each other at an horizontal angle α. Arrows denote the amount of shift between the coordinate systems (red to blue) resulting from rotation. Measuring points - partly obscured due to the intersection between the images - are present for the purpose of demonstration and control only, not for the purpose of determinating α! The lower part of fig. 3 illustrates the angle α resulting from the overlay of the two local systems (which in this case is just an arbitrarily selected narrow horizontal strip viewed from above). Averaging of several thousand coordinate values makes sure that the noise accompanying a distance measurement only distorts the resulting calculated angle at a manageable amount.

However, this method is not applicable in the case of a heavily bent object with the station at the center of its circle of curvature (cylinder, sphere). In the case of texture being present, direction determination may be carried out by means of the panorama method described above. A scenario which has both redundant methods – 2D image and 3D point cloud - fail at the same time is unlikely.

As far as the matching of local coordinate systems is concerned, the stationary recording method (see table 2), which - in practice – is constricted to a single degree of freedom, is more reliable than the dynamic mode of recording with its six degrees of freedom and the potential impossibility of determining translation.

3. Direction determination via observation of outliers

3.1 Signal overlay at the edges of objects results in range errors in the direction of the respective edge. Such outliers may be determined by testing neighbouring areas. Because of their property to reappear in *identical* directions to an object, as well as in similar shape after the station is turned at an angle α, they may be utilized for matching in a manner similar to the procedure applied when using feature-points.

3.2 Primary data regarding the quality of the amount of electrons at the integrating areas of each pixel (flags) may also serve to determine the direction in form of “misinformation” - in a similar manner to the aforementioned method.

Of note is the difference between all of these methods in terms of how residual errors affect angle determination. It is not necessary for the angle itself to be determined explicitly – e.g. as a combination of horizontal and vertical angle – instead determination of transformation parameters will suffice:

When generating panoramas the quality of angle resolution is correlated with the image resolution. When calculating the angle from **coordinates**, the quality of angle determination depends above all on the quality of the distances measured within the local systems. Thus, here, the size, density and potential residual distortion of the „3D pixels“ are **not** the relevant factor, instead it is the quality of distance measurements. In both cases the angle is determined via a large number of points. Systematical errors may be parameterized experimentally. All of the other methods specified in table 3 are generally less accurate.

Determining the degree of accuracy ultimately attainable, as well as the respective method to be preferred, still require additional research. Calibration procedures need to be refined. The accuracy of angle determination depends on very diverse factors. Current state of the art is 0.01 gon to 0.03 gon. In order to calibrate the system, the 2D/3D system was embedded in a frame that allows for measurements in two positions (comparable to practice with a tacheometer).

Right after matching (registration) a quasi-complete model of the surroundings, anchored to the viewpoint, is available, delivering adequate results for many purposes immediately after setting up, leveling up and a sweep of the area to be recorded. Additional measuring is generally not necessary, as long as connection points for geo-referencing were recorded simultaneously. Clicking the model allows for the extraction of single points and for the analysis of structures.

5. PRACTICAL APPLICATION OF THE 2D/3D TOTAL STATION

5.1 Measuring and recording specifics

5.1.1 Measuring of longer distances

As far as the 3D camera is concerned, the maximum range attainable, and the length of the scale (here: 7.5 m according to the modulation frequency of 10 Mhz), are often equated in literature. However, maximum range does actually depend solely on the quality of the detected reflection. If the measured distance exceeds the length of the scale only the remaining length insofar as it exceeds multiples of 7.5 m will be displayed. In order to clearly determine the amount of whole-number scale multiples, a second distance measurement with the modulation frequency e.g. reduced by 10 % may be conducted, standard practice in the early days of electronic distance measuring. The difference between both measurements is then used to calculate the amount of multiples of the scale. Switching between frequencies can easily be carried out via the controlling computer. In the practical examples given here, distances were frequently in considerable excess of the scale length of 7.5 m.

Thanks to excellent suppression of background illumination (SBI) and despite the comparatively low transmission power, it was possible to measure longer distances to two different types of cooperative targets, prism reflectors and reflective foils. Distances exceeding 100 m were measured to conventional single prisms (6 cm in diameter) and distances up to 30 m were measured to spheres covered with reflective foil (6 cm in diameter). The absolute difference in length was at ca. 2.8 cm, and thus within the expected range given the calibration uncertainty.

5.1.2 Technology of single-point-acquisition

Typically a total station is oriented at prism reflectors. With the 3D camera based total station this is possible, too, since directions acquired via the comparably high-resolution 2D images are assigned to distances attained via 3D measurements in order to achieve the necessary accuracy of directional measuring (Lipkowski, Scherer 2013). Thus ca. 50 pixels are allocated to a single distance. A successive approach is used to filter out the ideal direction to a reflecting point from a set of directions: Positions of reflectors are filtered out via the maximum signal amplitudes and their respective long distances (optionally supplemented by pattern detection or distance measuring with enhanced averaging time). The ideal direction is calculated next via analysis of the colour 2D image, in order to determine the respective reflector's center. Accuracy is at 1-2 pixels, thus lateral deviation at centimeter-accuracy for the configuration presented here yields an operating range of ca. 50 m.

5.2 Surveying via the 2D/3D total station

5.2.1 Geo-referencing via traditionally signalized terrestrial points.

Due to the instrument's ability to reach acceptable distances at suitable resolution, different instrument point systems may be linked - as is standard practice for terrestrial surveying (fig. 4). Automated identification of points may be carried out as described under 5.1.1, optionally supported by pattern recognition.

