

High Frequency Terrestrial Laser Scans for Monitoring Kinematic Processes

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SUMMARY

This paper works on the use of high frequency terrestrial laser scans for monitoring kinematic processes without considering the causal forces. The focus is put on the determination of the object's geometry as well as geometry changes. First, a discussion of geodetic monitoring in the context of terrestrial laser scanning is done including measurement and data analysis issues. The relation between the spatial and the temporal resolution of phase-based terrestrial laser scanner is discussed in detail. Second, two selected applications are presented to show the high potential of the terrestrial laser scanning technology with its high spatial as well as high temporal resolution. The first example treats the quasi-static bending of a bridge due to traffic load. And the second example discusses the monitoring of the highly frequent oscillations of a wind energy turbine due to wind load. The presented results show that terrestrial laser scanning is well suited for monitoring area-based deformations as well as highly frequent processes by reducing the resolution via filtering and aggregation in time and space.

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1. INTRODUCTION AND MOTIVATION

The monitoring of the kinematics and dynamics of structures is an important and safety relevant task in civil engineering which accompanies an effective life cycle management. In general, temporal sequences or time series, respectively, of physical and geometric parameters of the structure are derived as monitoring results which can be analyzed and interpreted according to the specific questions. In the following, the more general notion of a (spatial) object will be used instead of a structure. Engineering geodesy contributes to object monitoring by determining the deviations of geometric parameters such as position, orientation and shape of the considered object. Basic parameters provided through geodetic monitoring are the coordinates of discrete, signalized object points which describe the object's geometric states at different epochs. They are very precise with numerical measures typically in the mm to sub-mm range.

Although a great success has been achieved in the past, classical geodetic monitoring shows two main disadvantages which are due to the established sensor equipment: (i) for highly precise results artificial retro-reflecting prisms have to be used as (eccentric) target points restricting the monitoring to a coarse network of single points, and (ii) the ability to track object motions or deformations is limited to time scales of days and longer. The significance of these two problems was decreased to some extent in the last two decades through a couple of developments in total station technology (i.e., reflector-less electronic distance measurements and automatic target tracking). More recently, an even more fundamental breakthrough seems to be achieved with the upcoming of terrestrial laser scanning (TLS). The arising potential for a precise and directly centric geodetic monitoring with high spatio-temporal resolution of moving or deforming spatial objects is subject of this paper. The phase-based laser scanners are of particular interest as they enable a huge variety of kinematic applications.

The focus of the study is put on the monitoring of object kinematics which means the determination of the object's geometry and geometry changes without considering the causal forces. After a discussion of geodetic monitoring in the context of TLS including measurement and data analysis issues, the highly frequent oscillations of a wind energy turbine due to wind load and the quasi-static bending of a bridge due to traffic load are considered and discussed as applications. In the perspective, the presented methodology provides an essential and unique real-data input to model-based simulations, e.g., in structural engineering.

2. STRATEGY FOR MONITORING KINEMATIC PROCESSES

2.1 Modeling and analysis of kinematic processes

Within this paper, a kinematic process is understood as the (discrete or continuous) sequence of temporal changes of the geometry of an arbitrary spatial object without considering any causes such as, e.g., physical forces. These geometry changes can be described in terms of rigid body motions (translation and rotation) and deformations, respectively. The process velocity is expressed through the geometry changes with respect to time. It can vary in a broad range between high-frequent oscillations with periods below 1 s and very slow movements so that the object seems to be in rest over longer periods. Hence, when a kinematic process is monitored, the information about the process velocity is crucial. The sampling rate of the sensor has to be adjusted to this velocity. Each sampling of the process can be seen as a snapshot whose spatial dimension depends on the sensors in use and whose temporal resolution equals the sampling rate. Vice versa, the process characteristics restrict the meaningful types of sensors which have to be selected carefully.

