FIRST STEPS TO A TOPOGRAPHIC INFORMATION SYSTEM OF THE NEXT GENERATION

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Commission IV, WG IV/1

KEY WORDS: Topographic Information System, Digital Terrain Models, 3D City Models, Efficient Data Handling, Spatial Databases, Interpolation Algorithm

ABSTRACT:

Laser scanning had a huge impact on topographic information systems (TIS) and geographic information systems (GIS). Compared to other data acquisition methods, airborne and terrestrial laser scanner systems have a high degree of automation and allow capturing surfaces in various scales. It turns out that laser scanners are both, efficient and economical measuring tools for cultural heritage objects, detailed city models but also country-wide digital terrain models (DTM), to a previously unknown degree of detail. The increase of available data sets leads to higher demands on interpolation algorithms and efficient spatial data structures of TISs. Whereas country or planet-wide surface models are typically described in 2.5D (the terrain heights are described by a bivariate function over the ground plan domain), models of bigger scaled objects (e.g. city models) are nowadays (or least in the near future) modelled by full 3D approaches. Consequently TISs of the future will have to combine both, 2.5D efficiency and 3D capability. Such a strategy including an efficient data handling, as currently developed for SCOP-NG (SCOP Next Generation), will be presented within this article.

1. INTRODUCTION

Over the last decade major improvements in laser scanning (LS) have been made which opened up a huge range of new applications. It turns out that laser scanners are both, efficient and economical measuring tools for cultural heritage objects, detailed city models but also country-wide or even planet-wide DTMs, to a previously unknown degree of detail.

Modern airborne laser scanning (ALS, often also refered to as LIDAR (**LI**ght **D**etection **A**nd **R**anging)) systems measure with enormous data rates (various scanners reach up to 100 000 Hz). Hence, typical ALS projects consist of millions of points which can be characterised as randomly distributed points without topologic information. Similar situation arises in digital (aerial) Photogrammetry where matching algorithms automatically extract surface points. Considering the data acquisition process, modern DTM interpolation strategies have to take this huge amount of randomly distributed point clouds into account to generate high quality DTMs. Such high quality DTM generation algorithms usually consist of a classification stage, to identify terrain points from off-terrain points, and the actual interpolation stage, which implies an appropriate filter process to compensate for random measurement errors. Furthermore, the presented interpolation strategy of SCOP-NG uses a structure line extraction step which helps to avoid unwanted surface smoothing along geomorphological structures (i.e. break lines.). This line information is also added to the final DTM.

From a processing time point of view, better laser scanners with higher measurement rates and bigger project areas cancel advances made in computer technology to a certain degree. Therefore, the huge amount of point data produced by modern measurement techniques still requires efficient data handling. For SCOP-NG a custom data structure was developed considering data configuration and special needs of future TISs as described in Chapter 3.

State-of-the-art DTMs are based on a 2.5D approach. Whereas it is still possible to 'numerically' model vertical elements in 2.5D, such an approach is unable to describe general 3D structures like overhangs, caves or complex artificial buildings (i.e. bridges). From an application point of view this has been of minor concern so far since it was not possible (or least far too expensive) to capture detailed 3D data in a large scale. However, technological improvements are starting to change this. Full 3D models of several cities already exist (Kobel et. al, 2005) which cannot be described by a 2.5D approach any more. Hence, it is just a matter of time until applications arise which require the full 3D information within TIS.As described in this paper, SCOP-NG uses a combined 2.5D and 3D approach to optimise efficiency and flexibility.

2. FROM POINT CLOUDS TO HIGH-QUALITY DTMS

LS is nowadays a well accepted measurement technology and therefore used for many commercial applications. As an example ALS projects, which are carried out by the provincial governments of Austria, should be mentioned. The survey of the Province Voralberg has been carried out last year. Other

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Austrian Provinces are currently preparing similar projects or at least planning to do so in the next years. The situation is comparable in other European countries such as Germany or Italy.

