Position Determination of a Moving Reflector in Real Time by Robotic Total Station Angle Measurements

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Abstract

Angle readings from Robotic Total Stations (RTS) can be acquired with a very high update rate in comparison with the update rate of the distance measurement. For short ranges these readings can be considered more accurate than the distance measurements. The currently presented system makes use of this feature and combines measurements captured from two Leica high precision RTS that have Automatic Target Recognition (ATR) sensors in order to determine the position of a moving reflector in real time based solely on angles. Both RTS are stationed in the same coordinate reference frame and controlled by a central computer running a LabVIEW program. It retrieves the angle measurements and calculates the current position of the moving reflector based on angle intersection principles. This increases the positioning frequency of the RTS system to 20 points/second, which is twice as fast as the normal tracking mode of these specific RTS. A miniature railway and trolley are used to move the studied reflectors.
In the first tests, different positions of reflectors placed on a stationary trolley are determined and compared to positions coming from classical measurements of angles and distances. The differences are in this case less than 1 mm. Further experiments, present the achieved position in kinematic mode by means of lateral deviations to a reference line, leading to an average value of 2.1 mm for the 360° reflectors and 3.3 mm for a normal reflector.

Keywords
Automatic Target Recognition, angle intersection, real time positioning.

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1. Introduction

Angle measurements can be considered the oldest means of determining the position of a remote object. These are used for purposes that vary from determining geodetic networks to close range photogrammetry.
The principle of angle intersections is nowadays mostly utilized in Theodolite Measurement Systems (TMS) that imply simultaneous measurements from at least two theodolites. After establishing a common coordinate reference system, the measured angles are used to calculate the 2D or 3D position of the desired objects. Depending on the distance between the theodolites and the angle measurement accuracy, very high accuracies are achievable. For example, with a base length of 10 m and angle measurement standard deviation of 0.7 mgon, objects up to 10 m can be determined with a precision of 0.3 mm (Hennecke et al., 1992). This is possible for nonmoving objects only. In order to extend the functionality of such a system to a kinematic application, the theodolites must be capable of following the moving object and delivering the raw data for processing in real time. Even though the idea is not new, there are, to our concern, few or tangential publications on this topic.
A RTS has a tracking function that can be used in combination with a reflector to reach the aforementioned purposes. For short ranges, accuracy of the point position is mostly influenced by the distance measurement. In comparison with the distance measurement, angle readings are available with a much higher update rate. In real time kinematic applications that rely on a RTS for positioning, 3D coordinates are determined using angle and distance measurements. This fact limits the position update rate to the distance measurement update rate.
In this paper, two Leica high precision RTS (TS 30 and TS16i) that are equipped with Automatic Target Recognition (ATR) sensors are used to deliver angle measurements to an external computer that calculates the position of a moving reflector in real time based solely on angles. The functional model and hardware implementation are explained in detail in the second part of the article.
Experiments undertaken in laboratory conditions, present the

achieved position of several reflectors placed on a moving trolley running on a miniature railway. This simulates a kinematic application that can resemble guidance and control processes for construction machines. The results are afterwards compared with measurements taken in static mode and tracking mode. Further enhancements and examples of possible applications are given in the last part of the paper.

2. Functional model and hardware implementation

Starting with the middle 80' electronic TMS became popular on the market as a solution to the high precision demands of industrial measurements. In Bill (1985) information about the functioning principles and first available hardware and software solutions from the companies Keuffel & Esser (Breithaupt), Kern, Zeiss and Wild has been published. In the same publication, examples of applications have been given and it can be commonly accepted that since then, the components of a TMS have seen many enhancements, but the principles remained basically the same.
The currently presented system resembles a TMS, but certain steps of the measurement and computation process are done differently. Figure 1 represents the setup with its individual components and computed or measured values needed for calculating the position of the moving target. In a first phase, RTS 1 will play the role of the system origin, thus fictionally receiving the coordinates *(0,0,0)* and the RTS 2 receives *(0,b,Δz)*.