Thus, the monitoring strategy for a particular kinematic process depends on the (modeling of the) process characteristics. It comprises the definition of both the measurement and the data analysis strategy. Independent of the actual choice it is essential to establish the temporal and the spatial relation between the different object states in a precise and consistent way. In other words, respective reference frames have to be defined. The temporal relation can be based on a unique time reference for all measurements. Concerning the spatial relation two variants are possible. In the first case the spatial relation is immediately given through a fixed physical link between the sensor and the object. This situation appears if the sensor or relevant parts of it are installed directly on the object. In the second case the spatial relation of the object is observed by a sensor without a physical connection between the sensor and the object. In this case the spatial resolution has to be established mathematically using homologous points or (in general) features of the object. In addition, state-space filtering such as the Kalman filter can be applied which links the states by the system equation.

For TLS applications it is straightforward to use the time stamps of the internal clock of the device as temporal reference. Alternatively, time can be introduced from an external clock such as, e.g., a GPS receiver; see, e.g., HESSE (2007) for a comprehensive discussion. The spatial reference is uniquely defined in case of just one position of the scanner by the scanner's origin, orientation and scale. For the spatial relations between the different object states additional targets or persistent object features can be used. This corresponds with the registration and geo-referencing procedure when scans from different positions have to be combined. The discussion in this paper refers to a single scanner position as it is assumed that the process velocity is too fast to move the scanner to a second position.

2.2 Measurement strategy for monitoring kinematic processes

As described in the preceding sections the object characteristics play the central role in a monitoring process. For this reason, both the measurement and the data analysis strategy depend on the object's behavior. Hence, in the planning phase several parameters have to be considered which can be seen as input parameters for the monitoring program and which limit the usable sensors.

In the following a brief overview of these parameters is given. First, there is the spatial extension of the object itself. Depending on this extension it has to be defined if the whole object or only regions of main interest are observed. Second, the expected kinematic behavior of the object is relevant regarding the amplitude and rate (or frequency) of the observable effects. These aspects were already treated briefly in Section 2.1. In addition, the observation interval is important. This corresponds directly with the question concerning epochal or continuous observations. The level of automation is also relevant. A higher grade of automation means that a minimum of user interaction is necessary to start and also to run the monitoring process. In the ideal case user interactions are only required for starting the monitoring process. It can be expected that automated observations are both faster and more reliable.

Directly related with these aspects is the time period for the measurements. Common are short-term or long-term measurement periods. Within a short-term measurement a single snapshot of the current object behavior is generated. For this purpose, the sensors are temporarily installed on or close to the object. In contrast, a long-term measurement requires fixed sensor installations with a high grade of automation. It is important to use robust sensors so that the down time as well as the support time of the sensors can be reduced to a minimum. The analysis should be capable for real-time purposes. Many long-term measurements allow to view a current object state online and to know at any time what happens with the object. Another important aspect is the accessibility to the object. This means the possibility to install sensors directly on or in the object. Otherwise the data acquisition has to be done with reflector-less remote-operating sensors. As last aspect there is the adaptability of the measurement strategy to a new object situation with a minimum of user interaction based on actual measurements. This aspect is of high relevance in the context of sensor networks.

The mentioned issues of a measurement strategy have to be linked with the pool of sensors for monitoring tasks. The typical pool in engineering geodesy consists of inclinometers, levels, total stations, GNSS equipment and some other devices. All these sensors allow only a discrete data acquisition at a limited data rate of 20 Hz at maximum for new GNSS equipments. Hence, they all are suitable for monitoring special kinematic processes but they are limited in general. However, with the upcoming of TLS in engineering geodesy a broader range of highly-precise monitoring applications is feasible.

Present terrestrial laser scanners based on the phase measurement technique allow to determine the slope distance to the object without additional retro-reflectors and thus directly centric. Thereby a high spatial resolution and a very high data acquisition frequency up to 500000 points per second are provided. The maximum range of such scanners is limited to short range up to mid-range distances due to the well-known range ambiguities of the phase measurement technique. In comparison to the typical geodetic sensors TLS is in principle a surface based measurement technique. The determination of the horizontal and the vertical angles is comparable to other polar measurement techniques like tachymetry. A predefined area (or window) is captured by a scanner through an emitted laser which is sent to a rotating mirror; additionally, the whole device is rotated about its vertical axis. As a result, 3D coordinates of the scanned points within the predefined area are directly obtained; they are defined in a local or sensor-based coordinate system. The geometric level of detail is controlled by the rotation speed of both the horizontal and the vertical motor. Note that a higher spatial resolution is associated with a reduced temporal resolution and vice versa.

