A HYBRID GROUND DATA MODEL TO SUPPORT INTERACTION IN MECHANIZED TUNNELING

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Tunneling processes are governed by diverse types of activities such as tunnel boring machine simulation, advance reconnaissance, or settlement detection. All these processes require detailed ground information on different levels of spatio-temporal scales. Therefore, a consistent ground data model is necessitated to store ground information of different categories such that diverse analyses and simulations can be provided. Due to the requirements posed by these analyses and simulations, a ground data model must be developed as a hybrid model to enable processing data in terms of boundary representation models as well as voxel-based octree models. To this end, the present paper gives an overview on how to create a ground data model tailored to the needs of mechanized tunneling. Also described is the process of reading data from an unmodified ground data model to handle tunneling specific queries. Finally, an outlook is given on future improvements.

INTRODUCTION

In July 2010, a Collaborative Research Center entitled "Interaction Models for Mechanized Tunneling" [7] was started at the Ruhr-University of Bochum. Within this research center, over a dozen sub-projects are concerned with important actual aspects of mechanized tunneling. The individual sub-projects deal with sophisticated research topics such as recognizing subsoil structures based on the analysis of machine data, applying acoustic techniques for underground exploration, developing process oriented simulation models for mechanized shield driving, employing methods of system identification used for the adaption of numerical simulation models and many other research topics.

Although existing simulations and analyses have their own focus of research, they are all interrelated to each other at a higher level. Obviously, all of them need specific and detailed ground information to fulfill their own tasks whereby each simulation or analysis requires different parameters in different scales depending on their research focus. Furthermore, many simulations are related to or based on one another. As a consequence, the exchange of data between them is essential if they have to be coupled. Therefore, a common data model is mandatory which can store every type of needed ground information and efficiently provide the interaction between simulations and analyses associated with the data requested.

A few promising geographic information models exist, such as GroundXML or GeoBIM, which offer data structures to store ground information efficiently. In addition, data of subsurface and subsurface related buildings can be stored. By way of example, the GroundXML [4] is an extension of the LandXML scheme, which is able to store a 3D subsoil model and can be linked with a geotechnical database. The improvement of GroundXML compared to LandXML is the ability to save semantic information such as interpreted ground data. On the other hand, GeoBIM is an extension of the Building Information Modeling (BIM) concept, which is the process of generating and managing building data during its life cycle [5]. GeoBIM manages subsurface constructions along with subsurface data such as geological, hydrological or geotechnical objects and their respective properties [6]. Like GroundXML, GeoBIM is able to read data from 3D subsoil models. These models consist of several layers represented by surrounding borders, where each layer represents a homogeneous region linked to solely one specific material along with its own characteristics. In reality, the material behaviors of layers are not completely homogeneous. Usually, there are often inclusions, boulders or the defined layer boundaries vary. Therefore, a concept is necessary which is able to capture the aforementioned uncertainties in an efficient fashion. A promising approach is to develop an extendable ground data model, which can manage different geometric representations and states consistently. In this paper a hybrid ground data model is presented using voxel and boundary representation. Furthermore, novel methods are highlighted to query and store certain ground data for different purposes.

HYBRID GROUND DATA MODELING

The ground data model has to be understood as a simplified version of the real world geological situation. It consists of two types of models, the boundary representation (B-Rep) model and the voxel model.

The B-Rep model represents mainly the geometrical ground data. It consists of so-called homogeneous regions, usually horizontal layers, where each region represents a single homogeneous material of rock or soil. Thus, the B-Rep model is defined by a set of surfaces (e.g. in terms of a set of triangles) which describe the boundary between adjacent homogeneous regions. Technically, the B-Rep model uses standard file format such as ACIS [1] or STL [2]. The boundary surfaces of the layers are provided by geologists who have performed preliminary studies based on selected boreholes. However, geology aspects of defining valid homogeneous regions are not in the scope of this paper. Rather, it is essentially assumed that the material properties associated with a homogeneous region are stored in a corresponding database, where all relevant rock and soil properties can be accessed as needed. The important aspect is that each homogeneous region has only one ground type and requires only one material identifier.

