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PHD THESIS

- Summary -

Interactive applications development methodologies for spatial data processing and visualization

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The availability of large volume of spatial data, broadband Internet access, high storage and processing capability devices, and the Web technologies accelerate the usage of geographic information into our daily lives. The Earth Science related domains (e.g. hydrology, meteorology, agriculture, air and water pollution, urban planning, etc.) offer standard services for storing, processing, analyzing, and visualizing spatial data of different types and formats.

Spatial data is a generic description that encapsulates information from different domain fields and can be classified into satellite images, aerial images, and ground-based measurements. Satellite imagery consists of images of the Earth captured by artificial satellites that orbit around the Earth's atmosphere. The ground-based data collection techniques complement the aerial images because they can inform surveys in areas where the airborne laser cannot penetrate (e.g. dense forests, building shadows, etc.). The resulting models are used in many applications, such as: vegetation growth, building and road measurements, river basin erosion, water quality, etc

There are several issues when talking about the spatial data usage within the Earth Science domains, such as: optimal execution of large volume of data, the flexible description of complex scenarios, data sharing among various categories of users, etc. The existing applications usually do not allow the processing of a large volume of data, and are more oriented on the small and medium use cases. On the other hand, to overcome this issue requires an intensive usage of hardware capabilities provided by the distributed platforms (e.g. Grid, Cloud, clusters, etc.).

The process of modeling the complex use case studies requires first the natural description of the inner functionality, and usually involves: a solid understanding of the background context, the collection of the adequate input data set, the syntactic and semantic description of the adopted solutions, the execution over distributed environments in order to speed up the entire process, optimized tools for partial results integration, and some special interaction techniques for visualizing and analyzing the final outputs. The main difficulty is to define a general data model that is able to represent complex algorithms that are connected by certain rules and policies.

The spatial data are currently used in a variety of experiments and studies that are performed by means of software platforms, involving specialists that are geographically distributed. One of the most common issues in such situations is the spatial data availability and data sharing between these researches' communities. The large number of formats and types complicates things even more and impose additional policies for accessing these data from specialized remote repositories. The mechanisms used for retrieving data from one storage does not provide access to other repositories, while the software platforms that process the spatial data tend to encode the results in a proprietary format. All these issues require the improvement of data sharing and platforms communications.

The title of the thesis contains several keywords that are highly used throughout this entire paper: interactivity, methodology, processing, and visualization. Most of today's Earth Science applications do not provide easy-to-use features when modeling complex use case studies, and require the users to learn complex programming languages in order to fulfill this action. The interactive application refers to the development of features that overcome this issue and provides dynamic modules that can be use by any type of users.

One of the main research directions of this thesis is to define a methodology for developing applications that provide solutions for all the previous mentioned issues. The theoretical concepts are inspired from the mathematical graphs theory that facilitates the flexible and interactive description of the complex use cases. The nodes represent specific geospatial algorithms while the graph's edges define the entire data flow of the scenario.

The processing of large volume of spatial data is another research direction that was intensively studied within this thesis. In order to achieve this goal, a complex data model was defined that is able to represent large use case scenarios (experiments, phenomena) that take place in the real world or that are simulated for specific purposes. The processing term refers to the actual execution of algorithms that manage the spatial data in various forms, such as: the classification of geographic areas based on vegetation indices formula, the creation of thematic maps, the prediction of water quantity/quality for specific hydrological catchments, etc.

Taking into account the large size of spatial data (for some complex case studies it can reach a few hundred GB) the standalone applications do not provide enough computation power in order to process them in a reasonable amount of time. Instead, new platforms had to be developed that make use of the capabilities offered by the distributed infrastructures (e.g. Grid, Cloud, clusters, multi-core, etc.). The proposed methodology is flexible enough to allow the spatial data execution over different computing platforms, but the actual implementation of the theoretical concepts were experimented only on the Grid and standalone infrastructures.

The last step in processing the spatial data is related to the results visualization and analysis. Due to the fact that the outputs of the complex phenomena (experiments, scenarios) are usually visualized by various categories of uses, it is important to present this information in an easy to understand manner, such as: results overlapped onto the interactive maps, dynamic charts, static images, statistics and text-based data, etc.

