Image Interpretation and GIS Analysis as an Approach for Moor Monitoring

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ABSTRACT: In this Paper we present an approach for an automatic moor monitoring that include three steps which can combined together to do this automatically. For the analysis of thematic maps which are represented as vector or raster data techniques are needed for a consistent interpretation of this different data. This techniques such as overlaying or spatial search are realized in VGIS with 20 basic operators to work consistently with this two representations.

To generate actual and accurate landuse data we use a knowledge based interpretation system on base of a semantic net for knowledge representation and realized the possibility to present prior knowledge of remote sensing data. In addition we show a multitemporal interpretation of moorland, where the temporal constraints are formulated in a state transition diagram to improve the results of the monitoring.

To handle varying image quality and different sensor types an adaptiv and modularized agent system is presented. The agent system learns which image processing operator is best suited for the applied task and adapts the parameters of this algorithms automatically.

The presented systems are used for the interpretation of moorland in aerial images. The prior knowledge about the different land use states is formulated in a semantic net and used to control the interpretation process. Furthermore we suggest a concept for the extension to a multitemporal interpretation of moorland, where temporal constraints are formulated in a state transition diagram and exploited to improve the monitoring. For the segmentation of the moorland the adaptive image processing system is used. The user friendly GIS VGIS make it possible to work with the results

KEY WORDS: Moor Monitoring, Remote Sensing, Hybrid System, GIS, Knowledge Representation, Image Interpretation, Adaption and Learning Agent System, Multitemporal

ABSTRACT: Moor monitoring includes supervision of administrative as well as ecological parameters within moor areas to help solving conflicts between contradictory claims and demands. Especially the observation of the development in landuse over time plays an essential role in protecting this sensitive environment. To acquire basic landuse data, aerial images offer most actual information. In this paper we introduce three independent research groups and their approaches that fit together well to automate necessary steps from image segmentation to GIS analysis.

For the userfriendly analysis of different data sources which are represented in vector or raster data structure, techniques are needed for a consistent and combined interpretation. The Virtual GIS (VGIS) offers a hybrid analysis of vector and raster data on a workflow like interface with 20 basic operators like overlay, buffer or spatial search.

To generate actual and accurate landuse data we use a knowledge based interpretation system on base of a semantic net for knowledge representation and realized the possibility to present prior knowledge about remote sensing data. For further improve of monitoring results we have develop a multitemporal interpretation strategy where the temporal constraints are formulated in a state transition diagram.

To handle varying image quality and different sensor types an adaptive and modularized agent system is presented. The agent system learns which image processing operator is best suited for the applied task and adapts the parameters of this algorithms automatically.

1. INTRODUCTION

Moorland often appears as just one single class in land use classifications. At a closer look a moor area consists of regions with quite heterogeneous and to a certain extent contrary use. Conflicts arise especially between the need for protection of the highly sensitive ecosystem of raised bog areas and the existing industrial claims for peat exploitation. In order to protect the moor areas certain conditions according to law have to be observed. Some areas may only be cultivated during fixed periods, which are determined by administrative authorities. Thus it is obvious, that control of the activities in moor areas is required. In Germany several moor areas of quite different character can be found and especially in the State of Lower Saxony raised bogs naturally used to be a widespread kind of ecosystem. As these areas are quite large and partly inaccessible, complete ground control would be difficult, time consuming and expensive. Hence remote sensing can offer suitable solutions. As the automatic interpretation of moor areas needs a higher resolution than provided by satellite images currently available, aerial images will be the more adequate data source for this task.

Up to now the usual approach for comparable problems has been the application of data driven multispectral classification methods, in most cases without using auxiliary data. The other existing data sources like land use data and development plan will not be used.

In this paper we present three works which offer possible solutions for different steps of multitemporal moor monitoring. The three different steps are:

- Adaptiv segmentation of remote sensing data
- Multitemporal interpretation (monitoring)
- Integration of different data sources, like raster and vector data in order to do a verification and to draw particular conclusions, like the localization of ecological sensitive areas

Until now these three approaches have been developed independently as part of the joint research project `Semantic Modeling and Extraction of Spatial Objects from Images and Maps' funded by the 'Deutsche Forschungsgemeinschaft' since 1993. The whole project consists of 10 research groups, focussing on different research areas. Overall goal and motivation is the integration of research in Photogrammetry, cartography, image understanding and pattern recognition.

Modeling of object acquisition, -description and use in Geoinformation Systems has been chosen as joint application area in order to foster research cooperation. The concept

’Semantic Modeling’ shall serve as link for integrating the techniques developed.
Modeling user interaction is explicitly integrated into the project as operational systems will always need an interactive component.

2. KNOWLEDGE BASED INTERPRETATION SYSTEM

For the automatic interpretation of remote sensing images the knowledge based system AIDA (Liedtke, 1997) has been developed. The system strictly separates the control of the image analysis process from the semantics of the scene.

2.1. KNOWLEDGE REPRESENTATION

The knowledge representation is based on semantic nets. Semantic nets are directed acyclic graphs and they consist of nodes and edges in between. The nodes represent the objects expected in the scene while the edges or links of the semantic net form the relations between these objects. Attributes define the properties of nodes and edges. The nodes of the semantic net model the objects of the scene and their representation in the image. Two classes of nodes are distinguished: the concepts are generic models of the object and the instances are realizations of their corresponding concepts in the observed scene. Thus, the knowledge base which is defined prior to the image analysis is built out of concepts.

