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ON THE DETERMINATION OF THE PERFORMANCE OF TRACKING TACHEOMETERS

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Tracking tacheometers are capable of aiming at a target automatically, following it, determining the position during the movement and in some cases executing a coarse location. The performance of these instruments is difficult to evaluate, because of insufficient manufacturers' specifications and specific error sources of these instruments. New test and calibration methods have to be designed, which are a challenging tasks in respect to the demanding time dependence. This essay collocates important aspects and presents a number of investigation devices installed at the calibration lab at the geom*ETH of the ETH Zürich.*

1. INTRODUCTION

Today more and more total stations are equipped with tracking features, which enable the user to make the instrument automatically aim at targets. Depending on the instrument's features, these targets, which have to be reflective, have to be taught in a first step by the user or they can be searched by the instrument itself. Furthermore, a moving prism can be followed. Subsequent automatic target recognition (in this essay referred to as ATR, although this term is legally protected) features accelerate the measurement. Because one does not have to point to the target not manually/visually, the observer does not fatigue. The ATR delivers constant accuracy even in the darkness. Some instruments can be equipped with a remote control by radio link, which enables process control from the target point. If the instrument is equipped with a coarse location device including appropriate search features, an observer at the instrument can be fully abandoned.

Because the function principles of the instruments differ more or less, they deliver slightly different features, and, naturally, the manufacturer's specifications are not comparable in all aspects. In addition to the common instruments' errors of tacheometers, specific shortcomings related to the tracking module have to be considered. This demands for particular examination and calibrating methods. If the cinematic mode of the instruments shall be investigated, the methods have to be optimized in temporal respect.

Regarding economical aspects, the features which have to be investigated should result from the requirements of the application. Of course, mapping and setting out are the main surveying tasks. Apart from fast coarse location procedures they have the lowest performance demands, and additionally, they take advantage of a lightweight hardware. For deformation monitoring, including dams, tunnels, earth movements etc., accuracy and robustness are more important than the cinematic performance. Navigation, position control and guidance of construction machines require the most varying standards. Besides robustness in rough environments, these applications mostly claim for proper cinematic performance in different velocity and acceleration ranges, whereby the accuracy demands also vary. For example, the velocity requirement for grader guiding can be met usually, but the backward acceleration of these machines causes easily a lost of lock. Some guidance methods carry the tacheometer on the moving machine, hence vibrations are induced, which also can effect the accuracy. Highest accuracy is demanded for rail placing machines constructing high-velocity-tracks. Another field of application with very high requirements in respect for accuracy, robustness against beam interruptions and tracking velocity are robot calibration processes.

2. FUNCTION PRINCIPLES

2.1 Terminology

In general, tracking algorithms are divided in *coarse location* and *precise detection*. With coarse location procedures, a reflector is searched in the object space. By using modulated light a specific target can be distinguished confidently from other objects. Additionally, using an active reflector gives the opportunity of coding the target point. For precise detection, the target must lie in the field-of-view (FOV) of the tracking device. Image processing or a scanning algorithm, called *ATR*, follows, which determines the deviation of target image from the telescope-axis as a correction value. As a distance measurement has to be executed also, which should as less as possible be affected by phase inhomogenities, in most realizations the telescope is finally centered to the prism and a second deviation determination follows. This process describes the simple *static case* for automatic target recognition; [*Ingensand, Böckem, 1997*] presented more details for these techniques.

In case of a moving target, a *tracking algorithm* is applied. It operates like a control loop with the aim to minimize the pointing deviations independently from the target velocity. Beam interrupts (*lost of lock*) are managed by an extrapolation algorithm based on a movement model including simple or sophisticated numerical filters. If the observed target remains fixed, the measuring mode is classified as static, during motion, the mode is called "*Stop and Go*". If the coordinates are determined during the movement, the measuring mode is treated as "*cinematic*". This is very demanding mode, because all sensors have to be synchronized and read out simultaneously; furthermore, the measuring and responds time should be short for many applications.

To meet all requirements of tracking tacheometers, the instruments have to be equipped with *motorization*, *ATR*, tracking algorithms (sometimes called *auto-tracking* or *autolock)*, and possibly a coarse locating module. The motorization entails the replacement of the clamps by slipping clutches or similar, which may cause additional torque on the support of the tacheometer.