Thesis objectives

The development of interactive applications that allow the spatial data modeling, processing, visualization, and analysis represents the main research of this thesis. Based on these aspects, we can define the following list of objectives:

1. The definition of a general methodology for developing interactive applications that model, process, and analyze various formats of spatial data. At each step, the proposed methodology should provide the theoretical and practical solutions that solve the issues described earlier;
2. Provide optimal solutions for processing large volume of spatial data, regardless of their type and location. Usually, there are several public remote repositories that store these data, and implement specific policies for accessing them. This objective also takes into account the definition of an architecture that is able to retrieve the needed information;
3. The development of a flexible data model that is able to represent the complex use case scenarios from various Earth Science related domains. The theoretical concepts are inspired from the mathematical graphs theory that facilitates the internal representation and organization of the dynamic elements;
4. Provide interactive techniques for modeling the complex use case studies. Most of today's applications do not allow the visual description of the experiments and use instead text based editors that leave room for syntactic errors, generated by the users that perform the scenarios description. The interactive solution intends to overcome this issue and provides visual modules that facilitate the description process;
5. Improve the process of spatial data sharing and platforms interoperability that use the Grid infrastructure in order to perform the execution process.

Thesis outline

The current thesis is organized in 9 chapters, with 162 bibliographic references. The contributions highlighted throughout this paper were published in 12 ISI and B+ scientific journals, 12 articles in national or international conferences indexed as ACM and IEEE, 1 book chapter, and 12 presentations given at different workshops and trainings.

Chapter 1 describes the general context of this thesis, together with the motivation and the proposed objectives that are further detailed throughout the paper.

Chapter 2 details and classifies the spatial data that are relevant for this study into three types: satellite images, aerial images, and ground based measurements. Due to the fact that the spatial data are more and more present into our daily lives, several initiatives were proposed in the last years that intend to provide optimal solutions for data sharing among different scientific communities and between specialized repositories from where they can be accessed by means of standard services.

The critical survey regarding the state of the art on spatial data related applications is the main subject of **Chapter 3**. The existing solutions provide similar services, but they address different types of requirements: the first ones are suitable for the execution of simple geospatial algorithms, while the second category uses the distributed computing environments in order to provide optimal solutions for processing a large volume of data. The current thesis aims to fill the gaps between the issues encountered when analyzing these applications. This is the main reason why this chapter also highlights the differences between the existing solutions and the ones adopted within this thesis. The theoretical concepts defined by the proposed methodology are going to be implemented as functionalities of the GreenLand platform that provides features for spatial data modeling, processing, and analysis. Based on this aspect, the current chapter generally describes the GreenLand platform as an example of interactive application, developed on the proposed methodology.

A parallel description of the methodologies used for developing the classical software products and the spatial data related applications, is presented in **Chapter 4**. The first one is based on 5 methodological steps, while the other one is a 7-phase process that starts with the context problem definition and the identification of the requirements, and continues with modeling the system related architecture, specifying the methods that can be used for processing the spatial data over different computing infrastructures, and identifying the most suitable presentation techniques that can be used in the visualization and the analysis process. The last two steps of the proposed methodology describe the use cases that can be developed for testing and validating the application, together with the guidelines for installing it on different platforms.

The main theoretical concepts related to the abstract representation of the complex use case scenarios are presented in **Chapter 5**. The proposed solution uses the concepts of basic operators and complex workflows for describing the experiment's functionality. These concepts are inspired from the mathematical graphs theory and allow the data flow description and organization as a graph, where each node encapsulates the behavior of a specific geospatial algorithm (as basic operator) or groups of algorithms (as complex workflows). The connections between these items are specified as uni-directional edges that also have the role of transferring the output results of one item as input to other elements. The abstract definition of the workflow needs to be encoded into a digital format that can be executed over different computing infrastructures. This stage involves its transcription into a high-level programming language, by taking into account all the concepts defined earlier. The XML internal format is recommended, due to the fact that it allows the definition of entities closely related to the graph notion. In cases of complex experiments, the size of these _les is large and can be managed only by computer scientists, but usually these scenarios are developed by the Earth Science domain field specialists. The proposed solution is based on the OperatorEditor and WorkowEditor tools that provide interactive techniques that simplify the development process to the level of specifying the operators and workflows in a visual manner, avoiding this way the direct management of the text-based files.

One of the main research directions of **Chapter 6** is the execution of a large volume of spatial data in a reasonable amount of time. This means that the geospatial algorithms should be processed on powerful machines that provide parallel and distributed capabilities (e.g. Grid, Cloud, clusters, etc.). On the other hand, the proposed methodology also addresses the small scale scenarios that are not so computing intensive. This chapter starts with a general overview of the most important computing environments (e.g. Grid, Cloud, clusters, multi-core, etc.) and particularizes the execution process onto the Grid and standalone platforms. Another important aspect is the fact that the entire processing is divided into 4 stages: pre-processing, actual execution of data, monitor, and results analysis. Each level describes the features of the methodology that are representative, and provides details about the GreenLand platform's mechanisms for partitioning the workflows into tasks and execute them onto the Grid worker nodes. The resources sharing improvement between the applications that use the Grid infrastructure is also described within this chapter. The OGC standard seems to provide the best solutions for invoking geospatial algorithms that are resident on external platforms. In the standalone environments the default solutions are working just fine, but when dealing with large data processing that takes a lot of time to complete, those methods do not provide the proper guidelines. This methodology recommends the extension of the WPS service to include a monitor operation that is able to periodically query the status of the execution.