During interpretation a symbolic scene description is generated consisting of instances. The object properties are described by attributes attached to the nodes. They contain an attribute value which is measured bottom- up in the data and a range which represents the expected attribute value. The range is predefined and/or calculated during the interpretation. For each attribute a value and range computation function has to be defined. A judgement function computes the compatibility of expected range and measured value.

The relations between the objects are described by edges or links forming the semantic net. The specialization of objects is described by the is-a relation introducing the concept of inheritance. Along the is-a link all attributes, edges and functions are inherited to the more special node which can be overwritten locally. Objects are composed of parts represented by the part-of-link. Thus the detection of an object can be simplified to the detection of its parts. The transformation of an abstract description into its more concrete representation in the data is modeled by the concrete-of relation, abbreviated con-of. This relation allows to structure the knowledge in different conceptual layers like for example a scene layer and an image layer. Based on this knowledge representation scheme a common concept has been developed to distinguish between the semantics of objects and their visual appearance in different sensors. Furthermore domain specific knowledge like GIS data can easily be integrated to support and strengthen the interpretation process. An example of a semantic net for the interpretation of moorland is described in section 4.

2.2. CONTROL OF THE SCENE ANALYSIS

To make use of the knowledge represented in the semantic net control knowledge is required that states how and in which order scene analysis has to proceed. The control knowledge is represented explicitly by a set of rules. The rule for instantiation for example changes the state of an instance from hypothesis to complete instance, if all subnodes which are defined as obligatory in the concept net have been instantiated completely. If an obligatory subnode could not be detected, the parent node becomes a missing instance.
An inference engine determines the sequence of rule execution. Whenever ambiguous interpretations occur they are treated as competing alternatives and stored in the leaf nodes of a search tree. The best judged interpretation is selected for further investigation. Using a mixed top-down and bottom-up strategy the system generates model-driven hypotheses for scene objects and verifies them consecutively in the data.
Attribute values are transformed from world units like meters to image units like pixels. Expectations about object properties are translated into a task description for the adaptive image processing module which is described in section 3. The semantic net uses the segmented image primitives and assigns a semantic meaning to them.

2.3. EXTENSION TO MULTITEMPORAL IMAGES

Currently the system is being extended for the interpretation of multitemporal images. Applications like change detection and monitoring require the analysis of images from different acquisition epochs. By comparing the current image with the latest interpretation derived from the preceding image land use changes and new constructions can be detected. Prerequisite for this is the possibility to save scene descriptions in form of instantiated semantic nets and to load and reuse them as expectation for the next image. To increase the reliability of the interpretation the knowledge about possible state transitions between two time steps should be exploited.
For the representation of these state transition diagrams in the semantic net the different states are modelled by concept nodes. They are connected by a new relation: the temporal relation. It is used to model the possible or most probable state transitions within a time step. For each temporal relation a priority can be defined in order to sort the possible successor states by decreasing probability. As states can either be stable or transient, the corresponding state transitions differ in their transition time which can be also specified in the temporal relation.

During scene analysis the state transition diagram is used to generate hypotheses for the next observation epoch. For each of these possible state transitions a hypothesis is generated. All hypotheses are treated as competing alternatives represented in separate leaf nodes of the search tree. Interpretation continues using the next image in the chronological order. An example for the exploitation of a state transition diagram is outlined in section 4.

3. AGENT SYSTEM FOR ADAPTIVE IMAGE PROCESSING

The term agent is known from the AI (Artificial Intelligence) and describes autonomous working units (Newell, Simon 1972). Agent technology is one of the fastest growing areas of research and new application development. Agents are used in almost all applications that claim some intelligent functionality or will perform tasks automatically. Jeffrey (1997) offers a classification of agents based on the following characteristics.

1. The functionality of the individual agent e.g.:
    - a simple sensor / actor system like a function
    - a function that can distinguish different situations
    - autonomic systems with flexible behavior
    - learning and reflexive agents
    - collective working and collaborative agents
2. The communication among the agents.
    - communication only between two agents
    - communication via a blackboard
    - variable communication between the agents
3. The location of the agents
    - the whole system runs only on one computer
    - a distributed system on different computers/operating systems
    - mobile agents that can change their location

In our application the task of the agent system is the automatic parameter adaptation for remote sensing data interpretation. The semantic net supplies a task description formulating the goals for the image processing operator and information about the images used. The goals refer to the features of the image processing results e.g. the features of the segmented areas. Necessary information about the image are for example size, resolution and sensor model.

Another requirement of the agent system is its learning ability. The system should learn which image processing operators are suitable for which tasks. Further the favorable start parameters for the image operators should be learned to speed up the adaptation process.

In the following, the design of the agent system and the parameter adaptation for the image operators is presented, focussing on the information required for adaptation and its connection. As operators we use the tools from the Khoros (Khoros, 1997) system.

3.1. DESIGN OF THE AGENT SYSTEM

The agent system is implemented as a distributed system with learning and reflexive agents under CORBA (Common Object Request Broker Architecture). CORBA is the specification of the interfaces and architecture of the ORB (Object Request Broker) by the OMG (Object Management Group).

One agent, the main or client agent represents the interface to the semantic net or an user and communicates with the other agents, called server agents. Each server agent contains an image processing operator and an adaptation unit for this operator.

The structure of the agent system design is depicted in Fig. 1. The ORB manages the communication between the agents and provides basic services like name service and trading service.