2.2 Function principles of commercial instruments

The following instruments are commercially available at present: the Geotronics System 600 with PT-module; the A-models of Leica TPS1000 series, with TPS1100-professional coming up; the TOPCON 3rd generation instrument AP-L1A, the new GTS 800A with coarse location and GRT2000, the latter being a special model for machine guidance; and the Zeiss Elta S series. In the following, special features are mentioned as far as they are thought to be relevant for the performance. The list does not claim for completeness.

For the confident location of the target Geotronics uses an active reflector emitting visible radiation. The track-light-axis is not coaxial to the telescope axis impeding second face measurements. Synchronized observations can be ensured within 5 ms. Detailed information on the function principle of the system 600 are not available at present for the author.

All instruments of the Leica TPS1000/1100 series are equipped with a CCD-array. Lines and rows are sampled separately with each centroid delivering the deviation from the telescope axis horizontally and vertically, respectively. Interlaced scanning with a frequency of 50 Hz gives sufficient information for long range tracking tasks. EDM, ATR-axis and line of sight are coaxial, technically demanding but convenient in use. The coarse location is executed by spiral scanning in an angular range of approx. 1.5°, if the target is not detectable within the ATR-FOV (0.5°). Details are presented in [*Bayer*, 1997], [*Zeiske*, 1999].

The instruments of the Zeiss S Track series are also equipped with a fully coaxial system and use image processing algorithms. Image acquisition time is announced to be 40 ms. System controlling by interrupt handling supports fast data acquisition. In addition to the AutoLock®-feature, the S space series is supplied with a QuickLock device, which enables a coarse location by a rotating vertical laser fan followed by fine location in the resulting vertical plane. Therefore, a radio link has to be established, which provides target coding also. For more details see [*Feist et al*, 1998].

The function principle of a TOPCON instrument differs extremely, because a scanning method is used: a laser beam scans in horizontal lines a range of 40’ horizontally and vertically, respectively. One scan takes 105 μs for a line and 6.72 ms in total. The time interval between the start of the scanning procedure and the first reflected signal is measured and the coordinates in the scan range are recalculated. Even in the worst case this method is with a data rate of approx. 150 Hz for the angle determination very fast. A noteworthy feature is the data transfer via Hyper-Terminal, which is very easy to handle.

3. EVALUATION OF PERFORMANCE

3.1 General remarks

First of all, the performance of an instrument can be estimated by the manufacturer’s specification. Using *testing* procedures these specifications can be checked in different respects: e.g. if a newly obtained instrument fulfils the specifications, or if an instrument has retained the specifications after excessive use in rough environments. In respect of the tracking tacheometers’ attributes, the manufacturers’ specifications are often incomplete or not comparable. This complicates the purchaser’s decision making, especially for non-standard applications. In the definition of *“instrument test”* , elaborated in the working group 5 of DVW [published by *Staiger*, 1998], and as mentioned above, the investigation of additional features are excluded, because in a test process the performance is verified solely according to the manufacturers’ specifications.

Upon this, *calibration* procedures deliver functions, which model the deviation and enables the correction of deterministic errors; this might improve the instruments' performance by increasing its accuracy. Regarding *common* tacheometers, users expect that nearly *all* instrumental errors can be corrected by the measuring method or by calibration functions, which are requested to be implemented in the instrument. Regarding *tracking* tacheometers, common observing methods to eliminate deviations fail or decrease the advantage of acceleration in the measuring process. Furthermore, the investigation of all possible error sources is uneconomical, because not all the features of tracking tacheometers are of interest in a specific application. Therefore, the user is advised to formulate his expectations. Thereafter, a catalogue of aspects can be created from which test rules are derived. Finally, experiences and additional investigations enable the development of calibration procedures. Then testing and calibration rules can be established, which finally led to a certification. In all this respects, the operation modes of a tracking tacheometer (static and cinematic) have to be treated separately. Within the static mode, we have to distinguish between the repeated observation of given points as used in the deformation measurements ("teach-in-mode") and the "stop and go" mode, which means, that the reflector is carried to a new point and observed in a static position, too. The following chapters demonstrate, in which respect the performance of tracking tacheometers can be characterized, in each case regarding specifications, operating characteristics and accuracy.