Chapter 7 describes the theoretical concepts that are used in order to visualize and analyze the spatial data, regardless of their type and storage location. It identifies the proper presentation techniques of the results obtained during the execution process. Based on the categories of users that are going to utilize these applications, the spatial data results should be visualized as: text _les, dynamic charts, static images, statistics, interactive maps enriched with the actual image result, etc. The Earth Science related applications usually exchange a large volume of spatial data, in various formats. The execution results can also be included into this category, and represent important resources for many scientific communities. Based on these aspects, the proposed solutions recommend the usage of standard services for improving the data visualization and analysis that also implies the concept of data sharing. The OGC standard provides the best methods for visualizing remote data, and retrieving them in a highly interactive manner. The spatial data visualization process also involves the identification of a common set of interaction techniques that should be integrated onto multiple platforms, in order to simplify the user related actions for accessing, retrieving, visualizing, and analyzing data, regardless of their storage location. Otherwise, the users have to utilize multiple tools (that provide similar functionalities) with proprietary interaction mechanisms that have to be learnt in order to be able to perform a complete visualization and analysis process.

The theoretical concepts proposed within this thesis define a methodology for modeling, processing, and visualizing various use cases from the Earth Science activity domains. Even though these concepts were partially validated in the sections they were described, **Chapter 8** proposes two complex experiments in order to test all the functionalities implemented throughout this methodology. These two scenarios represent real use case studies that were formulated by domain field specialists and reflect the current problems they are confronting with, in terms of water quality/quantity and land cover/land use aspects.

The main contributions of this thesis are presented in **Chapter 9**, together with the conclusions and the future work research directions.

Thesis contributions

The main contribution of this thesis is the creation of a new methodology for developing interactive applications that model, process, visualize, and analyze a large volume of spatial data. Other contributions that have a direct impact in achieving this feature are listed in the following paragraphs:

1. The definition of the basic operator and workflow concepts that can be used for modeling the scenarios from various activity domains. This contribution (in combination with the GreenLand services) can also be used in order to solve the issue of extending the platform to other disciplines, besides the Earth Science related ones;
2. The abstract description of the basic operators and complex workflows;
3. The identification of a predefined set of types, rules, and constraints that can be used for specifying the inputs and outputs of the operators and workflows;
4. The development of two applications (OperatorEditor and WorkowEditor) that implement these theoretical concepts and provide interactive techniques for developing the complex use case scenarios;
5. The identification of the phases required for the spatial data execution process. Each step contains the theoretical background and the practical solutions implemented within the GreenLand platform;
6. The development of an interactive platform (GreenLand) that is able model, process, visualize, and analyze various types of spatial data. It is the direct result of the development process performed through the methodology proposed within this thesis;
7. The implementation of specific modules that are able to process the spatial data in near-real time, by accessing and retrieving the corresponding information from remote repositories, based on the FTP protocol and OGC standard services. This is useful for scenarios that predict certain phenomena and require up to date information;
8. The possibility of achieving platforms interoperability by allowing the execution of the workflows as WPS services. This means that the GreenLand geospatial algorithms can be accessed by other external platforms that implement this standard. The reverse process is also

valid, meaning that the GreenLand is able to remotely execute functions developed by other applications;

9. The extension of the WPS service, with the Monitor operation that can be used in Grid based processing of data;
10. The implementation of an interactive module that is able to monitor the workflows execution over the Grid and standalone infrastructures. This tool allows the users to interfere during the runtime phase, and stop the processing if necessary;
11. The definition of an automatic mechanism that translates the XML based response of the OGC services into visual components that facilitate their utilization by various types of Users;
12. The development of a communication architecture (based on OGC services) between the GreenLand platform and remote spatial data repositories. This module is able to improve the data sharing and applications interoperability that provide services for the same activity domains;
13. An identification of the most important visualization techniques that can be performed for various types of users, regardless of their background domain knowledge;
14. The definition of experimental tests for improving the processing of large volume of spatial data. The obtained results demonstrate that the proposed solutions were good and allow the achievement of such goals.

List of publications

Journal articles

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