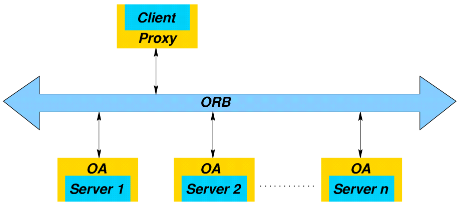


Fig. 1: Agent system design

3.2. ADAPTATION

Each server agent contains one image processing operator which usually has a number of parameters. With different parameter settings different results are returned from the operator. The goal of the adaptation is to find the parameter set that provides the best result. To determine the best result the features of the segmented image are calculated and compared with the task description.

The adaptation of the parameters for the image processing is based on the iteration shown in Fig. 2. The image processing operator is applied to the input image with the predefined start parameters. Then the resulting image is compared with the given task description according to the features of the areas found. The parameters are adapted by a set of rules and the calculation is repeated. For each operator the rules must be supplied by the user. This iteration continues until the optimal result has been found (Rost, Münkel, 1998).

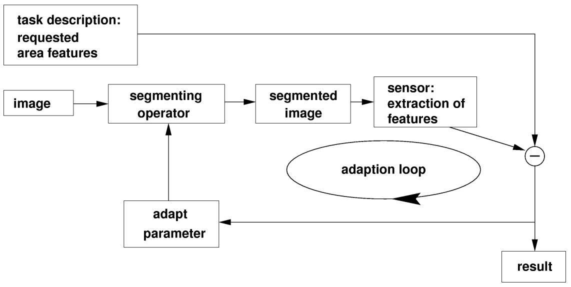


Fig. 2: Parameter adaption

The set of possible goals consists of given values for the attributes of the extracted regions. These are:

area size
compactness
ratio of holes
roundness
length
area count
convexness
texture
rectangularity
radial ratio

These measures are modeled according to (Rosenfeld, 1976) and (Abmayr, 1994) and they are normalized to the range of [0..1]. The goal value of one attribute can also be given as a range. The importance of an attribute is set by means of the interval width. A predefined attribute range of [0..1] indicates for example that the value of this attribute is irrelevant for the given task. The narrower the range, the more important the attribute is.

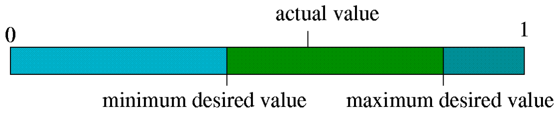


Fig. 3: Attribute range

To describe a segmentation result either the attributes of all segments are averaged or only the best segment for the adaptation is used (Fig. 3). In this way for example the following tasks can be formulated:

4. Find a round object whose area size should be within a default range.
5. Find areas as rectangular as possible (man made) and larger than a minimum size.

3.3. COOPERATION

Cooperation means to process a task in common (Albayrak, 1993). This cooperation is implemented as a contract negotiation in which the client agent negotiates with potential server agents, the so-called contract-net procedure (Davis, 1988). Three steps of negotiation are distinguished in the presented agent system:

1. The advertisement of a global task. In this step, the agents unsuitable for the task are excluded from the following negotiations.
2. The remaining agents receive information about the data and the goals of the operation to estimate their suitability to solve the task.
3. In the last step, one or more agents are instructed to process the task.

3.4. LEARNING

The basis of the learning procedure is the above mentioned set of negotiation functions between the hierarchically structured agents. The aim of the learning procedure is to organize the behavior of the agents in such a way that the task given to the agency can be processed as well and as specifically as possible.

Learning within the agent system requires two steps to be carried out, the selection of a suitable image processing operator and a reasonable initialization of the parameters to be adapted. In order to accomplish these tasks the described procedure of the contract net is extended in two aspects:

1. The acquisition of credit values in accordance to the quality of an agent to solve the specific tasks.
2. Selection and activation of agents as contractors according to their credit values.

Consequently the result of learning is a more specific selection of the contractors but also a faster adaptation of the parameters for the image processing by use of a data base. The agents learn for which tasks they are suitable and how to solve known problems. An agent learns its task specifically by using a credit vector.

For the automatic acquisition of these credit values, the results supplied from an agent are matched with the required goals. This comparison describes the ability of the agent for the current task and is stored in the credit vector. The credit vector consists of the following four entries:

1. order count: the number of tasks for the agent and/or an agency.
2. work count: the number of tasks, that are processed by the agent and/or an agency.
3. success count: the number of tasks which are processed successfully by the agent or an agency.
4. confidence: this value represents a kind of self appraisal of the agent and/or of the agency in solving the current task. This value consists of the current setting of a task (sensor

type and ground resolution) and the previously mentioned credit values.

If the server agent has already processed tasks with different goals, it selects the credit vector which is most similar compared to the current task. To choose this vector the ratio of the agreement and the difference to the current task is computed. For initialization the stored parameters from the most similar task are used as start parameters.

4. INTERPRETATION OF MOORLAND IN AERIAL IMAGES

In section 4.1 we will describe briefly the prior knowledge we used for interpretation of moorland, and in section 4.2 the further input data. The conversion of prior knowledge into our knowledge based system as semantic nets and the interpretation procedure itself will be shown in section 4.3, the results in section 4.4. The concept to extend the system into a multitemporal interpretation and further results will be described in section 4.6.