Country-wide laser scanner projects use a typical point density of 1 point per 1 m^2. Considering project areas of i.e. 7000 km^2 in the Province Tyrol, 70 millions points and more have to be handled to carry out such projects. An adequate DTM generation process is required to meet the high demands for such large projects.

The raw point information is appropriate for visualisation, more advanced tasks, however, will fail because of the missing topology. A triangulation of the unfiltered point data can resolve the topology problem, but the quality of the resulting surface is usually very poor since all measurement errors are modelled into the surface (Figure 1). Simultaneous filtering during the triangulation process is an absolute requirement for high quality surface descriptions (Ackermann, Kraus, 2004). The SCOP approach goes even further using a surface description independently of the original point distribution. This is justifiable since the data distribution is random and does not reflect the surface characteristics.

In the following the SCOP-NG DTM generation process is described. It consists of three major steps: A structure line extraction stage, a point classification stage and the actual interpolation process.
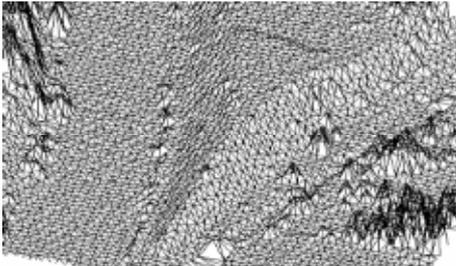

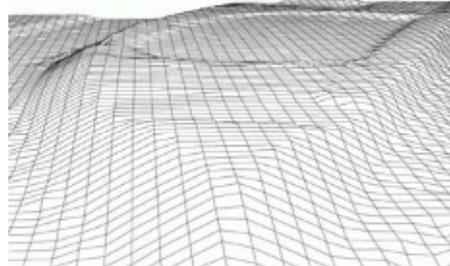Figure 1: Triangulation of the unfiltered point data
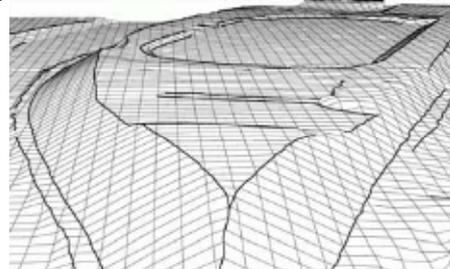

Figure 2: Filtered DTM without extracted break lines

Figure 3: Filtered DTM including extracted break lines

2.1 Extraction of structure line information

As mentioned before, a filtering of the original points is essential to achieve smooth surface descriptions. However, any filter process will also smoothen surface areas that contain high gradient or curvature changes, as they appear along geomorphological structures (cf. Sithole and Vosselman, 2003). This leads to smooth but low-precision DTMs. To eliminate this problem SCOP-NG uses a structure line extraction and modelling process developed by Briese (2004a). The algorithm uses a rough 2D approximation of the break lines and the original unfiltered point data to describe the break lines with the help of overlapping patches along the break line. Within this method, the local break line segment per patch is modelled by the intersection line of two adjusting planes determined with the help of the point cloud data in the surrounding of the structure line. Special weight functions in conjunction with robust least-squares methods allow removing off-terrain points (Figure 4). The final 3D break line is then described by a sequence of representative points and tangent directions. Furthermore, in order to automate the process Briese (2004) introduces the concept of break line growing to reduce the problem of 2D line approximations.