Based on this overview of the measurement principle of TLS the focus is now put on the relation between spatial and temporal resolution; see Figure 1 for a general outline. The traditional (spatial) operating mode of TLS is the so called 3D mode. In this 3D mode the highest spatial resolution as well as the minimal temporal resolution is available. Parameters which control this 3D mode are the point density (a.k.a. scan resolution), the range accuracy and the predefined area size. The area size is given as operating range for both the horizontal and the vertical motor. With respect to kinematic applications the temporal resolution plays a key role: the temporal resolution can be increased in 3D mode by a smaller observation window or by a coarser spatial resolution. If this is not sufficient for the application of interest, one of the following two modes may be used.

In the 2D mode (a.k.a. profiler mode) the rotation of the scanning device about its vertical axis is disabled. Therefore there is only one degree of freedom for the motion of the scanner (i.e., the rotation in a defined vertical plane). The 2D mode is characterized by an obviously reduced spatial dimension but with a much higher temporal resolution as the same profile is repeatedly observed. For this reason, the maximum spatial resolution within this profile is possible for more applications in contrast to the 3D mode where a coarser spatial resolution is due to a finer temporal resolution. The data acquisition in 2D mode is done for one predefined vertical section of the object which is characterized by the fixed horizontal direction and the corresponding vertical angles and slope distances.

The 1D mode (a.k.a. static mode) is characterized by the minimal spatial dimension and resolution, respectively, and the maximal temporal resolution. Actually, there are no remaining degrees of freedom as only the distance between scanner and object is repeatedly observed along one particular spatial direction. There is no rotation of the scanner at all. The 1D mode allows the highest sampling rate up to 500000 slope distance measurements per second to a predefined position given by both the horizontal and vertical angle.

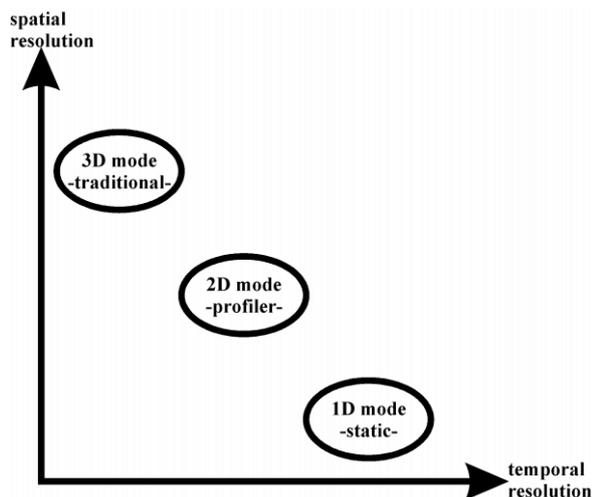


Figure 1: Relation between spatial and temporal resolution for TLS

In the following a brief assessment concerning the use of TLS for the monitoring of kinematic processes will be given.

The 3D mode is partly qualified for monitoring kinematic processes. If the frequency of the process is slow enough that it rests about several minutes in one stable state the 3D mode could be a good alternative to traditional sensors. The benefit regarding the traditional sensors

is the area-based data acquisition as well as the very high spatial resolution. If a kinematic process could be divided in quasi-static parts, e.g., a predefined static load on a defined position of a bridge structure (see Section 3.1), TLS is very suitable for such short-term measurements.

Without doubt, both the 2D and the 1D mode are qualified for monitoring also faster kinematic processes because of the high temporal resolution. Both modes provide a much higher temporal resolution than traditional sensors without accessing or even touching the object of interest. In addition, the object surface is derived directly without the need to take eccentricities into account. For these reasons completely new applications are feasible. The determination of high-frequent oscillations of the pylon of a wind energy turbine is one example which will be discussed in Section 3.2. In addition, the precise observation of the dynamic bending and oscillations of a bridge structure under real traffic conditions is a realistic goal.