3.2 Performance characteristics in the static mode

3.2.1 General manufacturers' specifications

Generally, Hard- and Software must be looked at. Hardware aspects are the *effective range*, *scan area*, *accuracy* and *data transfer*. The effective range indicates the minimal and maximal distances, in between which the ATR works. It includes the ATR's FOV as the angular range, in which a target is detected without moving the telescope. The scan area marks the auto-tracking range, in which a target is searched by moving the telescope, if it was not detectable inside the ATR-FOV. This feature is less important in the teach-in-mode, if the points' movement do not exaggerate the ATR-FOV. In many cases, the scan range can be set by keyboard-input. Additional settings controlling the scan-procedure might be advantageous for some applications; this is supported e.g. by TOPCON instruments.

Usually, accuracy specifications published up to now are poor, because they give only a precision value for one or two specific distances. This implies, that the instrument does not meet the specifications at other distances. Especially here, test and calibration routines have to be applied. The hardware design concerning the data transfer determines the possible application modes: If a radio link can be established, the instrument can be controlled from the target point; this is essential for all guidance and navigation processes, which demand that the operator/machine is moved together with the reflector; especially for mapping, a mobile computing system at the target point is efficient. In the case of storing the data at the instrument, the type and capacity of the memory device must be sufficient for the high data volume going along with tracking tasks.

The software must guarantee a convenient handling of the auto-tracking controlling algorithms, and, if an external controlling is aspired, drivers for the auto-tracking, for data acquisition and data transfer and eventually for coarse location must be available, preferably for the main programming languages. For common surveying tasks a convenient interface to customary mobile field computing systems is advantageous. For more complex applications it can be useful, if instruments and data acquisition programs from different manufacturers are compatible.

3.2.2 Performance during operation

In this section, the performance during operation is discussed. Even in the static mode, time aspects are important as the efficiency of operation increases with decreasing the time for precise positioning. The performance of coarse location algorithms are even more critical in regard of effective field operation. For nearly all “stop-and-go” and cinematic applications the maximum allowed velocity and acceleration of the target has to be considered. Lateral or vertical target movements at low ranges are most decisive, because these correspond to large variations in the horizontal or vertical angle. Therefore, the maximal allowed velocities are often specified as angular velocities, although the distance tracking performance remains unmentioned. Large rotations around the vertical axis may affect the compensator performance, especially if it operates with a liquid. Deviations can minimized by placing the compensator device into the vertical axis (Leica TPS1000-professional) and/or observing the surface integrally. Additionally, the data gathering can be delayed until the liquid is leveled. Vibrations, e.g. occurring from the construction machine on which the instrument or the reflector is mounted, can cause similar effects. Up to now, nothing is published about implemented filter algorithms for reducing such effects. E.g. Leica meets the problem by offering different vertical-axis correction modes: if large acceleration or vibration effects on the compensator are expected, it is possible to use the correction value determined foregoing in a mode assumed as static. Moreover, large rotation accelerations around the vertical axis cause considerable torque upon the substructure: The support, tripod or even the pillar can rotate also in significant amounts. Detailed analyses are envisaged at the geom*ETH*.

Furthermore, the instrument’s reaction on signal interrupts characterizes the performance of a tracking tacheometer in the “stop-and-go”-mode as well as in the cinematic mode. Well operating instruments are equipped with extrapolation strategies, which take the recent reflector movements into consideration. They differ in respect of the extrapolation model, which in the simplest case is a linear model. The predetermined reflector position decides, where the new locating procedure starts. This procedure will fail, if the reflector did not move in the expected way or the interrupt remains. A sophisticated solution offering several possibilities to proceed after the signal is aborted completely would be helpful. However, extrinsic radiation and reflections can influence the measuring process also: Most disturbances are eliminated by using modulated radiation for the ATR, but a second reflector in the ATR’s FOV can only be handled correctly, if it delivers a code (e.g. Zeiss Elta S Space uses the radio link). Regarding measurement conditions with high extinction, multiple prism reflectors must be used. Hereby, a intensity-balanced configuration around the line of sight, which is also centric to the vertical axis, must be ensured.