Finally, the computed break lines can be integrated in the further DTM generation process (off-terrain point removal and interpolation) allowing a high quality description of discontinuity areas (cf. Figure 2 and 3).
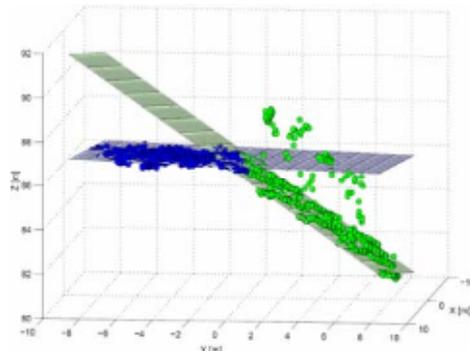

Figure 4:   Example of adjusted plane pair using robust least-squares (vegetation is filtered, cf. Briese, 2004b)

2.2 Classification Stage

A traditional DTM describes an idealised terrain surface, without building and vegetation. However, the original point cloud contains points on such unwanted objects which is why classification strategies have to be applied to find an adequate surface descriptions. In SCOP++ (current version of SCOP) the hierarchic robust linear prediction, which already allows considering structure line information, is used (Kraus and Pfeifer, 1998 and Briese et al., 2002). For completeness a paper by Sithole and Vosselman (2003) should be mentioned which gives a good overview and comparison of different classification methods.

All these classification strategies have one thing in common: they use geometric criteria to differentiate between terrain and non-terrain points (some methods support even more than two point classes). From today's point of view this will change in the near future. Full-waveform scanners allow extracting physical features for a single laser point (Wagner et. al, 2004). Based on these features the point cloud can be classified (Ducic et al., 2006). Whereas geometric approaches tend to fail for low vegetation (cf. Pfeifer et. al , 2004), tests at our institute have shown that full-waveform data can clearly improve classification results for such regions.

Hence, future strategies should support both, geometrical and physical point properties for the classification stage. For SCOP-NG a flexible classifier called Dempster-Shafer will be used.

Rottensteiner et. al. (2005) has successfully applied this method for automated building detection from LIDAR data combined with multi-spectral images. The method is comparable to fuzzy logic approaches since probability functions have to be defined which describe the correlation between input data and classification classes. Consequently the strategy allows introducing geometric, but also physical, point attributes which have been derived from full-waveform data. Moreover, in situation where multi-spectral images are available these data can also be applied to further improve the classification results.

The implementation of the proposed classification strategy is just at the beginning within SCOP-NG. So a rigorous and broad evaluation which shows the efficiency of the approach is still to come. However, first tests are looking promising.

2.3 Interpolation Stage

The robust linear prediction has proven as flexible and efficient interpolation method. Therefore, it is used for classification and interpolation within SCOP++. Although the interpolation method itself is well suited for many different applications, the implementation of the overall process has turned out to be inflexible for adoptions and extensions since it is more than 20 years old. The data handling and the interpolation method were strongly interlinked which caused this inflexibility.
For SCOP-NG a new interpolation framework was designed which allows adding different interpolation methods in an easy and comfortable way. Additionally it was demanded that the framework also supports new multi-core CPUs, namely multiple interpolation threads.
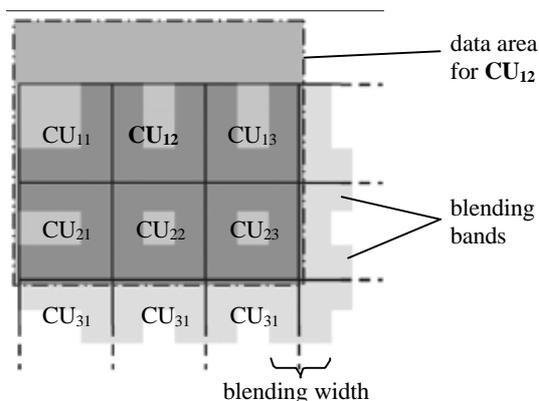

Figure 5: Computing units with blending bands

Interpolation methods can be generally divided into two groups: local and global algorithms. Whereas local methods (i.e. moving least squares, nearest neighbour interpolation, etc.) only depend on the neighbourhood of the interpolation position, global algorithms (i.e. Constrained Delaunay Triangulation, linear prediction, polynomial interpolation, etc) require all source data for arbitrary computing positions. Considering memory limitations and processing speed local interpolation method are generally favoured compared to global algorithms. However, applying certain strategies even global algorithms can be turned into local algorithms as it is done for the linear prediction in SCOP. Therefore the interpolation area is split into 2D computing units (CU). For each CU the global interpolation method is applied also considering geometry data from adjacent CUs. To achieve a continuous surface description over the full interpolation area, SCOP-NG merges interpolated

values within defined distances to the CU borders(cf. Warriner and Mandlburger, 2005).

