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Topic

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Advancing 3D WebGIS – browser-based Methods for Visualization and Analysis and their Integration in Virtual Research Environments in the Context of Cultural Heritage

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The topic of 3D GIS has been with me since the days of my studies at the University of Trier, where I got the opportunity to intensively study the modeling and evaluation of 3D city models across three semesters at the Chair of Cartography with Prof. Jürgen Bollmann. Once the seed of interest was planted it grew steadily, nourished by the fascination of the technically feasible and the food of the interdisciplinary variety of topics that can be enriched with the topic of 3D. Later, at the University of Bonn, Prof. Alexander Zipf gave me the opportunity in 2008 to deepen the topic further. In particular, I was allowed to participate intensively in the creation and refinement of the 3D city model of Heidelberg. Other projects followed—3D Sutras and MayaArch3D—, they provided the scientific framework for the content of the present work.

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Abstract

Currently, our society experiences a profound transformation from an analog industrial society towards a digital information society that could evolve into a knowledge society in the future. In this change towards a knowledge society, the UNESCO expects opportunities, which can contribute to a sustainable human development. A prerequisite for this is to make the world's knowledge globally accessible. The developments in information and communication technologies that have brought about this transitional change can also be used to facilitate the generation and dissemination of knowledge.

Globally distributed and collaborative virtual research environments can bring together researchers around the world and support their activities through appropriate tools and access to research infrastructures. This also applies to scientific domains and actors involved in the research and preservation of cultural heritage. The existence of cultural heritage is linked to human activities that have taken place in certain places at certain times. Thus, they can be examined with geographical methods and approaches from geoinformatics. Cultural goods can be both tangible and intangible. In particular, the material cultural goods have a 3-dimensional appearance, so that often digital copies of the actual state are created, as well as digital hypothetical reconstructions in the form of 3D models. As a consequence, the spatial distribution of cultural heritage goods, the spatial relationships between locations inside and between heritage sites and the geometric properties of them can be well studied by using 3D geographic information systems. With the integration of 3D geographic information systems into web-based Virtual Research Environments, we get closer to the UNESCOs vision of a knowledge society where new knowledge about cultural heritage is created collaboratively by international and interdisciplinary research teams, and where that knowledge is shared and made publicly available worldwide.

The activities and workflows related to cultural heritage research are diverse and require the development of especially adapted research instruments and methods to design these work processes as efficient as possible. In order to understand the requirements for the handling of 3-dimensional data, their generation, representation, analysis and documentation, two case studies were observed in which web-based 3D geographic information systems (3D WebGIS) were integrated into virtual research environments. In the first case, the spatial context as well as the geometric properties of over 1000 year old Buddhist stone inscriptions from the time of the Tang Dynasty in Sichuan (China) was the subject of 3-dimensional visualization and analysis. In the second case, it was the documentation and analysis of the important World Heritage site of Cópan, located in today's Honduras, and its surrounding valley. Both the city with its temples

and the surrounding area are characterized by their unique Mayan architecture and settlement structures.

The two main areas that guide the research questions of this thesis are derived from the challenges associated with the case studies requirements. These are the extension and adaptation of the functional capabilities of 3D WebGIS and further, the question of integration of such a system into virtual research environments.

Two of the four articles in this work deal with new methods for browser-based analysis of 3D geodata. Publication II.2 evaluates the possibility of massive parallelization of raster algorithms to accelerate raster analysis by exploiting new standardized interfaces, in particular WebGL. The results show an acceleration of up to 100 times over the conventional sequential calculation, thus enabling new forms of "real-time" user interaction with geo-information on the Web. Publication II.4 deals with methods and strategies for the efficient calculation of a browser-based visibility analysis (line-of-sight). The performance and scalability characteristics that are important for a usage in web-based systems were evaluated in various application scenarios and could be achieved by using various data reduction and data pre-selection strategies.

Two further articles deal with the integration of 3D components into Virtual Research Environments and the handling of complex data models for the documentation of built structures. Publication II.1 is concerned with the integration of a 2D/3D WebGIS component, which plays a central role in the organization of the information about the inscriptions and related contextual material. It allows both geographical access to different scale levels and a realistic visual impression of the actual state of the site at the time of data collection. This way, the integrated virtual reseach environment is contributing to the conservation of the endangered Buddhist stone inscriptions in China. Publication II.3 presents new methods for storing, querying and visualizing complex semantic segmented multi-resolution 3D models and their integration into the virtual research environment for the investigation and documentation of Copán, Honduras.

The scientific results presented in this work contribute to the efficient and interdisciplinary scholarly cooperation with spatial 3D data in virtual research environments in the context of cultural heritage research, which could be enriched by methods of geography and geoinformatics.