4.1. PRIOR KNOWLEDGE

Originally, moors were upland moors. In Germany these have practically vanished. Today mostly grassland, forest and area of regeneration or degeneration are found in the former upland moors. In most cases parts of moorland are used for peat extraction. Degeneration is the state before peat extraction takes place. For this purpose the ground must be drained by means of ditches. Then peat extraction is possible. Usually harvester machines are used. In aerial images the use of the machines can be recognized by tracks. After peat works have finished, a regeneration of the moorlands will begin. In most cases people will simply stop working on the land and leave it to regenerate, which eventually will result in increasing vegetation. Hence in this state of land use vegetation can be found on these areas as well as tracks from the harvester machines from the state before. (Göttlich, 1990)

4.2. INPUT DATA

Our test area is the moor area near Steinhude in Lower Saxony. We work with aerial images with a resolution of 0.5m/pel. The main input sources are CIR-images, but we also tested the results with grayscale images. The reason is that although color images have more usable information, most recorded aerial images are grayscale images.

The second input source is a label image. In this step we presume to have the segment borders. This follows from the fact that a biotope mapping is performed at least one time for every moor area in Germany by ground survey. This is also prior knowledge we use in our system. For this we use a label image based on a biotope mapping. The label image masks the different segments of the aerial image, which is to be interpreted.

4.3. INTERPRETATION WITH SEMANTIC NETS

We use the knowledge based system with the explicit representation of prior knowledge, as described in section 2, to interpret the regions in the moor area. Therefore, the prior knowledge about the relevant area is formulated in a concept net. Fig. 4 shows a simplified version of the concept net. We determined four states of land use for moorland: forest, grassland, area of de-/regeneration and area of peat working. The states area of degeneration and area of regeneration are combined, because their distinction in aerial images is very difficult. As shown in Fig. 4 we distinguish two layers of abstraction in the concept net: a scene layer and an aerial image layer. In the scene layer the different states are described with their obligatory parts. E.g. the state area of peat working has on the one hand harvester tracks, on the other hand no vegetation density. The state area of de-/regeneration has also harvester tracks in one part, but the second part is mid vegetation density. The nodes in the second layer, the aerial image layer, describe the depiction of the scene layer nodes, the land use states, in aerial images and their properties. The nodes describe the structures and colors to be looked for, if a state is to be assigned to a segment. At the bottom of Fig. 4 segment analysis operators are shown. Every node at the bottom of the aerial image layer has access to a special operator. The task of the respective operator is to verify the meaning of the node for a particular segment. The interpretation process is called instantiation. To show the instantiation process in our case, it is described in the following. It starts with a start node in the instance net. According to the strategy and its priority of rules the instantiation proceeds in a particular order along the relations postulated in the concept net, until no more rules can be applied and the instance net is complete.

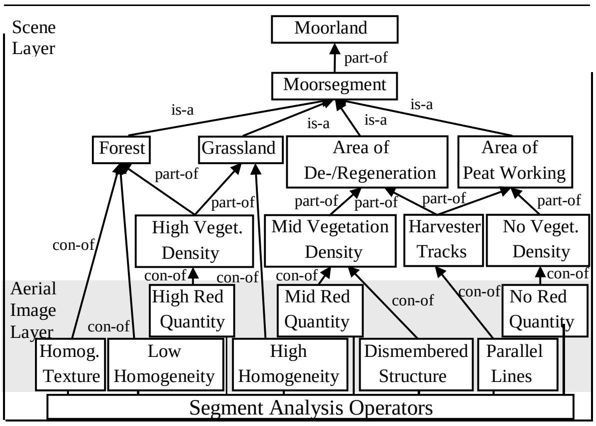


Fig. 4: Concept net for the interpretation of moorland

Here the instantiation process starts with the creation of a hypothesis of the concept moorsegment. At this point one segment is taken from the label image. The interpretation for this segment will now be performed. As shown in Fig. 4 there are four different possibilities of interpretation (states) for the segment. These possibilities exclude each other and therefore compete with each other. The first state to be verified is area of peat working: A concept node area of peat working will be created. Two obligatory parts of this node have to be present: harvester tracks and no vegetation density. This leads to the top-down instantiation of the concept harvester tracks along the part-of relation. The concretisation of harvester tracks is parallel lines, which also leads top-down to a creation of a hypothesis parallel lines. Now the bottom layer is reached and this hypothesis has to be verified. The node calls a special segment analysis operator. The operator examines the aerial image within the given segment and returns whether parallel lines were found or not. If the result is positive the operator returns a certainty to the node, which describes the quality of the result, and then the instance node parallel lines changes its status from hypothesis to complete instance. This leads bottom-up to a complete instantiation of the node harvester tracks. In the same way the second obligatory part of the node area of peat working will be verified and for the second verification also a certainty will be determined. Now all obligatory parts of area of peat working are present and the node is instantiated completely. Also a certainty for this node will be computed from the nodes below. The result is a possible interpretation of the moorsegment with a certainty value. If the certainty is not good enough the other competitive interpretations have to be verified in the same way.

4.4. RESULT

In Fig. 6 the result of the interpretation based on the label image of the biotope mapping and on the CIR aerial image of the test area (Fig. 5) is shown. The result of the interpretation reveals, that all 33 segments were interpreted as a human operator would interpret them using only the aerial image without stereo and ground truth information.