The voxel model represents the geological description of the ground data model. Therefore, a voxel is a three dimensional cube. The voxel model consists of thousands or even millions of voxels depending on the chosen degree of accuracy. Each voxel has its own material identifier and represents a homogeneous region of material. The voxels can be structured using an octree. In short, the basic idea of an octree is to define a three-dimensional region, which is completely homogeneous in a well-defined sense. If it is not completely homogeneous because it has, say, a different material property in some corner, the entire region is divided into eight identical parts. Then the inspection process is recursively repeated for each of the eight sub-cubes, that is, each sub-cube is checked to figure out if it is completely homogeneous. If not so, the smaller cube is again divided into eight smaller sub-cubes and re-checked again. The recursive inspection process thus ends when a sub-cube is either completely homogeneous or a minimum size of the voxel is reached which will not be divided further. With respect to the software implementation of octrees, the method proposed by Mundani [3] has been used. One advantage of an octree is the efficient structuring of three dimensional regions which leads to a minimum amount of voxels to be saved. Furthermore, the hierarchical data structure of the octree allows a quick finding of the direct path from the root voxel to the requested voxel.

Since the ground data model is in charge of coupling individual simulations, it has been decided to facilitate Internet-enabled interfaces to the ground data model. As a result, any data, status information, actions or events etc. should be readable, writable as well as executable by using standard Internet software and technologies. To this end, an application has been installed on a server which handles queries for reading and writing data from a special database system. The description of the application and the database system are not subject of this paper.

GROUND DATA REQUESTS

While geologists usually model the entire alignment of a proposed tunnel which may have a length of several kilometers and a width and depth of some hundreds of meters, researchers are often interested in only selected small parts or regions. In particular, they focus on regions where something "interesting" appears to happen, where detailed computations must be carried out, or where safety requirements must be checked. Accordingly, users in research define their region of interest in a straightforward manner in terms of a "bounding box", which geometrically is a cuboid with lateral, horizontal and vertical faces. Therefore, although the entire ground data model for the complete alignment must be stored online in a database, the actual amount of information calculated and retrieved for a typical user request is of an order of magnitude smaller. In fact, users often only want to know key material parameters for a small set of selected points (a so-called point cloud) or, for advanced users, a request for a B-Rep model in a relatively small bounding box is of interest. At the present point of development, the implemented queries are effective only to reading ground data as long as there has been no updated data added to the model for the requested region. The three basic types of queries are as follows.

1. **Create a new ground data model extract for a bounding box by defining a new B-Rep model within the given region.** This is requested from the advance exploration simulation which analyzes the ground in front of the tunnel boring machine (TBM). It imports the geometry of the generated extract of the ground. By comparing measured data from the TBM with results of simulation, boulders, inclusions or even displacements of layer boundaries are identified.
2. **Create a new point cloud within a given bounding box and return material properties for each created point.** The point cloud can either be given as a list of point coordinates, or defined as a set of equally spaced points within the bounding box. Simulations performing ground analysis to optimize the prediction of the behavior of the ground while the tunnel boring machine moves forward use this query to receive ground information in terms of points to build their mesh.
3. **Return the material properties for a given point cloud within the enclosing bounding box.** This request type is used to provide the driving simulation with detailed ground information at specific points. In a FE-simulation these points are so-called Gaussian points, where an interpolation is accomplished to determine the distribution in the ground between these points.

So far, the ground data model only consists of the B-Rep model in the region considered because the voxel model is created and extended only through writing operations. For handling data

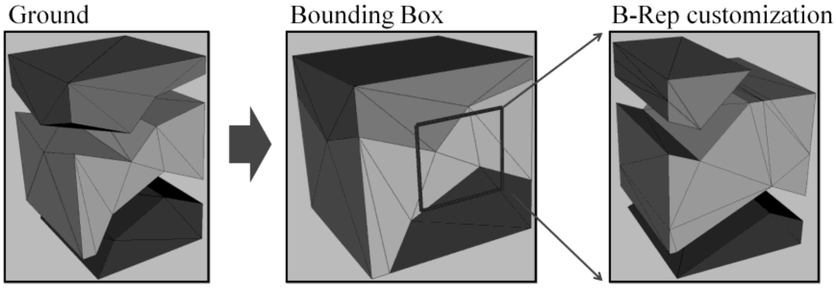

Figure 1. Creation of a new B-Rep model extracted from the ground data model.

requests, queries have to identify the material parameter at specific points in a volume element. To this end, a method has been developed based on the already introduced octree concept and their hierarchical data structure.