Kurzzusammenfassung

Unsere Gesellschaft durchläuft derzeit eine tiefgreifende Transformation von einer analogen Industriegesellschaft hin zu einer digitalen Informationsgesellschaft, die sich in Zukunft zu einer Wissensgesellschaft weiterentwickeln könnte. Die UNESCO sieht in diesem Wandel Chancen, die zu einer nachhaltigen Entwicklung der Menschheit beitragen können. Entscheidend hierfür ist der Zugang zu Wissen. Die Entwicklungen im Bereich der Informations- und Kommunikationstechnologien, die diesen Wandel hervorgerufen haben, können gleichzeitig dazu genutzt werden, die Erzeugung und Verbreitung von Wissen zu erleichtern.

Global verteilte und kollaborativ arbeitende virtuelle Forschungsumgebungen können Forscher auf der ganzen Welt zusammenbringen und deren Aktivitäten durch geeignete Instrumente und den Zugang zu Forschungsinfrastrukturen unterstützen. Dies gilt auch für den Bereich der Wissenschaften und Akteure, die sich mit der Erforschung und dem Erhalt von Kulturerbe befassen. Die Existenz von Kulturerbe ist an menschliche Aktivitäten gekoppelt, die zu bestimmten Zeiten an bestimmten Orten stattgefunden haben. Somit können sie auch mit geographischen Methoden und Fragestellungen untersucht werden. Kulturgüter können sowohl materiell als auch immaterieller Art sein. Insbesondere die materiellen Kulturgüter haben durch Ihre Körperlichkeit eine 3-dimensionale Erscheinung, so dass häufig digitale Kopien des Ist-Zustandes, sowie digitale hypothetische Rekonstruktionen in Form von 3D Modellen davon angefertigt werden. Die räumliche Verbreitung von Kulturerbe und die räumlichen Beziehungen zwischen Kulturerbe-Orten können somit gut mit Hilfe von 3D Geoinformationssystemen untersucht werden. Mit der Einbindung von 3D Geoinformationssytemen in web-basierte Virtuelle Forschungsumgebungen wird die von der UNESCO beschriebene Chance zur Entstehung einer Wissensgesellschaft größer, in der neues Wissen international vernetzt und interdisziplinär geschaffen und der Menschheit das Wissen um ihr kulturelles Erbe weltweit und offen zur Verfügung gestellt wird.

Die Aktivitäten und Arbeitsabläufe im Zusammenhang mit der Kulturerbeforschung sind vielfältig und bedürfen der Entwicklung speziell darauf abgestimmter Forschungsinstrumente und Methoden, um diese Arbeitsprozesse bestmöglich und effizient zu gestalten. Um die Anforderungen im Umgang mit 3-dimensionalen Daten, ihrer Erzeugung, ihrer Darstellung, ihrer Analyse und Dokumentation zu erfassen, wurden zwei Fallstudien herangezogen in denen web-basierte 3D Geoinformationssysteme (3D WebGIS) in virtuelle Forschungsplattformen integriert wurden. In einem Fall war der räumliche Kontext sowie die geometrische Beschaffenheit von ca. 1000 Jahre alten Buddhistischen Steininschriften aus der Zeit der Tang Dynastie in Sichuan Gegenstand 3-dimensionaler Darstellung und Analyse. Im zweiten Fall war es die Dokumentation und Analyse der bedeutenden Weltkulturerbestätte Cópan im heutigen Honduras und dessen

Umgebung in Form eines mit Siedlungsresten übersäten Tales. Sowohl die Stadt mit ihren Tempelanlagen als auch die Umgebung zeichnen sich durch ihre einzigartige Maya-Architektur aus.

Die Herausforderungen, die sich in dem Zusammenhang mit den Erfordernissen der Fallstudien und deren Umsetzung ergaben, betreffen zwei Hauptbereiche, welche die Forschungsfragen dieser Arbeit leiteten. Zum einen, die Erweiterung und Anpassung des Funktionsumfanges von 3D WebGIS und zum anderen die Frage der Integration solcher Systeme in Virtuelle Forschungsumgebungen.