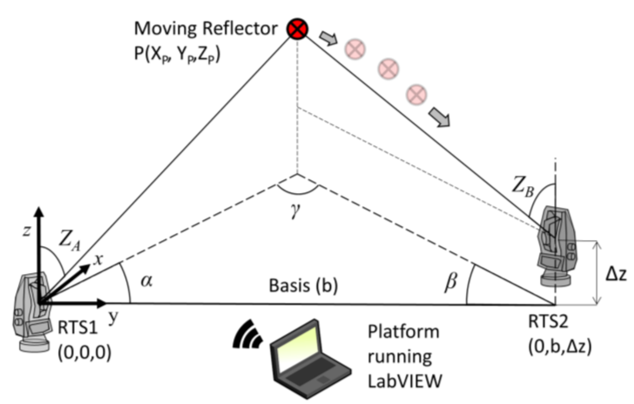

Fig. 1 – System components and measured/computed values

Intersection approach measures angular (direction) observations to the unknown position; with the measuring instrument occupying each of the known stations. It has the advantage of being able to position an unknown point which cannot be physically occupied (Awange et al., 2010). Nevertheless, in the presented system, the observed object needs to be accessible at least once when fixing the reflector. Afterwards, the only condition is that the line-of-sight between each RTS and the reflector is not interrupted during the measuring process.

Before the actual measurement, there are some steps that need to be followed. The 3D coordinates for both RTS need to be determined in a local or global coordinate system. There are multiple methods of doing this, but here a predefined known coordinate frame has been used to determine the station points through resection (Möser et al., 2012). Besides the position of the RTS, the orientation of the coordinate system is fixed, too. From this point on, several elements can be calculated. The 2D distance b is determined as the Euclidian plane distance between the two RTS and the height difference Δz by subtracting the two heights. Also the orientation angle t_{12} between the origin RTS and the second RTS is calculated with help of coordinates.
The next step implies calculating the plane angles α and β with the help of the orientation angle in each point of time as follows:

$$\alpha = t_{12} - r_{1P} \qquad \beta = \pi - t_{12} + r_{2P}$$

where r_{1P} and r_{2P} are the directly measured directions from the RTS to the observed point P.
Having these, the relative coordinates may be delivered by the following equations (Kahmen, 2006):

$$\Delta x = b \cdot \frac{\sin\alpha \cdot \sin\beta}{\sin(\alpha+\beta)} \qquad \Delta y = b \cdot \frac{\cos\alpha \cdot \sin\beta}{\sin(\alpha+\beta)}$$

$$\Delta z = \frac{1}{2} \cdot \left(b \cdot \frac{\sin\beta \cdot \cot Z_A + \sin\alpha \cdot \cot Z_B}{\sin(\alpha+\beta)} + \Delta z_{AB} \right)$$

These relative coordinates are available in a Cartesian Coordinate System (CCS) in which the origin is fixed in the optical center of one RTS, the y-axis is pointing horizontally the second RTS, the x-axis is perpendicular on the y-axis and the z-axis corresponds with the plumb line of the first instruments. Due to this fact, absolute coordinates of the observed point are retrieved only after a transformation. One simple method implies transforming the plane coordinates with the aid of the rotation angle between CCS and the absolute or local coordinate system in which the RTS were stationed as follows:

$$\varphi = t_{12} - \frac{\pi}{2}$$
$$X_P = X_O + \Delta x \cdot \cos\varphi - \Delta y \cdot \sin\varphi$$
$$Y_P = Y_O + \Delta x \cdot \sin\varphi + \Delta y \cdot \cos\varphi$$
$$Z_P = Z_O + \Delta z$$

All these equations yield the functional model that is implemented in the LabVIEW graphical programming interface. Some input parameters like the coordinates of the RTS and implicitly basis length and orientation do not change during the measuring process. These are considered error free, even though this is not entirely true even in laboratory conditions. Other elements like the directions and zenith angles are constantly changing during the measurement process. In order to accomplish these tasks, the two RTS are connected via a serial connection RS232 to the computer running LabVIEW. A constant inquiry about the current status of the RTS takes place and as a response, the two angles are retrieved. In comparison with other connections, the serial one is preferred due to its standardization and simplicity of use (Georgi & Metin, 2007). This is also facilitated from the RTS manufacturer's side through the Leica GeoCOM interface which permits server-client based interactions (Leica Geosystems, 2018). The GeoCOM command used for the angle measurement is TMC_GetAngle5. If more information about each angle measurement is needed, the command TMC_GetAngle1 can be used to obtain internal or instrument specific information, but for the present case most of that information is redundant.