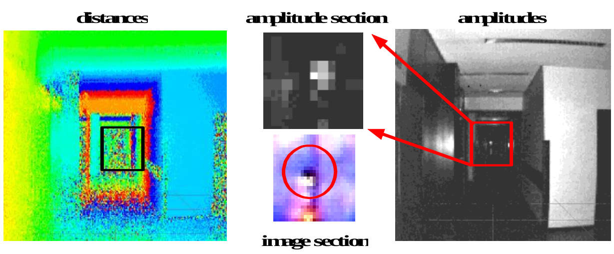

Figure 4 Recording of a room linked to a prism reflector (section; distance ca. 63 m)

5.2.2 Use of snap-shots for indirect coordinate determination

Acceptable distances up to 30 m were achieved measuring not only to prism reflectors, but as mentioned before also to spheres covered with reflective foil (fig. 5). In order to allow for reliable and automatic identification of terrestrial points, a rod was produced with several reflecting spheres fixed to it at predefined intervals. The scheme of intervals is then extracted from the data via a search algorithm and a plausibility check is carried out. Range may be extended by replacing the reflecting spheres with small 360° prisms.

In order to avoid potential problems caused by excessive signal intensity, the coordinates used for the final calculations of the tip of the rod pointing to the ground point are calculated from the measurements to additional less reflective spheres dyed red (ideal reflective properties reside in the infrared).

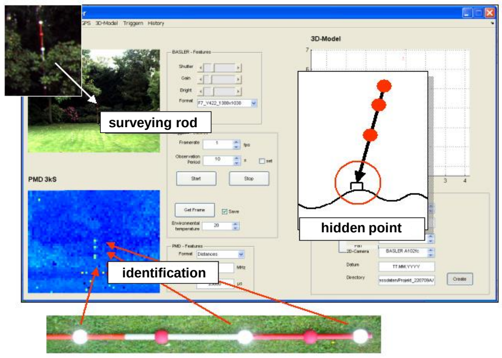

Figure 5 Automatic recognition of signalized points

5.2.3 Integration of GNSS

Inclusion of a moving satellite antenna into the field of view has also been tested. The antenna, signalized by reflecting spheres, (see 5.2.2) was directed across the field of sight, with coordinate output of the GPS times recorded and the 3D camera in sync. This made it possible to directly geo-reference camera position and direction of vision.

5.2.4 Local surveying tasks

An operator handling the automatically detectable rod within the measuring range of a stationary camera may work in a manner comparable to a one-man-operation of a prism locked to a total station: Recording may be triggered via remote control.

5.2.5 Setting out

Real time supervision and control when setting out and positioning objects may be carried out very efficiently with the 3D camera, due to its unique property to snap-shoot an entire point cloud, for instance when installing and aligning objects (Lipkowski 2013).

6. Outlook

In principle the device presented here exhibits all the relevant characteristics of a modern video total station. This in itself provides sufficient justification to label it a „2D/3D total station". In addition, when gathering RGB-coloured point clouds, it features true „snap-shot-functionality", as opposed to sequential recording like TLS. Moreover, it is possible to record coordinate films (ca. 200,000 points per second at 5 fps). Thus, all areas of terrestrial surveying are covered by a single piece of equipment.

In order to attain useful results extensive calibration of the pmd camera is required. Currently, accuracy and range leave a lot to be desired. Absolute distance measuring accuracy to none-cooperative targets yielded ca. 0.7 + 2.4 cm / 10 m, and to cooperative targets ca. 2.8 cm at a distance of 60 m. Range is ca. 10 m to none-cooperative targets, and up to. 150 m to cooperative targets. However, several indicators allow us to conclude that accuracy, range as well as several other parameters of the 3D camera may improve in the foreseeable future:

1. Accuracy and range have already improved by a factor of two each within two successive generations of pmd cameras and within a total span of five years only.

2. Resolution was greatly increased, susceptibility to extraneous light was reduced further, rapid revision of integration time may now be programmed, quality of data may now be evaluated on the basis of flags et cetera. All of these improvements facilitate handling in praxis tremendously.

3. Currently, deviations of distance measurements due to optical crosstalk put the most significant constraints on practical recording projects, since they may result in systematic deformation, e.g. corner arcs of inner edges (Scherer 2009). However, this influence of external crosstalk may be reduced significantly by replacing phase distance measurement techniques with real interval transit time measurements (ToF = time of flight); new developments are pointing in this direction.

4. Rapid extension of the span and scope of applications for pmd-cameras in industry, manufacturing, medicine and automotive engineering accelerate further development, affecting a diverse set of parameters. Compared to the current changes the development of geodetic electronic distance measurement between 1950 and 1990 was very slow and focused on the small area of surveying.

Maximum coordinate accuracy (especially directional accuracy), as well as a range comparable to what a total station is capable of, will not be attainable with the device presented here, even in the future. However, in most instances an inexpensive medium-range device capable of comprehensive object recording at a point-accuracy of ½ cm - 1 cm via point clouds that simultaneously allows for precise surveying would be adequate - wouldn't it?

Recording in the areas of facility management, documentation of accidents, general indoor recording, recording for forensic or speleological applications, even field surveying utilizing the aforementioned reflecting rod are already advantageously possible with the prototype presented here. Due to the unique ability to „snap-record" a point cloud, the latter may even be carried out simpler with this device than it would be using a modern total station. A combination of the modes of operation mentioned above utilizing geo-referencing via GPS/GNSS including reflector signalized targets allows for some very appealing new possibilities in the fields of surveying, object recording and visualization in all areas utilizing low/medium - accuracy coordinates at low/medium ranges.

The 2D/3D total station is universally applicable for point-acquisition (as a total station), for the recording of RGB-point-clouds (like a laser scanner) and for visualizing and documentation.

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