3.2.3 Precision and accuracy

Additionally to all common tacheometer errors, further aspects determine the precision and the resolution of a tracking tacheometer. First of all, the resolution of the ATR replaces the ordinary visual aiming error, which depends on the observer and the measurement conditions. Although the resolution of the ATR is regarded as constant compared to the observer’s aiming error, external influences as signal intensity – which might be distance dependent –, extrinsic radiation and scintillation effects because of the propagation through the turbulent medium air affect the accuracy. Beside these stochastic components, deterministic ones result from the deviation between the collimation axis of the ATR and the line-of-sight, which influence the observation, if visual and automatic targeting is combined. Furthermore, the straightness of the ATR collimation axis has to be proved. If the ATR-device is not coaxial to the line of sight (Geotronics), two-face-observations, which usually eliminates collimation errors, are not possible offhand.

Regarding the target side, the alignment of the reflector remains important: e.g. a rotation of 20° causes a distance error of about 2 mm, depending on the construction of the prism mounting. 360° reflectors with different structural shapes were designed to redundantize prism alignment completely. But investigations showed, that periodic deviations up to some millimeters occur in dependence of the orientation of the prism and of the steepness of the sight [*Favre, Hennes,* 1999]. (The manufacturer reacted by re-designing the prism, which is now being investigated.)

3.3 Performance characteristics in the cinematic mode

3.3.1 General remarks on the uncertainty relation influencing the performance

Additionally to all deviations and accuracy losses discussed above, further effects influence the performance in the cinematic mode. They are much more related to the time dimension, because now the data acquisition takes place while the target is moving. This implies, that the three position coordinates (polar or cartesian) have to be acquired exactly at the same time: If the object travels with 1m/s and the time delay between the acquisition of first and the last coordinate of the triple amounts to 1 ms, the object has already moved 1 mm. (The value is directly proportional to the velocity of the object.) Vice versa: due to the time delay (of 1 ms) in the reading of the observations the coordinate triple is inaccurate (by 1 mm). This example demonstrates the high demands for the data acquisition with respect to internal observation readings as well as to data transfer. This coherence can be formulated as an uncertainty relation: With a specific data acquisition rate given, a target can not be located better than a definite value; and, vice versa: if a moving target has to be located with a specific accuracy, the data acquisition must be faster than a definite value. In this respect, we have to keep in mind, that the particular measuring processes are not of equal length: an angle reading is completed much faster than a distance measurement; and furthermore, it takes much more time to perform a whole distance determination than to make the distance value available for the data transfer. In addition, the ATR-process has to be performed. Its length may depend on external influences: scintillation may cause a repetition of the CCD-reading and a subsequent calculation of the mean value. The parameters for this mode might be set by the manual input of a-priori accuracy limits. In conclusion, the determination of a coordinate triple depends on the slowest process and demands for sophisticated algorithms. However, the performance of a tracking tacheometer is mainly describable by the allowed maximum target velocity and acceleration. Hereby, the extrapolation strategies may have an additional influence. In regard to the subsequent data processing, the exact data observation time is of interest. Up to now, no manufacturer delivers these information within the common data output. As the uncertainty relation applies to the merging of the single coordinate components, the uncertainty can be reduced, if each coordinate is labeled with its time mark. Regarding the requirement of delay-free data transfer, the demand can be nearly met by using interrupts, but considering, that they are not supported delay-free by sophisticated operating systems as Windows.

3.3.1 Accuracy aspects

As mentioned above, accuracy is reduced by the non-simultaneous data acquisition process. Furthermore, the precision of the measurements might be reduced, because the number of repetitions is decreased to accelerate the observation process. The uncertainty relation applies once more. Moreover, a number of internal reference measuring processes might be diminished producing further systematic errors. For example, distance drift effects, are usually eliminated by determining the internal reference distance – but significant deviations in the order of 5 mm show up during the auto-tracking mode. Detailed investigations suggest, that the manufacturer optimized the timing of the reference measurements with respect to the data acquisition speed. Beside the drift of the common measurement elements, a drift of the ATR-line-of-sight is imaginable. Even more than in the “stop-and-go”-mode, the behavior of the compensator during and after accelerations is a crucial point for the accuracy of the vertical angle. Although the effect reduces much more cinematic applications, details are already described above. In respect of signal interrupts, the sophistication of the extrapolation algorithms are essential for the accuracy.