The discussion shows that TLS is a very qualified methodology for monitoring kinematic processes. There is on the one hand the adaptable relation between spatial and temporal resolution and on the other hand the sensor's flexibility in use. There is no time consuming preparation and installation work. Moreover, in many cases the access to the object is not critical because of the remote observation techniques.

3. APPLICATIONS

This section deals with applications of monitoring kinematic processes with the TLS technology. Due to the fact that TLS is an area-based as well as reflector-less technology the accurate mutual spatial referencing of scans of different object states plays an important role. In KOSAK ET AL. (2008) the evaluation of the monitoring of a lock chamber is presented. The spatial referencing was achieved by evaluating the digital terrain model of differences; further details are given in the named paper. Another method for achieving the spatial reference between different object states based on planes is presented by GIELSDORF ET AL. (2008). In this paper the spatial reference will be established by spatial aggregation as described in the following.

In the following two selected projects of monitoring kinematic processes with high frequency terrestrial laser scans are treated which were performed by the Geodetic Institute of Hannover. These projects cover all aspects discussed in Section 2, in particular the spatial referencing of scans of different object states.

The terrestrial laser scanner which was used in all applications is the Z+F Imager 5006. It is a phase-based laser scanner with a unique measurement range of 79 m. The maximum data acquisition rate is up to 500000 points per second. The maximum rotation speed of the vertical motor, which is relevant for the 2D mode, is limited to 50 rotations per second. For further details see the datasheet of the manufacturer (ZOLLER+FRÖHLICH, 2007).

3.1 Monitoring of a bridge structure

The first example deals with the monitoring of a bridge structure. This project was realized with the Institute of Concrete Construction of the Leibniz Universität Hannover.

The data acquisition in this project was done in all three spatial modes (see Section 2.2) which are provided by the Z+F Imager 5006. Note that this paper concentrates on the measurements in 3D mode. Both the analysis of the 2D and the 1D mode as well as a comparative analysis with the measurements of the Institute of Concrete Construction will be presented in a second paper.

The data acquisition in 3D mode was done while the bridge structure was loaded with a specified weight at predefined positions. The upper left part of Figure 2 shows the situation in a side-view. In it the predefined positions are marked and numbered with green color. The region of interest was scanned in 3D mode. It is marked in light blue color. The lower left part of Figure 2 shows a part of the original 3D scan where the region of interest is again marked in light blue color. The distance between the TLS and the bridge structure varies for the region of interest from 14.9 m up to 19.9 m. The width of the region of interest is at the farthest point away from the TLS about 5 m and at the nearest point to the TLS about 7 m. The length of the region of interest in direction of the structure is about 6 m. The data acquisition was done stepwise for the predefined position. The specified load rested at each of the four positions until the TLS had finished the data acquisition. Additionally one object state was registered while the structure was free of any load. As a result of this quasi-static process a discrete temporal sequence of four predefined loaded positions is generated.