The management of CUs requires some computational resources, contrariwise it makes it easy to support multiple interpolation threads. This way the computation can be parallelised without parallelising each interpolation algorithm itself. Based on this consideration a multi threaded interpolation framework for both, local and global interpolation algorithm was designed and it is currently implemented in SCOP-NG. A flow chart of the process using the blending option is given in the following (The framework also supports the consideration of a local or a global trend as it is a required for certain interpolation methods. To simplify Figure 6 this was not reflected in the flow chart)
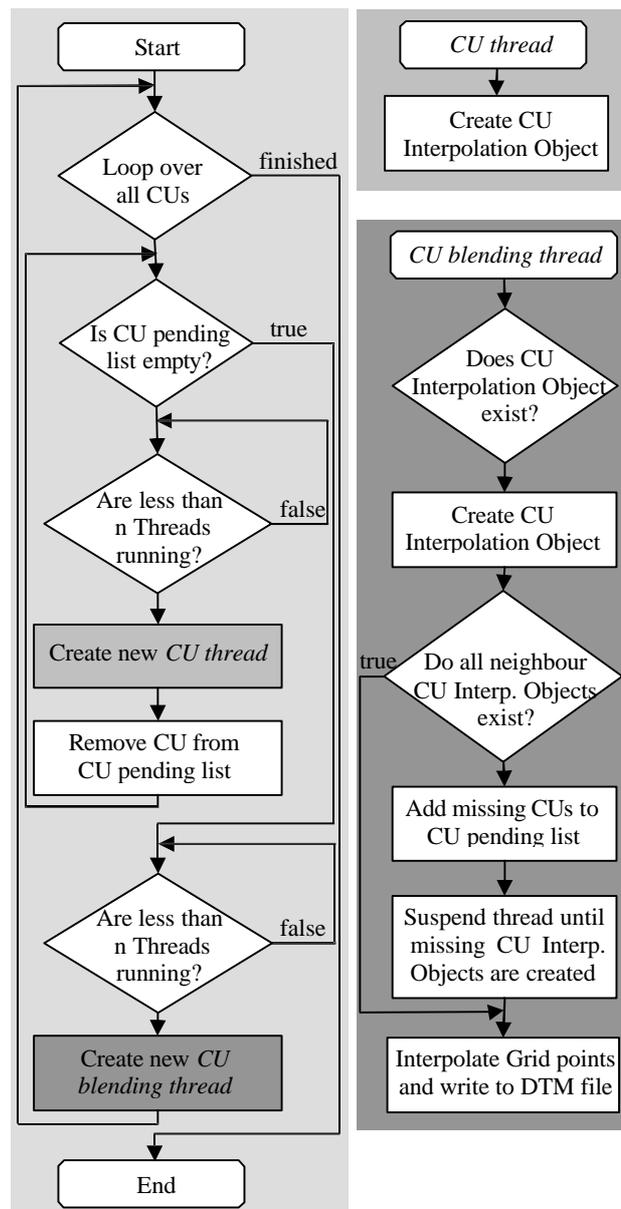

Figure 6: The process creates n parallel interpolation threads
The process scales from 1 to n threads depending on the available CPU cores. The creation of a CU interpolation object also implies pre-interpolation steps (data management

operations, equation solving, etc.) which are necessary to do the actual interpolation.