None of the above described implementations would have made sense if the ATR Module in the RTS had not tracked the reflector with a high frequency of about 20 Hz. This has also been tested and proved in Lienhart et al. (2017). Shortly described, a laser beam is emitted and based on the projected laser spot that returns from a reflector on the CMOS-Picture-Sensor, the difference between the reflector center and crosshair center can be calculated and reduced to 0 by guiding the telescope. Considering that the processing in the ATR module takes place with a speed of up to 200 picture segmentations per second, following a reflector is a stable process even at short ranges (Stempfhuber & Kirschner, 2008). The Leica TS30 has an ATR Module and the Leica TS16 benefits from the enhancements of the ATRPlus Module. For more specific technical information about these developments, the reader should consult Stempfhuber & Kirschner (2008), Grimm et al. (2015) and Kleemaier et al. (2016).

Another decisive factor worth mentioning is the reflector. Usually, 360° reflectors are used in tracking applications due to the flexibility offered by the angle of incidence between line-of-sight and reflector. Nevertheless, due to the constructive solution of these reflectors, mostly made out of six bundled single prisms, there are several negative influences on the measurements of horizontal respectively vertical angle and slope distance. These lead to, depending mostly on how the 360° reflector is rotated, systematic position falsification of up to 8 mm; a fact proved in Lackner & Lienhart (2016). It is mostly due to double reflections at close ranges of the same reflector on the CMOS-Picture-Sensor; in this case the telescope may be directed to the ''false'' reflector center. A solution to overcome this issue is to use a normal reflector which is not subject to such systematic errors, but the disadvantage is, that the maximum incidence angle at which ATR still functions is around 50gons. If only one RTS is needed in the tracking application, there are some possible solutions of using a normal reflector and adapting it to a sensor platform that actively turns to always face the observing instrument (Horst & von Gösseln, 2012). Normally such enhancements are used for active targets working in combination with laser trackers.

After having the hardware and software components set up, several experimental measurements were made to firstly test the system and secondly have an idea about the offered accuracy based on comparisons between the different measurement modes.

3. Experiments

Three different Leica reflectors were put to test in two measurement setups (figure 3). The main difference between them is the position of the two RTS with respect to the reflectors. In case 1, a normal reflector cannot be adequately tested due to the increasing angle of incidence when the reflector is approaching the base. After a certain point, the ATR Module cannot track the reflector anymore; therefore, case 2 is studied to evaluate the system with a normal reflector. In case 1 the base (b) has around 4 m and case 2 it is reduced to 1.5 m. The distances to the moving reflectors vary in both cases from 1 m to 3 m.

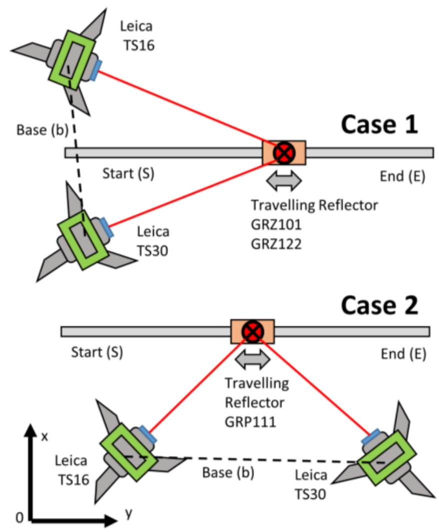

Fig. 3 – Measurement setups used to test the functionality of the system

In each case, the reflectors were mounted on a trolley (figure 4) that can be manually shifted on a miniature railway in two directions. This was chosen mainly for two reasons:

- ease of testing and repeatability
- resemblance to mobile measurement systems that rely on total station assisted measurements e.g. (Amberg Technologies, 2018).