Fig. 5: Aerial image of the used test area

A second interesting result of the interpretation is achieved, if we use a grayscale aerial image instead of a CIR aerial image. For this purpose all upper nodes in the aerial image layer of the concept net in Fig. 4 were removed. Hence the interpretation is only supported by texture information. 5 of the 33 segments could not be interpreted and 4 differed from the result shown in Fig. 6. The misinterpreted segments were mostly small, narrow or not typical for the land use states. This result shows, that color information brings in fact additional information, but for most unproblematic regions texture information is sufficient.

Fig. 6: Interpretation result of the test area

4.5. MOORLAND SEGMENTATION

The assumption, that for every moorland a biotope mapping exists is true for Germany, but not for every country. In that case an initial segmentation is necessary. For this task it is also possible to use the adaptive image processing system described in section 3. For the adaptation an image processing operator based on the split and merge procedure has been used. In addition the course of the roads is included in the segmentation. The adaptation goals were the same for all the image segments. The result of the adaptation is depicted in Fig. 7.

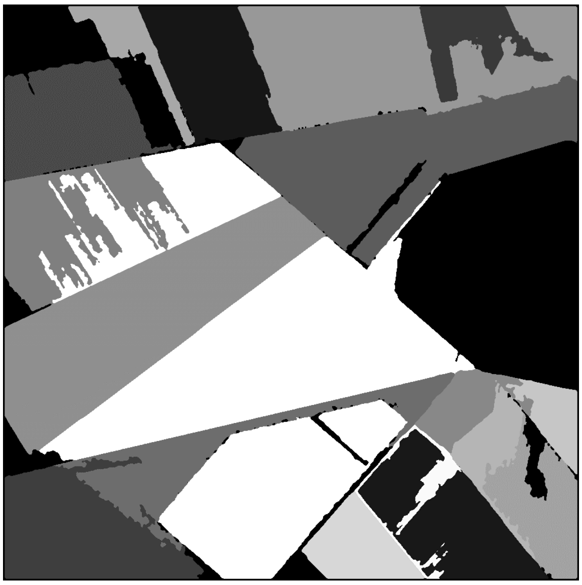


Fig. 7: Segmentation result using Split and Merge

4.6. MULTITEMPORAL IMAGE ANALYSIS

The goal of multitemporal image analysis is the monitoring of moorlands. We have to extend the system described so far by multitemporal strategies. The multitemporal interpretation begins with an initial interpretation for the aerial images taken at the first epoch t to be interpreted. Then the next epochs t+n have to be interpreted in cyclical intervals based on the results of the interpretation before. These results restrict the search space and lead to an improvement of monitoring. Fig. 8 shows an overview of the structure of the system concept.

Beginning with the part knowledge based interpretation an initial interpretation of the segments is performed. The results are interpreted segments of moorland. These segments are the input for a prediction of state transitions. This prediction uses prior information concerning the possible changes. The possibilities are represented in a state transition diagram. A description follows below. The output of the prediction are predicted new states for every segment. The borders of the segments may change between the interpretation intervals. Therefore, for the multitemporal approach we include a module to examine segment splitting by segmentation. The approach of the adaptive image processing module is described in section 3. This approach shall later use the information of the predicted new states. The results of this step are updated segment borders, which are integrated into the knowledge based interpretation for the new epoch, just like the predicted new states and the multitemporal data. The state transition diagram in Fig. 9 describes the most probable state transitions. Although many more state transitions are possible there are restrictions by law and nature (see section 4.1). This enables us to use the restrictions in order to improve the interpretation. In contrast to the concept net in Fig. 4 this diagram contains six different states. The first state, upland moor, is implemented only to complete the diagram. Because upland moor does not exist anymore in the test area it will not be used in the interpretation.

The states area of degeneration and area of regeneration are now separated. As mentioned in section 4.3 their distinction in aerial images taken at one epoch only is very difficult. But in a multitemporal interpretation with the prior knowledge described in the diagram the development of the different segments can be used also. For example given an area of peat working the system will know, that this segment has passed the state area of degeneration, and if in a new epoch an operator will find for example vegetation, the only states can be area of regeneration or forest. Every link in the state transition diagram has a priority, which describes the probability of the state transitions. This value affects the order in which the different state transition hypotheses will be verified. As shown in Fig. 9 every state has a transition link back to itself. This is in each case the link with the highest probability. Consequently for every new epoch this is the first transition concept to be verified. In Fig. 10 a result of the usage of the state transition diagram is shown for two grayscale aerial images taken at two epochs. The aerial images were divided into five segments. For every segment the system determined the state transition. The semantic net we used for the multitemporal interpretation is a refinement of Fig. 4.

Fig. 8: Concept for a multitemporal moorland interpretation

In addition to the separation of the states area of regeneration and area of degeneration the state area of degeneration has also the description high homogeneity, because this is also a possible appearance of this state. The reduction of the search space for the possible successor states leads to a correct interpretation of the segments. For segment 1 a transition from area of peat working to area of regeneration is stated using the knowledge about the previous land use of the Interpreted Knowledge