The computing time consumption for the interpolation object creation and for the interpolation itself will clearly vary for different interpolation method. The linear prediction, for example, is time-consuming at creation time (equation system has to be set up and solved) compared to the actual interpolation process (dot product of two vectors). On the other hand the nearest neighbour interpolation requires no operation at creation time but a nearest neighbour query for the interpolation. The special design of the overall process secures an high performance for local and CU-based interpolation algorithms. As indicated before, the interpolation objects do not have to be thread safe (in contrast to the data manager - described in the next chapter - and the DTM output routines) which reduces development time for new interpolation strategies.

3. THE SCOP-NG DATA STRUCTURE

Efficient and flexible data handling is essential for many applications, especially in cases where huge data have to be administered and fast data access is required. Such a situation arises in TISs in conjunction with ALS projects. From a current point of view, as mentioned before, this is not going to change in the near future since the development of LS is far from over, which caused data volumes to steadily increase. In case of full-waveform projects the resulting amount of data is at the edge of what can be handled by today's high performance workstations.

Compared to the flexibility and the generality of spatial databases (i.e. Oracle Spatial), the DTM generation requires only a limited set of spatial operations onto the original data. For example window and nearest neighbour queries are key operations of any interpolation algorithm. Considering the properties of the source data and queries which have to be supported, special data structures can be designed to achieve maximum performance. Hence, a data manager was developed for SCOP-NG which operates as cache if a spatial database is running in the background (see Figure 7).
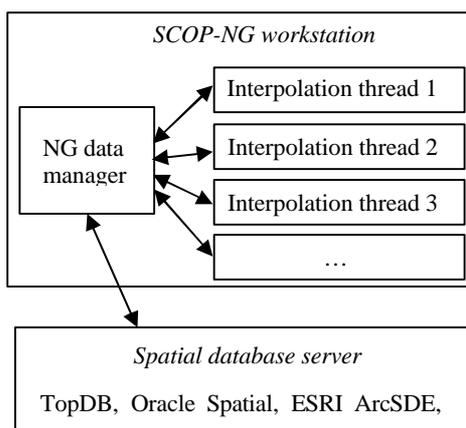

Figure 7: Communication overview in SCOP-NG

The data manager stores points in a K-d tree (generalisation of a binary search tree introduced by Bentley, 1975) and other geometry objects (i.e. structure lines) in an R*-tree (cf. Beckmann et. al., 1990). The K-d tree is an extremely fast spatial indexing method. Although this static indexing structure (limited support for insertion and deletion, which is not relevant

for this application) only supports point data, its speed is outstanding which is why the disadvantage of two separated spatial indices was accepted for SCOP-NG. The developed data manager warps both indices, such as if all data were managed in one spatial index structure. Since the K-d tree and the R*-tree are n-dimensional indexing method, the data manager supports 2D or 3D indexing. Both indexing method have to be thread safe as n interpolation thread will access the data manger.

The SCOP-NG K-d tree code is based on a K-d tree implementation of the Computational Geometry Algorithms Library (CGAL[2]). Since all points required being in memory in the CGAL implementation, the amount of processible point data is limited to available memory. Huge LIDAR projects, however, can clearly exceed the memory of today's computers. Hence, it was necessary to develop an extended K-d tree class which swaps unneeded data onto disk. Therefore the overall data area is spilt into tiles. The point data of each tile are then indexed by a K-d tree. Since the point data are symmetrical managed to the CUs of interpolation process (though tile size and CU size do not have to identical), a low degree of data swapping is guaranteed. Additionally, a special caching algorithm keeping several K-d tree tiles in memory to further reduces swapping operations.

As mentioned before, the data manager uses an R*-tree index for line or area based geometry objects. The implementation is based on the Spatial Index Library developed by Hadjieleftheriou (2002). The library directly supports a caching system which made an extension, as required for the CGAL K-d tree, unnecessary.

It should be noted that the developed data structure considers the special characteristics of today's source data (mainly point data) and therefore, providing high performance for different interpolation algorithms.