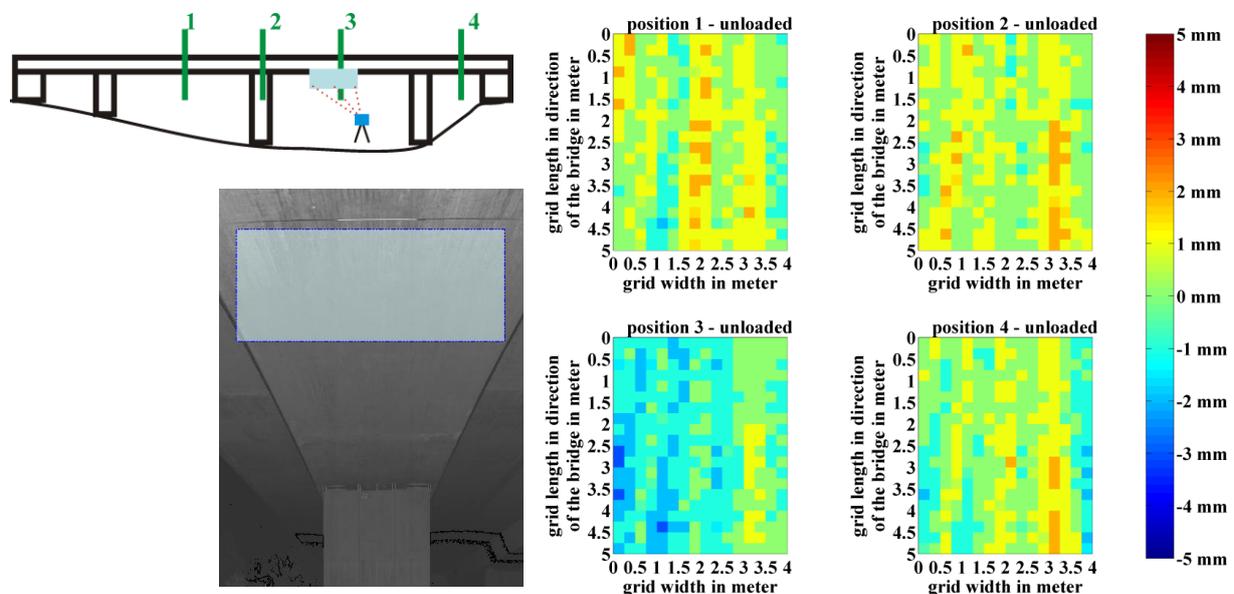


Figure 2: The upper left part shows a side-view of the bridge structure with the predefined load positions numbered and marked with green color. The lower left part shows a part of the 3D laser scan with the region of interest marked in light blue. The right part shows the change for the region of interest from red to blue color for positive to negative values. The quadratic patches within the region of interest have a size of 0.25 m x 0.25 m with approximately 360 points per patch. The overall number of patches is 320 with approximately 117800 points.

To interpret these data and for a comparison of the different discrete states it is important to get an accurate mutual spatial referencing of the scans of the different states. Therefore an equal spatial prediction was done in each of the states by defining the origin of a regular grid

within the region of interest. This origin is exactly equal for all states, so that each state could be spatially compared to another state. The regular grid in the region of interest was defined with a width of 4 m and a length in direction of the bridge of 5 m. The quadratic patches of the grid were defined each with a size of 0.25 m x 0.25 m. The overall number of points in the tiled part of the region of interest was about 117800 points. Each of the 320 patches consists of approximately 360 points. As preparation for the further analysis for each patch the median of the z-values was computed as representative value for the further analysis. The standard deviation of the z-component of the points in each patch is on average about 3 mm. Hence, the standard deviation for the representative (median) value is on average about 0.2 mm. The specific size of these standard deviations depends on the distance between TLS and bridge. In the further analysis spatially referenced differences for each corresponding patch element in the unloaded state and the four loaded states for the representative (median) value of the z-component of the points were computed. In the right part of Figure 2 the differences of the four loaded states and the unloaded state are shown. A downwards deflection is shown in blue color and an upwards deflection in red color. Figure 2 shows that if the load is placed in positions 1, 2 and 4, the representative (median) values of the points' z-component in the region of interest are increasing by about 1 mm up to 1.5 mm which indicates a slight lifting of this part of the bridge. If the load is placed in position 3, which is directly above the region of interest, the downwards deflection for the representative (median) values of the points' z-component with numerical values up to 3 mm is clearly visible. These first results of this project show the potential of the terrestrial laser scanning technology for monitoring tasks. Nevertheless the analysis strategy will be improved as well as a consideration of side effects like, e.g., wind load. This ongoing work will be published elsewhere.

3.2 Monitoring of a wind energy turbine

The second example deals with the monitoring of a wind energy turbine (WET) south of Hannover. This WET is of type Tacke 1.5 S and has an overall pylon height of about 77 m. The conical pylon made of steel was built on a concrete base. The steel thickness reduces in a range of about 22 mm at the bottom down to 8 mm at the top. This WET was observed several times with different sensors so that the kinematic behavior is well known (HESSE ET AL., 2006, VENNEGEERTS & KUTTERER, 2007).