4. EXAMINATION METHODS

4.1 General remarks

As shown above, the additional modules for the ATR are assumed to develop their specific error budget. Besides, a multitude of aspects arise with the time as the fourth dimension. Examination procedures have to consider these aspects and, if they has to be developed for calibration, they have to account for the error *sources*. This implies, that the original observations/readings (polar coordinates) are to be investigated in spite of the requested results, which are usually cartesian coordinates. Although testing-only methods might look at the latter ones, their accuracy determination will not be the crucial point of this essay.

However, besides distinguishing between the error sources, we have to consider, which of the operation modes of the tracking tacheometers is investigated. Table 1 shows, which information of the performance is delivered in dependence of examination method, the application mode and the origin observation. Details to some devices are given below.

In general, all examinations of the static mode can be executed without computer supported data acquisition. Of course, automation of the reference device remunerates, if a lot of tests were performed. For the investigation of the performance for cinematic and accelerated movement, controlling by computer is not strictly necessary, but useful. In principle, data can be stored on the memory device implemented in the tacheometer. Besides, with this method the advantages of the instruments’ features are not completely taken, because then special controlling commands (as data rate, scanning mode, compensator mode) cannot be fully exploited to increase the instrument’s performance. However, the methods 1 to 7 qualify by an elementary functional model: the reference values can be described by a geometric/physical model and need no additional controlling device, as long as the reference to the time-dimension is disregarded. For example, the linear test can be performed by tracking a prism, which is travelling on straight rails: The resulting coordinates must fit to a straight line, which is defined by the position of tip and tail in the static mode. However, especially the linear rail test suggests computer controlling; at the geom*ETH* first steps are made with an examination device, which was originally designed for the determination of cyclic errors. (Similar installations are available at most calibration laboratories.) Here again, the uncertainty relation applies. The free fall test and the pendulum test can be treated in a similar way with the pendulum test being capable of generating acceleration changes, but in both procedures eventually occurring prism errors may reduce the test accuracy.

	Examination process	Hz	V	D
1	Linear horizontal test – sledge	S (K)	-	S (K)
2	Linear horizontal test – railway	S A I	-	S K A I
3	Vertical sledge	-	S (K)	-
4	Circle line test – vertical	A I	A I	-
5	Circle line test – horizontal	A I	-	A I
6	Free fall test	-	A I	A I
7	Pendulum test	A I	A	A
8	Prism investigation	S	S	S
9	Beam interrupts by rotating disk	+	+	-

S Static
K Cinematic   Movement   I Beam interrupt by masking
A Accelerated

Tab 1: Examination methods

4.2 Details of the geom*ETH investigation equipment*

At the calibration laboratory of the Institute of Geodesy and Photogrammetry at the ETH Zürich some devices for the investigation of tracking tacheometers are available, some are in development. The static linear test can be performed with a sledge (cross support) with a resolution of 1/100 mm over a measuring range of 25 mm. The vertical sledge has a measuring range of 540 mm, whereby the digital controlling (using a step motor and an angle encoder) is in development. It is envisaged to use it also in cinematic mode with low velocities.

The linear test for the cinematic mode is performed using the equipment, which is also capable for the evaluation of cyclic distance errors. On a length of 52 m, a sledge can be moved with a constant velocity up to 0.75 m/s, whereby the position can be determined by an interferometer up to a travel velocity of 0.3 m/s. The interferometer's accuracy is given by 0.2 µm + 0.5 ppm. The combined controlling of the motor drive, the interferometer and common tacheometers is in development. Up to now, the basic geometric model is used assuming straight rails, that means, that the instrument tracks the moved prism. Different instrument stations in the vicinity of the track enable the investigation of the performance during acceleration as well as the focussing mainly on distance or on horizontal angle measurements, respectively. Angular velocities up to approx. 60 gon/s can be reached, with accelerations depending on the lateral distance to the rails.