Create a new ground model extract for a bounding box

The frist query handles the case that geometric and material properties are requested for a given bounding box. The ground data extraction process is schematically shown in Fig. 1. Starting with the entire ground data model (left), the given bounding box (middle) is used to extract a part of the ground data model. Thereby, the intersections with the different layers have to be calculated temporarily, leading to an incomplete partial B-Rep model.

Consequently, re-meshing must be carried out to establish a new, consistent partial B-Rep model within the three-dimensional bounding box. The B-Rep re-meshing step is depicted in Fig. 2 (*B-Rep Customization*), where the newly created sets of layers are shown which exist inside the bounding box. Thus, assuming the user has the necessary software to process B-Rep models, this sub-region can then be returned along with the corresponding material parameters.

Create a new point cloud within a given bounding box

This type 2 request can be divided into two individual parts, depending on whether the point cloud is a regular array of equally spaced points or a variably spaced set of points. In the latter case, more points are defined near boundaries or other places of interest, and fewer points are defined within large regions of homogeneous material. In both cases, the first few steps are equal. If an unevenly spaced set of points is requested, as shown in Fig. 2, the point cloud is defined through the mid-points of each voxel generated by an octree.

The first three steps up to the figure *B-Rep Customization* in Fig. 3 are identical, where the steps are shown two dimensionally. To be clear, the depicted meshes are by no means comparable to finite element meshes, rather they only emphasize the structure of the B-Rep model in the three dimensional case. Based on the new B-Rep model defined within the bounding box, an octree can be generated (*Octree Generation*) and discretized at the boundaries (*Octree discretization*). This means that each voxel gets linked to its corresponding material. The smallest voxels are assigned to either border, depending on the ratio of layer volume within the voxel. The approximation at this level is, however, not too critical because the detail of initial geological modeling is usually much coarser than the spacing of the requested point cloud. The level of detail for the octree depends on the minimum distance between requested points, assuming that the smallest voxel

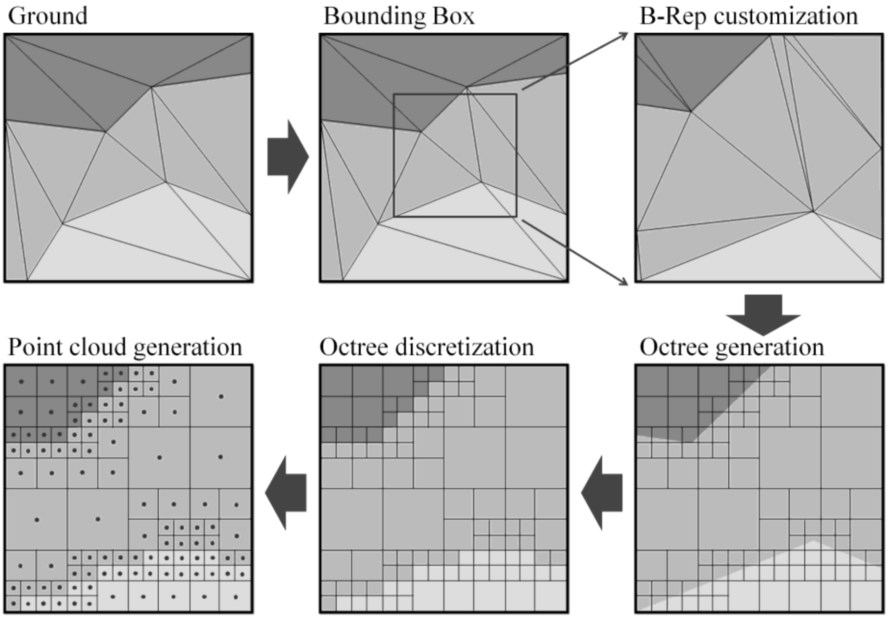

Figure 2. Generation of a point cloud for a given bounding box

should only contain one point from the cloud. This assures that at the borders between layers the best changeover is taken.

When the discretized octree has been created, the cloud of points can be derived (*Point cloud generation*). This approach guarantees an efficient way to generate the point cloud because many points are created at layer boundaries and less points in homogeneous areas. A small disadvantage is, however, that additional information regarding the area of influence (the size of the associated voxel) must also be included besides material information.