The data acquisition was done from two different stations using the 1D mode as well as the 2D mode of the Z+F Imager 5006. The first station was perpendicular to the wind direction and the second one was frontal in wind direction.

At the first station measurements in 2D mode with a rotation speed for the vertical motor of 12.5 Hz were done for several minutes. Afterwards the TLS was switched to 1D mode with a measurement rate of 62000 Hz. In this mode several points in different heights from about 35 m up to 64 m were scanned, each for a few minutes.

Figure 3 shows an interval of about 3 minutes of the 2D mode measurements in a slope distance of about 40 m. The raw data were spatially aggregated with two different vertical class widths. The red colored data series is the horizontal mean of a vertical class width of 0.1 m consisting of 13 points in each class. The black colored data series shows the mean values of a vertical class width of 1 m with 127 points in each class.

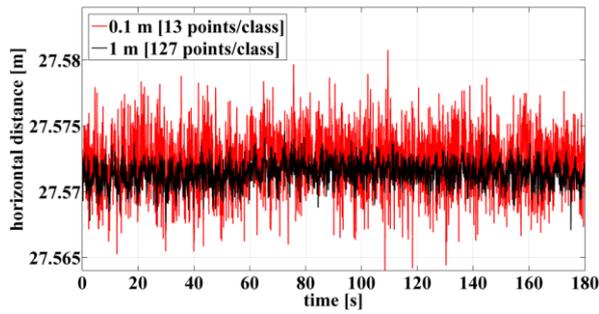


Figure 3: Comparison of mean values of two vertical class widths

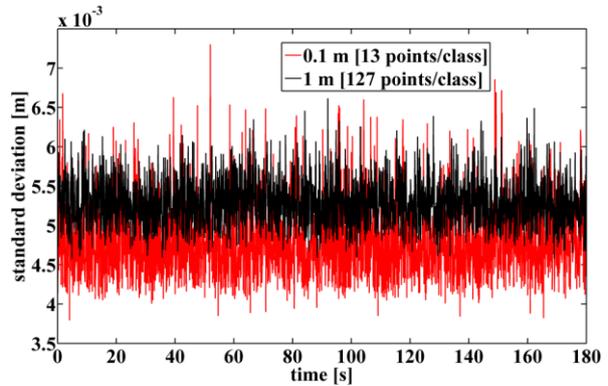


Figure 4: Corresponding standard deviations of the two vertical class widths

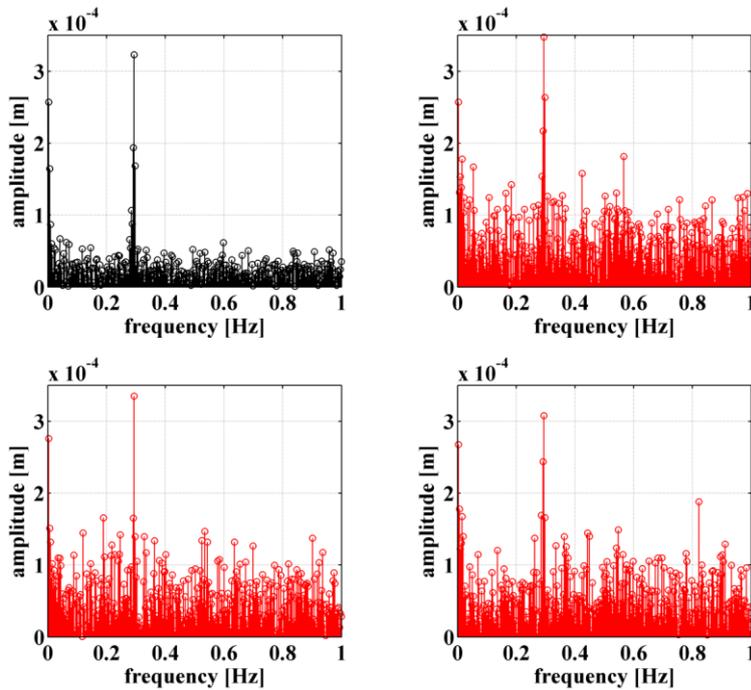


Figure 5: Upper left part: Amplitude spectrum of the vertical class of 1 m width in black color. Upper right and lower part: Amplitude spectra of the vertical class of 0.1 m width within the class of 1 m in red color.