4. FROM 2.5D EFFICIENCY TO 3D FLEXIBILITY

As mentioned earlier, state-of-the DTMs are based on a 2.5D approach. Whereas it is still possible to 'numerically' model vertical elements in 2.5D, such a strategy is unable to describe general 3D structures like overhangs, caves or complex artificial objects (i.e. bridges). From an application point of view this has been of minor concern so far since it was not possible (or least far too expensive) to capture detailed 3D data

in a large scale. Over the last years, however, the situation has started to change, mainly caused by the huge improvement in both laser scanners and computer technology. Full 3D models of several cities already exist (Kobel et. al., 2005) which can no longer be described by a 2.5D approach. Hence, it is just a matter of time until applications will arise which require the full 3D information within DTMs.

So why not simply switch to a general 3D approach for TISs? 3D strategies are very complex and slow compared to proven 2.5D algorithms. Additionally, 2.5D DTMs structures can be stored much more efficiently than general 3D models. A fact which can be substantial for country-wide or even planet-wide data sets. However, the probably most important argument against a general 3D approach is the fact that our environment 'is' largely 2.5D. This is why SCOP-NG uses a combined 2.5D and 3D strategy. The new concept relies on a 2.5D base model

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[2] http://www.cgal.org/ (accessed 28 June 2006)

which may contain enclosed 3D objects (3D enclaves), as shown in Figure 8. For 2.5D areas proven algorithms will be employed. Only within the enclaves new 3D strategies will be applied. Utilizing this concept 2.5D efficiency and 3D capability can be combined.
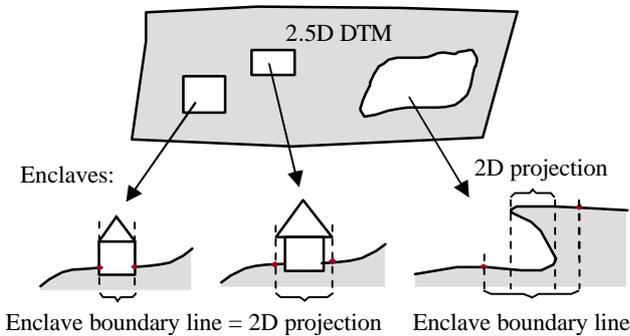

Figure 8: Examples of various 3D enclaves including their 2D projection and boundary line

4.1 3D Enclave Objects

A major problem of 3D point clouds is to resolve the unknown topology, as indicated in Figure 9 (compared to 2.5D where the topology is implicitly given).
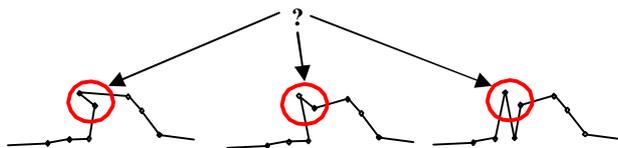

Figure 9: Ambiguities may arise finding the topology of 3D point clouds

Figure 10: Example of 3D point cloud. Left: unfiltered point data. Right: filtered data using the robust Fast Minimum Covariance Determinant (FMCD) method

Over the last years, however, major advances have been made in filtering (see Figure 10) and automated modelling 3D point clouds. Especially for automated building extraction LIDAR data brought huge quality improvement compared to image-based extraction methods. Whereas first strategies were limited to certain building primitives, current algorithms allow extracting complex roof sceneries (cf. Rottensteiner, 2003).

As it turns out there is no 3D modelling algorithm that is applicable to all situations since all algorithms have to make

assumptions about point distribution or object properties. This is why SCOP-NG uses an object oriented approach for the 3D enclaves. Each enclave object has to provide a set of operations. For example to represent itself as triangulation, do a filtering process, reduce itself to 2.5D, etc. These set of operations define an interface also allowing external modelling tools to interact with SCOP-NG which keeps the overall system flexible and extensible.