In the other case, a regular array of equally spaced points can be generated as requested by the user. In this case the structure of the generated octree is used to efficiently look up the corresponding material information of each point. The hierarchical data structure of the octree allows finding the direct path to the desired voxel starting from the root voxel.

Return the material properties for a given point cloud

This type 3 request is similar to the one where a regular point cloud is requested. Here, a point cloud is given and the corresponding material parameters are requested. At first, an appropriate bounding box must be generated so that each given point lies within (or on) the bounding box. Then, the procedure conforms to the previous one. Again, the ground data model is reduced to the bounding box, also a new B-Rep model is created and an octree is generated. Based on this octree, material parameters are looked up at the given points in the material database. The whole process is illustrated in Fig. 3.

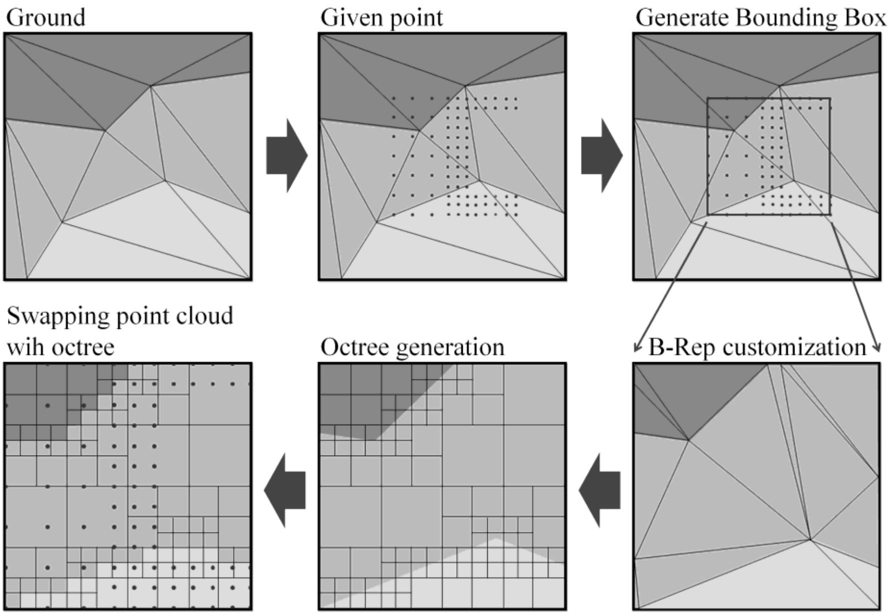

Figure 3. Identification of material parameters for a given point cloud

VALIDATION OF THE CONCEPT

For reading data from the ground data model a software application has been developed to visualize the steps and thus to validate the presented approach. In Fig. 4, a screen shot of the software application is presented. On the left the B-Rep model of the overall ground data model is

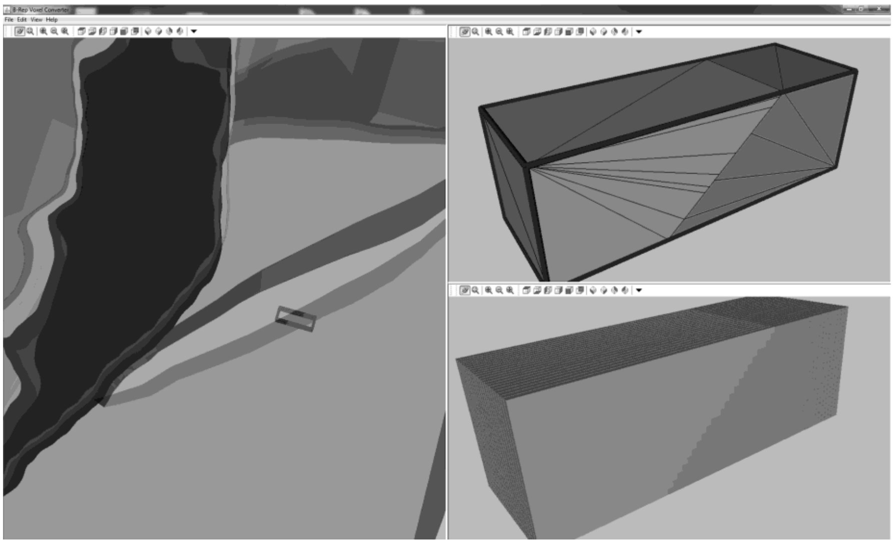

Figure 4. Software application to visualize the ground data generation and extraction steps