In this classification the spatial part of the pylon was the same for both class widths. This equal vertical center of both classes allows the comparison of the mean values of the two classes. It can be seen, that a smaller spatial class width corresponds with an increased noise level. In Figure 4 the corresponding standard deviations of the two vertical class widths are shown. For the smaller class width of 0.1 m the absolute value for the standard deviations is smaller than for the larger class width of 1 m. Theoretically the absolute values for the standard deviations should correspond to each other. The offset between the results for the two data series can be explained by the used class width as well as the class mean value calculation for the data aggregation. This data aggregation does not absolutely fit to the geometrically orientation of the corresponding pylon section. For this example this means that the pylon is not sufficiently vertical in the larger class width. This fact results in a higher sum of squares as well as in a higher standard deviation. This comparison shows the difficulties of

the data aggregation as well as the right use of the relation of the spatio-temporal resolution. An improved data modeling and data processing strategy is under development.

The corresponding amplitude spectra of the two vertical class widths are displayed in Figure 5. The upper left part of Figure 5 shows the amplitude spectrum of the vertical class of 1 m width in black color. The eigenfrequency of nearly 0.3 Hz is clearly visible. The energy level for other frequencies is clearly below 0.1 mm what is caused by the class width which has a smoothing effect. The upper right and the lower part of Figure 5 show three amplitude spectra of vertical classes with 0.1 m width within the considered class of 1 m in red colored. The eigenfrequency of nearly 0.3 Hz is visible in all three spectra but the energy level of the other frequencies is higher than for the larger class. This fact is due to the smaller class width and the associated, resulting higher noise level.

At the second station only measurements in the 1D mode were done. Figure 6 shows a 20 s part of the time series at a slope distance of about 64 m. The original data was filtered with the median with a filter length of 500 points. Figure 7 shows the corresponding amplitude spectrum including the eigenfrequency of nearly 0.3 Hz.

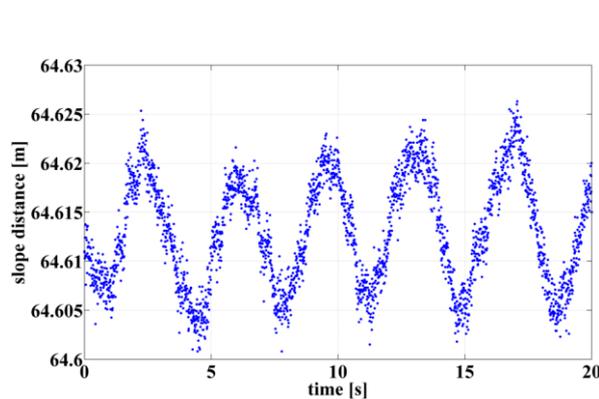


Figure 6: Filtered time series from station 2 (observed in wind direction)