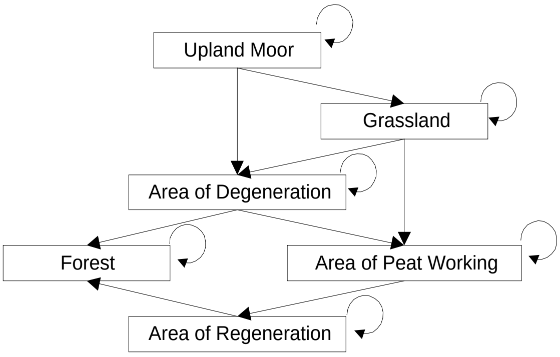
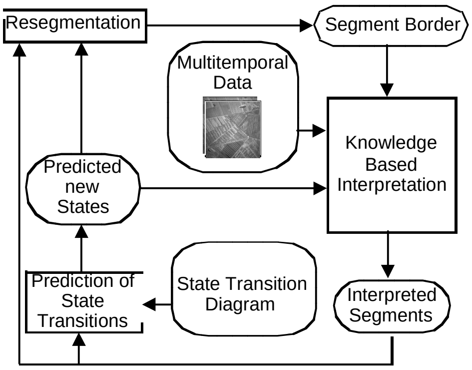


Fig. 9: State transition diagram for moorland developement



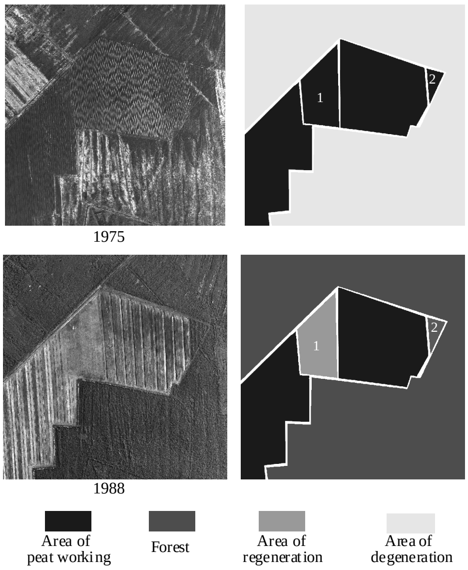


Fig. 10: Usage of state transition diagram for multitemporal interpretation

Without using this prior information the system could not distinguish the states grassland and area of regeneration in grayscale images because both states are also characterized by a high homogeneity. For segment 2 the land use state changed from area of peat working to forest although there is no direct state transition between them represented in the state transition diagram. Due to the elapsed time of 13 years the state area of regeneration was not observed. But using the knowledge about the mean transition times the system also generated the hypothesis for forest which was verified successfully for segment 2. In section 2 the tools for creating multitemporal interpretations in semantic nets were described. In the following the realization for the present case using these tools will be shown. We described above the overview of the system concept in Fig. 8. For the interpretation we have to implement the part for state prediction and the state transition diagram into the semantic net, described in section 4.3. The semantic net used for this purpose takes advantage of temporal links in addition to the other one shown in Fig. 4. These links will be included for the interpretation of the next epoch (t+1) after the complete interpretation of the initial epoch t. During the interpretation of every segment with a particular state several hypotheses will be created along the temporal links. These hypotheses exclude each other. According to the priorities the verification of the different state transition hypotheses will be processed in a particular order. The search tree splits (see section 2.2). In case of a good result of a verification, the other competitive hypotheses will not be verified anymore. At the end of the instantiation for t+1 all instance nodes of the interpretation for the time t will be removed, and the interpretation will continue for t+2 in the same way.

5. APPLIED MOOR MONITORING THROUGH SPATIAL ANALYSIS WITH DIFFERENT TYPES OF GEODATA

In a third approach a user friendly front end a tool has been developed, which enables the user to define application specific, spatial analytic tasks in a very intuitive GUI. The workflow environment offers a visual programming interface, where universal GIS operators (Albrecht 1996) can be assembled to a graph-like structure. These graphs can be stored, modified, and executed.

They represent an ideal environment to design and perform application specific tasks with different parameters and to compare results when analyzing multitemporal data. Data integration is achieved through the hybrid capabilities of the universal operators. Different geodata types with various geodata structures can be processed automatically, without having the user to care about conversion processes between data formats or the structure of the input data supplied. An implemented decision structure allows each operator to perform algorithms in a polymorph way, depending upon type and structure of the input data (Jung et al. 1997). All essential spatial analytical functions found in a standard GIS are included in the universal operators.

Encountered problems and suggested solutions for the main issues in hybrid analysis can be grouped in:

1. Mapping of different GIS functions to the universal operators (Section 5.1).
2. Conversion rules to deal with different kinds of geometric representation, formalized by a conversion matrix and optimized through an operator specific spatial index (Section 5.2).
3. Topological queries regarding the accuracy of various input data types (Section 5.3).

5.1. HYBRID UNIVERSAL OPERATORS

To satisfy the demand for a user friendly GUI, the design of the universal operators is essential. Design in this context implies a more or less self explaining taxonomy of the operators, a quality we have tried to reach by choosing an empirically supported top down approach to create the operators (see Fig. 11). On the other hand we wanted to realize nearly the complete range of spatial analytical capabilities included in standard Geographical Information Systems (GIS).

Hybridity shall express that the universal operators should be applicable to various geo data types with different data structure to relieve the inexperienced GIS user from caring about data type specific algorithms and command structure. As representative data structures we regard vector and raster data.

Universal operators can be categorized in single and multi input operators. *Single input* says that only objects out of one data set (meaning that they belong to just one data type and data structure) are subject of the performed operation. Single input operators, as the buffer operator, need to be polymorph more than anything else, in the sense, that they should perform their semantically triggered operation in a similar manner on raster and vector data structure.