shown. Additionally, a bounding box has been added which represents the volume which has been requested by a simulation or analysis. On the top right, the B-Rep extract of the requested bounding box is depicted. By adding new boundaries to the borders of the box, additional volumes have been created for each layer inside the box. Based on this new B-Rep model, a voxelization has been done which is shown in the lower right. This voxel model consists of a large number of voxels which can be seen in the approximation of the border between the layers. Although each voxel has its own material identifier, most identifiers point to the same value.

FUTURE IMPROVEMENTS

Based on the introduced results further important improvements have been identified.

- Enhancement of queries to store the computational results of simulation runs into the ground data model
- Expansion of query types to read data from an updated ground data model
- Definition of rules to record version changes to the ground data model

At present, there already exist basic ideas for approaches to accomplish such improvements. The idea of storing updated data into the ground data model is to generate an octree each time results of a simulation are added to the model. The generation of octrees is based on a given point cloud. Hereby, the points with an equal material identifier can be merged to less regions of influence with the same identifier. Since each octree generated for a bounding box starts with the same root voxel (the initial model), all octrees are comparable in the sense that if two or more octrees intersect, the resulting voxels will always be based on the same discretization scheme, although they might have

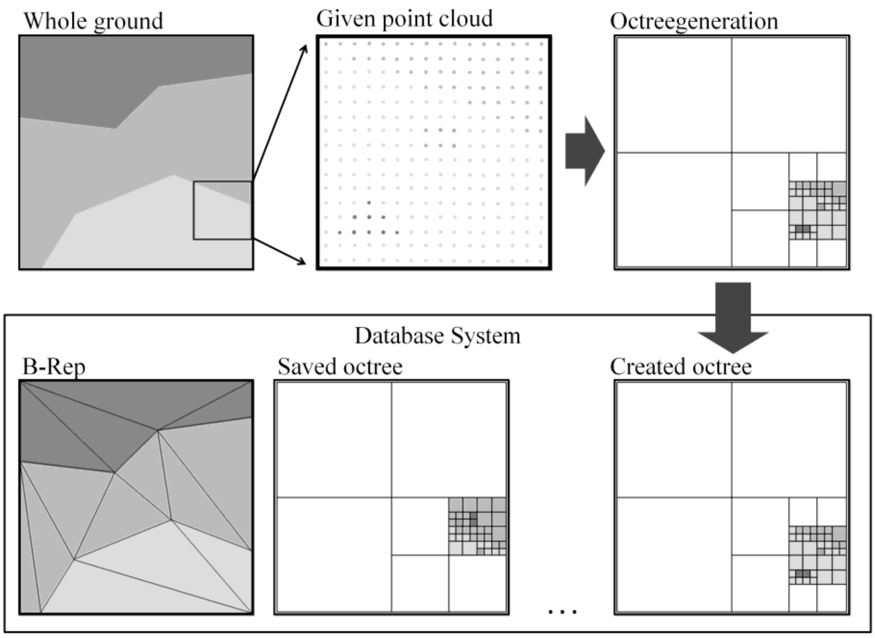

Figure 5. Process of updating the ground data model due to additional information

different material identifiers. This enables the model to perform different calculations to combine the octrees and give information to the requesting simulations or analyses. A possible query to save the results of a simulation is shown in Fig. 5. Here, a regular point cloud of an extract of the whole ground is given whereby each point is connected to a material identifier. In the next step an octree is generated based on the given point cloud and the root voxel of the entire model. Finally, the generated octree is added to the database system which also contains the B-Rep model and further octrees of former updates.

SUMMARY

In the preceding sections, a ground data model has been introduced that stores ground information consistently. By this, it is able to couple various simulations used in mechanized tunneling by exchanging data required for interoperability. The ground data model implemented consists of two different geometric representations, (i) a B-Rep representation and (ii) a voxel representation. While the B-Rep models primarily store the geometrical ground information, the voxel model mainly captures the geological conditions. Within the paper an appropriate approach has been introduced demonstrating how users can obtain information (ground material parameters) from the persistent ground data model.

ACKNOWLEDGMENT

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