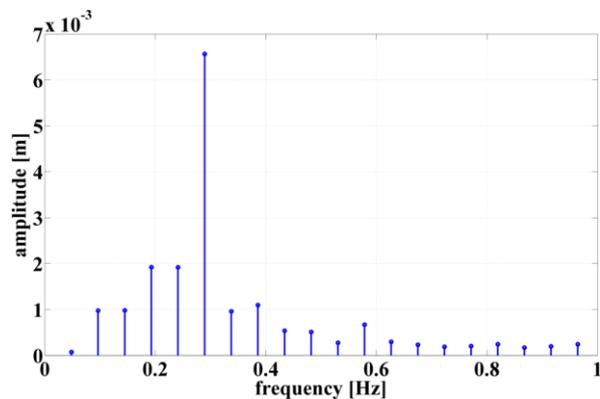


Figure 7: Corresponding amplitude spectrum with the characteristic frequencies

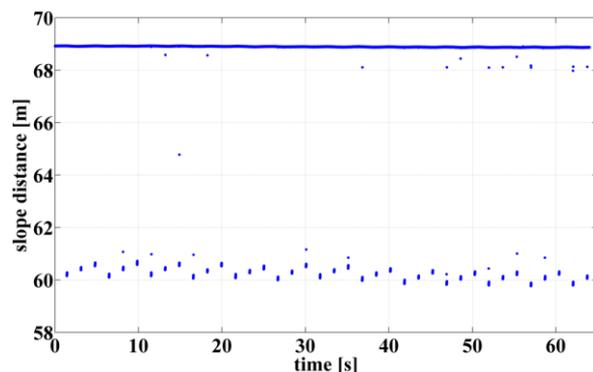


Figure 8: Frontal view (in wind direction) with rotor blade passes

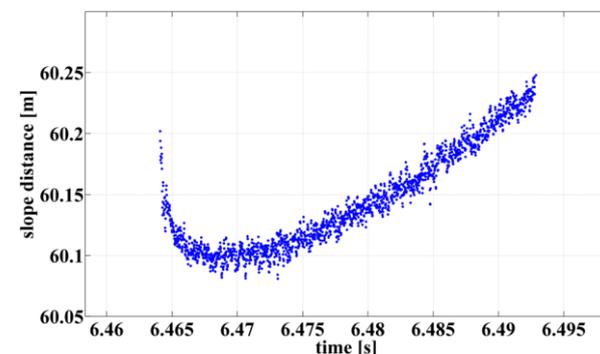


Figure 9: Rotor blade pass in detail

A 60 s part of raw data scanned from station two can be seen in Figure 8. The slope distance of about 69 m is near to the ambiguity range of the used TLS, in a respective height of the pylon. In this frontal direction to the WET the laser beam is interrupted periodically by the three passing rotor blades. As it can be seen in Figure 9 this interruption takes about 25 ms.

Together with a measurement rate of 62000 Hz, each profile of the rotating blade is represented by around 1500 points.

The results of the presented measurements at the wind energy turbine show the high potential of the TLS technology for monitoring kinematic objects. Nevertheless the results show also the current and coming working fields in the analysis of such measurements. These fields are mainly related with the questions about an improved spatial as well as temporal modeling and filtering.

4. CONCLUSIONS AND FUTURE WORK

This paper discussed the use of high frequency terrestrial laser scans for monitoring kinematic processes. The relation of spatial and temporal resolution of terrestrial laser scanning was treated in detail. The general usability in the traditional 3D mode with its high spatial resolution is well-suited for monitoring area-based deformations. The benefit of reducing the spatial and increasing the temporal resolution was shown by the monitoring of a wind energy turbine. The presented results showed that it is possible to capture even the surface of a fast-rotating rotor blade of a wind energy turbine. One can say that TLS and especially the capturing of high frequency laser scans is very qualified for monitoring kinematic processes. Future work will focus on an improvement of the analysis methods by a more consistent geometric and kinematic modeling. In addition, the intensity of the laser scans as well as the angle of impact will be taken into account.

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BIOGRAPHICAL NOTES

Prof. Dr. Hansjörg Kutterer received his Dipl.-Ing. and Ph.D. in Geodesy at the University of Karlsruhe in 1990 and 1993, respectively. Since 2004 he is a Full Professor at the Geodetic Institute of the Leibniz Universität of Hannover. His research areas are: adjustment theory and error models, quality assessment, geodetic monitoring, terrestrial laser scanning and automation of measurement processes. He is active in national and international scientific associations and designated Vice President of the Deutscher Verein für Vermessungswesen e.V. (DVW). In addition he is member of the editorial board of the Journal of Applied Geodesy.

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Harald Vennegeerts received his Dipl.-Ing. in Geodesy at the Leibniz Universität Hannover in 2001. In addition he passed his technical state examination in 2003. Since 2006 he is research assistant at the Geodetic Institute at the Leibniz Universität Hannover. Among industrial measurement systems his research activities are focused on terrestrial laser scanning in kinematic applications as well as in mobile mapping systems.

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