Fig. 4 – Miniature trolley with the used reflectors (from left to right: Leica Miniprisma GMP111, Leica 360° Miniprisma GRZ101, Leica 360° Prisma GRZ122)

After the resection has been completed for both RTS, the coordinates of the station points can be introduced or uploaded; the user must manually aim the target once and the connection can be started. From this point on, based on the calculated and measured values, the program delivers the position of the reflector with an update rate of 20 Hz. After terminating the program, the user can save the data for further analysis.

3.1 Static test

To verify the calculated coordinates, several points where measured while the trolley was stationary. These values were compared to the position obtained from a normal measurement (angles and distances) from each RTS. As it can be seen in table 1, the differences are very small, all of them having a magnitude of less than 1 mm. Even though a functional relationship between the intersection angle γ and these differences was expected, this test has yielded inconclusive results. The theoretical aspects for an optimal configuration regarding basis, angle and distance to the observed objects can be read in Kersting (1987).

Table 1 Differences between polar measured positions on the miniature railway and angle determined positions in static mode

Point	dX (mm)	dY (mm)	dZ (mm)	Intersection Angle(γ) (gon)
GRZ101-1	0.03	-0.75	0.08	93
GRZ101-2	0.25	-0.95	0.34	110
GRZ101-3	0.70	-0.75	0.40	133
GRZ101-4	-0.55	-0.45	0.35	165
GRZ122-1	-0.25	0.40	0.30	93
GRZ122-2	-0.85	-0.35	0.30	110
GRZ122-3	-0.33	-0.83	0.20	132
GRZ122-4	-0.18	-0.50	0.32	165
GMP111-1	0.35	0.10	0.00	29
GMP111-2	-0.40	-0.07	0.01	31
GMP111-3	-0.95	0.17	0.15	31
GMP111-4	-0.39	0.20	-0.03	28

The errors are well below a mm for all coordinates components; mainly they are on a tenth-mm level. Consequently, it can be assumed that the functional model leads to reliable positioning for static reflectors.

3.2 Kinematic test

For the kinematic tests, a reference was defined as measure of comparison. This reference is a straight line that best fits several points measured along the miniature railway in a stable state of the trolley. In such applications, lateral deviations are a good indicator for the achieved positioning quality. Therefore, each single point measured during the trolley movement is projected onto the reference line and the resulting distance is colorized depending on its magnitude. Figure 5 represents the lateral deviations with regard to the reference line for each reflector.

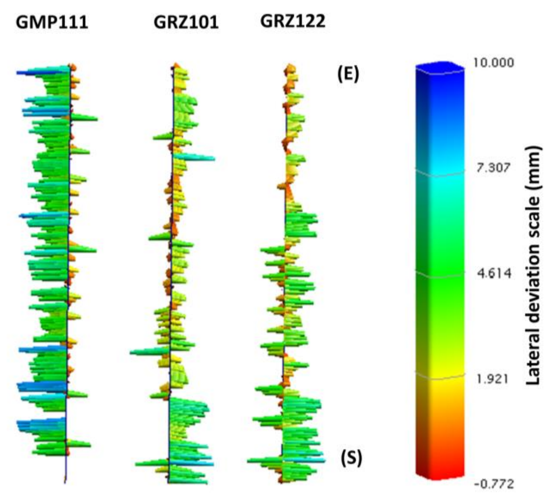

Fig. 5 – Lateral deviations with the position obtained in real time via angle measurements only (magnified 25x)

After the first tests, a systematic effect on the lateral deviations has been observed. The determined positions were all directed towards the TS30. This lead to the conclusion that the two RTS are not delivering data simultaneously, therefore synchronization of the data transfer rate needs to be achieved. Unlike in Schwieger et al. (2010) where the position of a point is influenced by internally (RTS) synchronized angles and distances, here the synchronization problem is extended to the whole system comprised of the RTS.