Besides polymorphism *multiple input* operators afford rules to perform and manage geometrical interaction to any necessary extend. Overlay and also spatial search, including topological queries, are representative multiple input operators.

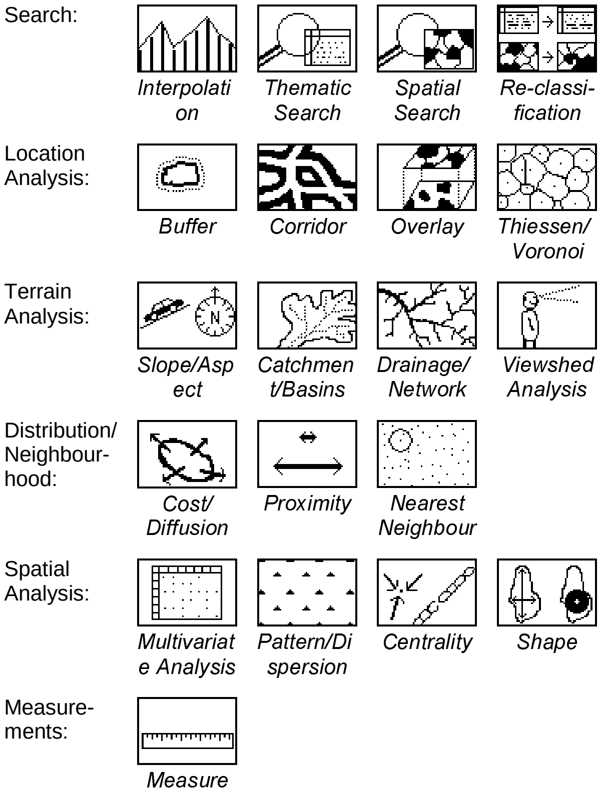


Fig. 11: 20 Universal operators

The mapping of GIS functions to universal operators is achieved by analyzing the structure dependent parameters of existing functions and translating them into semantic options that have a meaning to someone who uses the operators in an application specific context.

The buffer operator may function as a representative example. The semantic of the buffering operation can be described as a dilatation of an object with a specific distance, so that a region is generated around the input object with the supplied distance as a radius. Depending upon the different spatial concepts of each data structure (raster, vector) the semantics of the operator and it's parameters have to be translated into structure specific functions or algorithms. A comparison of functions and options, existing systems on the market and Tomlin's map algebra offer in the context of buffering for vector and raster data, shows that the universal buffer operator will be a compromise. Because of their data model, vector data can distinguish between different dimensions of data (point, line, different kinds of regions) and determine their direction and therefor allow a more differentiated buffering operation then raster data. Raster based operations only know arrayed integers as a spatial reference and are not able to represent one dimensional objects explicitly. Operations with Euclidean distances for example have to translate size and location of each involved raster cell and need rules to decide in which case a pixel still belongs to a certain region and in which case not.

As a result, a first version of the universal buffer operator (see Fig. 12) includes the potential to use lookup-tables to store and retrieve object specific buffer distances, the option to generate separate or contiguous areas as result and to buffer to the inside or outside of an object. These options can be reached for raster data only through integration of additional raster operations. Until now parameters based on direction of vector data are not taken into consideration. But we think about integrating data structure specific parameters of operations as a result of an input data analysis into the universal operators.

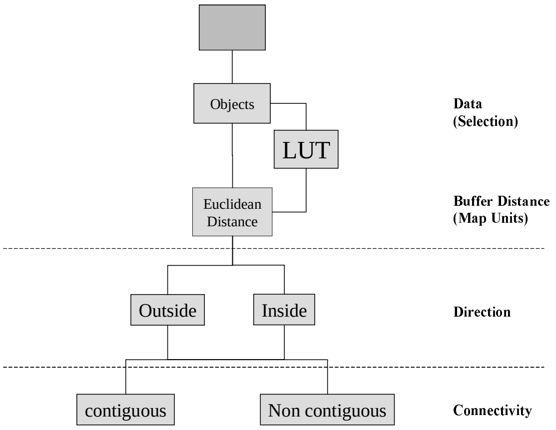


Fig. 12: Universal buffer operator

5.2. GEOMETRICAL INTERACTION

To make clear what different kinds of geo data we plan to include in VGIS a representative subset of different geo data types have been defined:

- Vector objects, topologically consistent (objects may not overlap, ...)
- Vector objects, not topologically consistent
- Raster objects, cell values are semantically labeled
- Raster fields, cell values represent numeric values that can be interpolated (e.g. DTM, temperature, ...)

Geometrical interaction becomes an important issue as soon as different data sets are involved. That happens in the introduced multi-input operators where data sets with different spatial reference systems meet. Whenever any kind of spatial overlay takes place, spatial reference needs to be unique. In the last consequence that always goes along with some kind of data conversion. Major principle in VGIS concerning conversion is to maintain data accuracy especially when administrative basic geodata (e.g. ALK ATKIS as German basic cadastre information) are part of an application. For that reason conversion algorithms go towards vector structure as a result, even if that stands for a loss of performance.