4.2 Interpolation strategy of a 2.5D DTM containing 3D enclaves

The crucial point of the combined approach is to realize smooth transitions between the enclaves and 2.5D areas (cf. overhang in Figure 8). This can be achieved by a hierarchical process which first interpolates the 2.5D base surface. In addition to the source data within the 2.5D area, the algorithm also collects geometry information from the 3D enclave objects which belong to the 2.5D base surface. After interpolating across the complete model domain, the algorithm passes the interpolated 2.5D surface to the enclave object which stores or withdraws the information within its boundary. This allows automatic modelling of the earth surface below artificial objects (i.e. bridges, eaves, porches, etc.) and inside enclaves (i.e. courtyards). Additionally the 2.5D interpolation explicitly stores the height and tangential plane information along the enclave boundary lines which is required to achieve a smooth transition. In the last step each enclave object is modelled by its own interpolation strategy which considers the previously computed height and tangential plane information at the boundary.
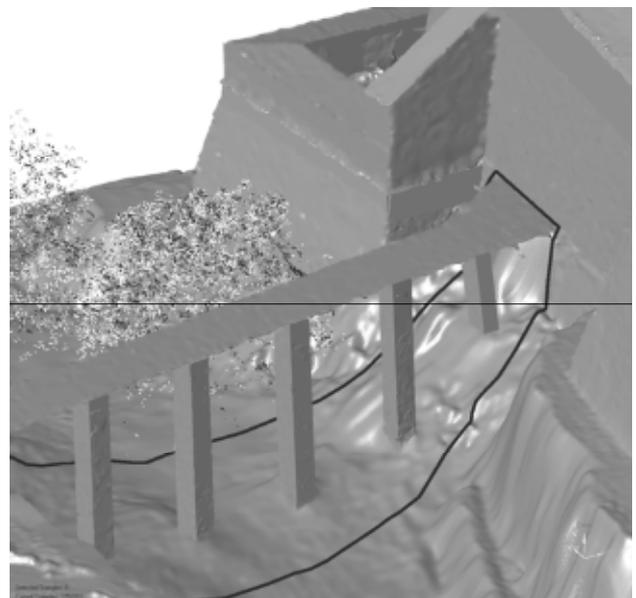

Figure 11: Test scene including a 3D bridge enclave. Also visible the enclave boundary (black) and as vegetation classified point data (bright dots)

5. CONCLUDING REMARKS

SCOP-NG is not an extension to the current version of SCOP; it is a complete new program introducing a set of new concepts to TISs. Beside the support of new observation and computer technologies such as full-waveform ALS data and multi-core computers, SCOP-NG facilitates full 3D objects within its DTM structure. The combination of 2.5D and 3D strategies

allows achieving a maximum degree of efficiency and flexibility.

Beside the mentioned innovations, SCOP-NG will use a surface description similar to the currently used hybrid DTM structure of SCOP++. It has proven as well suitable over many years. The hybrid DTM provides the advantages of grid models in general and restricts the TIN (Triangulated Irregular Networks) structure to complex geomorphological areas (Aßmus, 1976). Based on the hybrid DTM structure, a high quality reduction process was developed which greatly eliminates data points in smooth regions and preserves the important geomorphological structure lines information in full detail (Mandlburger, 2006). This is essential for many modern applications, as i.e. flood risk management systems, which cannot process the full amount of raw data. The developed process allows achieving reduction rates of 90% and higher in compliance with a certain approximation precision.

Finally, it should be mentioned the implementation of SCOP-NG is far from being finished. However, certain modules are already (i.e. structure line modelling, data manager, DTM reduction, full-waveform analysis) or at least in the near future (i.e. Dempster-Shafer classification) available as stand-alone applications or as integrated processes in existing software such as SCOP++ and DTMaster[3].

ACKNOWLEDGEMENT

In Memoriam: The authors dedicate this article to Prof. Karl Kraus (* 23. April 1939, † 5. April 2006) an outstanding teacher, researcher and friend, but also the 'father' of SCOP.

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[3] Product information about SCOP++ and DTMaster can be found at www.inpho.de