Furthermore, a circle line test equipment is also available: A prism rotates on a vertical circle (diameter 0.4 m to 1.6 m) with a rotation velocity of up to 3 m/s (~ 36 rpm). With this construction mainly the performance of the angular system is investigated, because the surrounding space does not allow an eccentric station, which would also generate distance variations. Nevertheless, various positions of the instrument in the circle rotation axis, prism mounts with different radii and continuously variable settings of the rotation velocities provide a wide range of angular velocities and measuring ranges for the tacheometer: e.g. an angular velocity 3 gon/s is equivalent to the position 20 m in front of the circle with a diameter of 1.2 m rotating with 16 rpm. In the moment, the analysis of the test data is restricted to the least squares fit of the circle. The distribution of the measured points on the circle line informs about the regularity of the tracking, eventually occurring dropouts and the achievable data rate; large residuals point to measurement failures and/or timing uncertainties – all under the assumption of a nearly unchanged distance. The equivalent investigation for distance performance can be executed by using the linear test equipment and locating the instrument in the elongation of the sledge movement line.

At the geom*ETH*, the reaction after beam interrupts are investigated by using the circle line test and the linear test equipment, whereby beam obstructions are generated by placing a shield in a part of the observed sector. From the deviations from the circle or the straight line respectively, the error distribution after beam interrupts is derived.

Last not least, the prism-constant-deviations of 360°-prisms are investigated by rotating the prism around its vertical axis in regular steps of 10°. For automation of the process, the prism is mounted on top of a motorized theodolite, which is solely used as a positioning support. This procedure is capable for the automatic determination of cyclic errors, which have shown to be extremely prism-dependent [*Favre, Hennes*;1999].

4.3 Controlling and data acquisition demands

As shown in various examples above, the fourth dimension, time, increases the complexity of investigation processes extremely. The hardware devices and software algorithms are very demanding in comparison with the static methods used up to now. The uncertainty relation, which causes imprecise results in the tacheometer itself, challenges the calibration processes even more, because it has to be applied with the next order of magnitude. This means, that the investigation equipment has to resolve at least the millisecond, as well for the simultaneous controlling of several devices as for the data acquisition from the tacheometer. As mentioned above, a few software drivers are available (sometimes on special request) for external instrument controlling tasks. However, the choice, which has to correspond with the choice of the programming language, may influence the performance of the instrument. Although high-level programming environments simplify the source code generation, they are only recommendable, if the application is not time-critical. Regarding the investigation procedure, it is usually accepted as a rule to use the examinee in combination with exactly the same devices - and software! - as in the application itself. This principle must be hurt, if the tacheometer testing processes include the time-related implementation of investigation devices: Because these are normally considerably time-consuming, they necessitate the change to a deviating programming language, which is faster in execution – omitting all related disadvantages.

The best language-choice depends on the manufacturer’s offer of drivers and how they can be implemented in the usually applied programming language. Regarding the calibration of the tacheometer, reference values have to be acquired from additional devices, which tend to communicate with the controlling PC over miscellaneous interfaces as RS232, digital I/O-ports, DMA or interrupts. This restricts the variety of suitable programming environments. Furthermore, using a high-level operation system at the controlling PC, several basic commands (DOS or even lower), which are known to be fast, become obviously slower or are not available any more, e.g. it is not possible to handle interrupts under MS-Windows offhand without time delay. Special data acquisition software with graphical surface (e.g. LabView, NI), which is mainly applied in metrology and electronic engineering, is capable for this tasks, because many restrictions concerning the (comparatively slow) operation system are solved. Furthermore, it seems, that sophisticated inter- or even extrapolation processes describing the target movements during the calibration process have to be developed to meet the acquirements.

5. FINAL REMARKS AND OUTLOOK

Although on first sight the accuracy of tracking tacheometers seems to be sufficient for standard surveying tasks as mapping or setting out, it is strongly recommendable to verify at least the manufacturers' specifications, for acceptance or certification reasons. Therefore, simple test procedures are sufficient. But with tracking tacheometers, instruments are at disposal, which are capable for more demanding tasks as controlling or guidance of construction machines. Here, time-related calibration procedures are necessary, which have to be developed with respect to the user's requirements and expectations. Additionally, new error types and observations' deviations occur, which require newly designed investigation methods. In most cases, they have to be time-related, which makes the data synchronization between instrument (examinee) and reference device the most challenging task.

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