	Vektor	Vektor (Top.)	Raster (Obj.)	Raster (Field)
Vektor	Vektor	Vektor	Vektor	Vektor
Vektor (Top.)		Vektor (Top.)	Vektor (Top.)	Vektor (Top.)
Raster (Obj.)			Raster (Obj.)	Raster
Raster (Field)				Raster (Field)

Fig. 13: Conversion matrix for different geo data types

To reduce further costs we worked out a conversion matrix (see Fig. 13) to regulate the output geodata type depending upon the datasets that have to be processed in combination and the operation performed. A spatially oriented reduction of costs depends only on the operator and can be achieved through minimization of the converted objects. That means that only objects inside the area that encloses all output objects will be converted during the operation. The operator itself will have to determine which objects are of interest and where their spatial boundaries are located. If different data sets of the same type are to be processed, no conversion takes place at all.

5.3. TOPOLOGICAL QUERIES

An essential part of spatial queries in general is some measure to describe the relation between objects in space. Topological relations are able to classify all possible relationships between two objects. Egenhofer's (Egenhofer et al. 1991) approach has become a standard in most standard GIS. Regions consist of a one dimensional border, an inside, and an outside. A nine intersect matrix that describes if there are intersections between the parts of two regions builds the base to separate eight possible relations. These relations completely and uniquely cover all configurations between two regions. For two dimensional objects the four intersect matrix regarding only the interior and the border of each object is sufficient to differentiate between the eight relations.

For VGIS, where data from various data sources and with different data structures have to be processed, Egenhofer's relations as they are will not be able to distinguish the fine differences that have to be taken into consideration when comparing raster and vector borders.

Structural differences as well as a varying accuracy in geometry and attributes of geo objects have to be regarded. To describe the relations between two objects more adequately either a different form of neighborhood rules or a modification of the existing topological relations has to be established.

We have chosen a universal approach by applying the system of topological relations on uncertain data.

In a first step a simple statistical model has been included to quantify the geometrical uncertainty, realized by an epsilon band with constant width that symbolizes a discretized value as a factor of the standard deviation. Then we adapted the idea of applying topological relations on objects with undeterminate boundaries (Clementini et al. 1996)(Cohn et al. 1996) and extended it to describe neighborhood relationships between uncertain objects.

Uncertain and objects with indeterminate (we will call them fuzzy objects) boundaries can be modeled similarly. Uncertain objects are sharp, but there is an uncertainty about where the border lies, even though probability differs inside the epsilon band. The most probable location of the border is always exactly the middle line of the epsilon band – the line that actually represents the border in the geo data set from where the epsilon band is derived. The border of fuzzy objects is not even in nature detectable and can be modeled as broad irregular border in contrast to the epsilon band.

If Egenhofer's topological relations will be applied to regional objects with broad boundaries, the four intersect matrix (4I Matrix) is not longer sufficient to describe all geometrically possible relations. Nevertheless the 4I Matrix is a good characteristic to group the other nine intersect matrix possibilities around it.

The 8 topological relations of fuzzy objects will be the relations with identical 9I matrix as the relations between discrete objects. Taking all possibilities of the 9I matrix, there would be 44 geometrically possible topological relations. Yet many of them are rather unlikely to be found in reality or describe quite similar neighborhood constellations. With certain assumptions (e.g. the border is not expected to be much larger than the object itself) and a classification of relationships 14 topological relations can sufficiently describe the relations between objects with uncertain borders. The 4 unstable relations (meet, cover, covered by, and equal) build an exception, because they reference the discrete one dimensional border representing the most probable case in uncertain boundaries.

As a consequence VGIS topological relations are a mixture between the indeterminate boundaries approach (Cohn et al. 1996, Clementini et al. 1996) and Egenhofer's discrete topological relations (Egenhofer et al. 1991). This way the possibility is given to model discrete and accurate as well as uncertain relations between two regional objects. A very important aspect is the integration of data accuracy in topological queries to achieve a certain degree of significance. How in end user interaction (spatial search operator) we will handle this discrepancy in an adequate manner has not been finally decided yet, but one possibility might be to add an option "uncertainty included".

5.4. EXAMPLE: APPLICATION MOORMONITORING

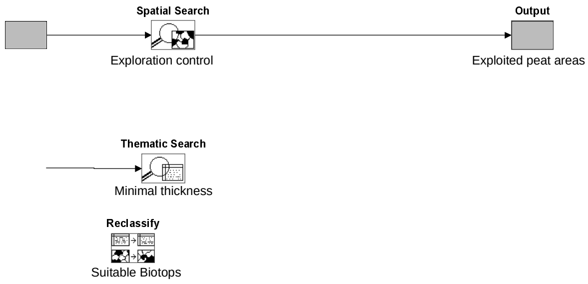
As part of the approach to perform moor monitoring, two representative applications will be generated focussing on some of the problems pointed out in the introduction.

1. Administrative control: Comparison between legal peat exploitation claims and observed cutting activities
2. Ecological optimization: Suitability assessment for moor areas to be regenerated (Bröcker et. al 1998)

Both tasks will be created with the flowchart GUI and include different data sources:

- Real landuse data from the interpretation tool
- Biotop data from ground acquisition
- Map of legal industrial peat cutting areas
- Ecological conservation and development plan

In an additional control procedure the plausibility of the real landuse compared to the other data sources could be determined, results and possible errors will be reported. The example flowchart in Fig. 14 shows how legal industrial peat cutting areas can be controlled and/or updated through comparison with actual real landuse data determined by the hybrid system (semantic net) described above. A second output string detects areas of conflict between ecological suitability for regeneration and potential peat cutting areas.


Spatial Search
Exploration control
Output
Exploited peat areas
Thematic Search
Minimal thickness
Reclassify
Suitable Biotops