Analyzing the data of both RTS, a time delay of 50 ms for all TS30 angles was empirically derived and afterwards applied in the software. This leads to an average lateral deviation in case 1 of 2.1 mm with the maximum deviation of 7 mm. In case 2 using the reflector GMP111 lead to an average lateral deviation of 3.3 mm. Simulations show that lateral deviations based on the angular measurement accuracy in this case should be smaller than 1 mm, but this was not reached. Even after applying the time offset correction, the majority of the positions in case 2 were directed towards the instruments. Because reflector has a limited aperture angle (~30°), the RTS showed difficulties of following it after a certain position.

During the tracking process angles are continuously used for position determination, but if one of the RTS receives a doubtable reflection (e.g. another reflector in the background) it shortly searches for the reflector again, fact that falsifies the position for short moments of time. Even if the search window is very narrow, the movements opposite to the travelling direction lead to outliers.

An independent test has been performed for the two cases, with one RTS set in synchro-tracking mode. This is what normally occurs when a single RTS is used for guidance and control. The single points are then obtained as polar points. Only the positions from one RTS in tracking mode (Leica TS30) are represented in the same way as before (figure 6).

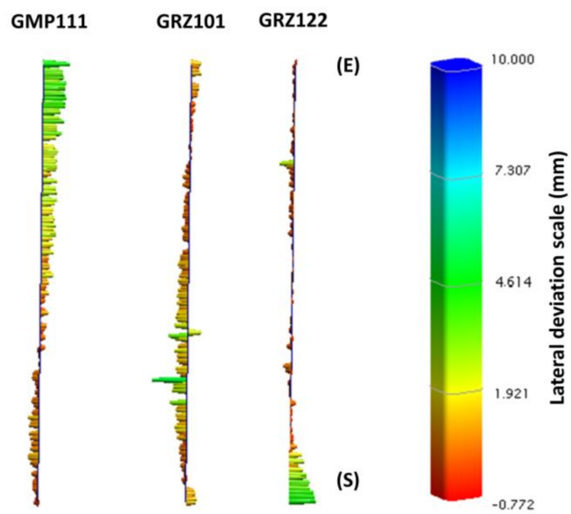

Fig. 6 – Lateral deviations with the position obtained in synchro-tracking mode via angle and distance measurements (magnified 25x)

A first observation is that all the lateral deviations of the points obtained in the tracking mode are smaller for all reflectors. The mean value of the lateral deviation for both 360° reflectors is 1.3 mm and for the miniprism 2.0 mm. In these specific conditions, the results are better than the ones obtained with the angles only measurements. A disadvantage is that the maximum measurement frequency is 10 Hz, but after analyzing the data, an average of only 6 Hz was reached in reality. Currently, high-end RTS that reach a maximum measurement frequency of 20 Hz are available on the market, but the present study dealt only with the presented RTS.

4. Conclusions

One of the main goals of this work was to present a possibility of increased position determination rate with the aid of angle measurements only received from a network of RTS (Kerekes & Schwieger, 2018). A LabVIEW program has been developed to connect the two RTS and based on principles of TMS, to deliver the position of a moving reflector with an update rate of 20 points/second. This is the current state of the developed system and further improvements are under research.

The synchronization issues that were encountered are not entirely resolved because there are many sources that affect the data flow. Solutions presented by Thalmann & Neuner (2018) in which Network Time Protocol is used to synchronize sensors may be adopted to determine the time offset and drift if these are present. Another possible improvement is a data filter that would automatically eliminate positions during the searching phase, therefore eliminating biased positions of the reflector.

A system that presents one order of higher accuracy degree can be used to establish a reference and help at calibrating the system. Lerke & Schwieger (2015) used measurements from a laser tracker as reference values to determine possible systematic errors and evaluate the positioning quality.

Nevertheless, if the desired accuracy is within the current limits (under 5 mm), the system can serve as a positioning sensor for kinematic application or guidance and control of machines, unmanned aerial vehicles or robots that are depending on a high position update frequency. In the context of building fast and efficiently, such systems may be used in combination with fast moving construction machines that benefit from a high positioning update rate. This generally reduces the control process.

All in all, advantages of the presented RTS System are flexibility, good positioning quality and high update rate of up to 20 Hz while facilitating the use with little or no user interference.

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