Zwei der vier dieser Arbeit zugrunde liegenden Artikel befassen sich mit neuen Methoden zu browser-basierten Analyse von 3D Geodaten. Publikation II.2 evaluiert die Möglichkeit der massiven Parallelisierung von Rasteralgorithmen zur Beschleunigung von Rasteranalysen durch Ausnutzung neuer standardisierter Schnittstellen, insbesondere WebGL. Die Ergebnisse zeigen eine bis zu 100-fache Beschleunigung gegenüber der herkömmlichen sequenziellen Berechnung und ermöglichen damit neue Formen der "real-time" Nutzerinteraktion mit Geoinformationen im Web. Publikation II.4 befasst sich mit Methoden und Strategien zur effizienten Berechnung einer browser-basierten Sichtbarkeitsanalyse (Line-of-Sight). Die für den Einsatz in web-basierten Systemen wichtigen Eigenschaften Performanz und Skalierbarkeit wurden in verschiedenen Anwendungsszenarien evaluiert und konnten durch die Verwendung verschiedener Datenreduktions- und Datenauswahlstrategien erreicht werden.

Zwei weitere Artikel befassen sich mit der Integration von 3D Komponenten in Virtuelle Forschungsumgebungen sowie dem Umgang mit komplexen Datenmodellen zur Dokumentation baulicher Strukturen. Publikation II.1 befasst sich mit der Integration einer 2D/3D WebGIS Komponente, die eine zentrale Rolle für die Organisation der bereitgestellten Informationen spielt. Sie ermöglicht sowohl einen geographischen Zugang zu verschiedenen maßstäblichen Ebenen als auch einen realistischen visuellen Eindruck, des zum Zeitpunkt der Datenerhebung existierenden Ist-Zustandes der untersuchten Kulturerbestätten. Die integrierte virtuelle Forschungsumgebung unterstützt damit den Erhalt der vom Verfall bedrohten Buddhistischen Steininschriften in China. Publikation II.3 stellt Methoden zur Speicherung, Abfrage und Visualisierung von komplexen semantisch segmentierten multi-resolution 3D Modellen zur Verfügung.

Die in dieser Arbeit erzielten Forschungsergebnisse leisten einen Beitrag zur effizienten und interdisziplinären wissenschaftlichen Zusammenarbeit mit räumlichen 3D Daten in virtuellen Forschungsumgebungen im Kontext der Kulturerbeforschung, welche durch Methoden der Geographie und der Geoinformatik bereichert werden kann.

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List of Abbreviations

2D	Two-dimensional
3DPS	3D Portrayal Service
3D	Three-dimensional
ALS	Airborne Laser Scanning
API	Application Programming Interface
ARIADNE	Digital Infrastructures for Archaeological Research
BOAI	Budapest Open Access Initiative
CAD	Computer Aided Design
CH	Cultural Heritage
CIDOC-CRM	Conceptual Reference Model of the International Committee for Documentation
CLARIN	Common Language Resources and Technology Infrastructure
CMS	Content Management System
CPU	Central Processing Unit
DAI	Deutsches Archäologisches Institut
DARIAH	Digital Research Infrastructure for the Arts and Humanities
DBMS	Database Management System
E-RIHS	European Research Infrastructure for Heritage Science
EAI	Enterprise Application Integration
ESFRI	European Strategy Forum on Research Infrastructures
GIScience	Geographic Information Science
GIS	Geographical Information System
GPS	Global Positioning System
GPU	Graphics Processing Unit
ICT	Information and Communications Technology
ISO	International Organization for Standardization
JISC	Joint Information Systems Committee (UK)
LiDAR	Light Detection and Ranging
OGC	Open Geospatial Consortium
OSM	OpenStreetMap
RI	Research Infrastructure
RQ	Research Question
SDI	Spatial Data Infrastructure
SOA	Service oriented architecture
SaaS	Software as a Service

SfM	Structure from Motion
TEI	Text Encoding Initiative
TLS	Terrestrial Laser Scanning
UGC	User generated content
URI	Uniform Resource Identifier
VGI	Volunteered Geographic Information
VRE	Virtual Reseach Environment
W3DS	Web 3D Service
WCS	Web Coverage Service
WFS	Web Feature Service
WMS	Web Map Service
WWW	World Wide Web
WebGIS	Web-based Geographical Information System
WebGL	Web Graphics Library

Part I

Summary and Conclusions

I.1 Introduction

This dissertation is about advancing 3D WebGIS. 3D WebGIS in this work is understood as a browser-based web application that can vary in its range of functionalities depending on which role it plays in the research process. Primarily it is able to visualize 3-dimensional geodata. Additionally, it may provide means to interact with the data, to analyze the data, query related data and manage data, e.g. to import or export local or remote data. 3D WebGIS can support activities in many areas, such as urban planning, disaster risk management, energy-site planning, environmental monitoring and many more. However, the focus of this study is set on the advancement of 3D WebGIS for Cultural Heritage(CH) research. This study evaluates methods to improve the performance, scalability, usability and interoperability of the web-browser-based 3D visualization and analysis of geospatial raster and vector data. Furthermore it is concerned

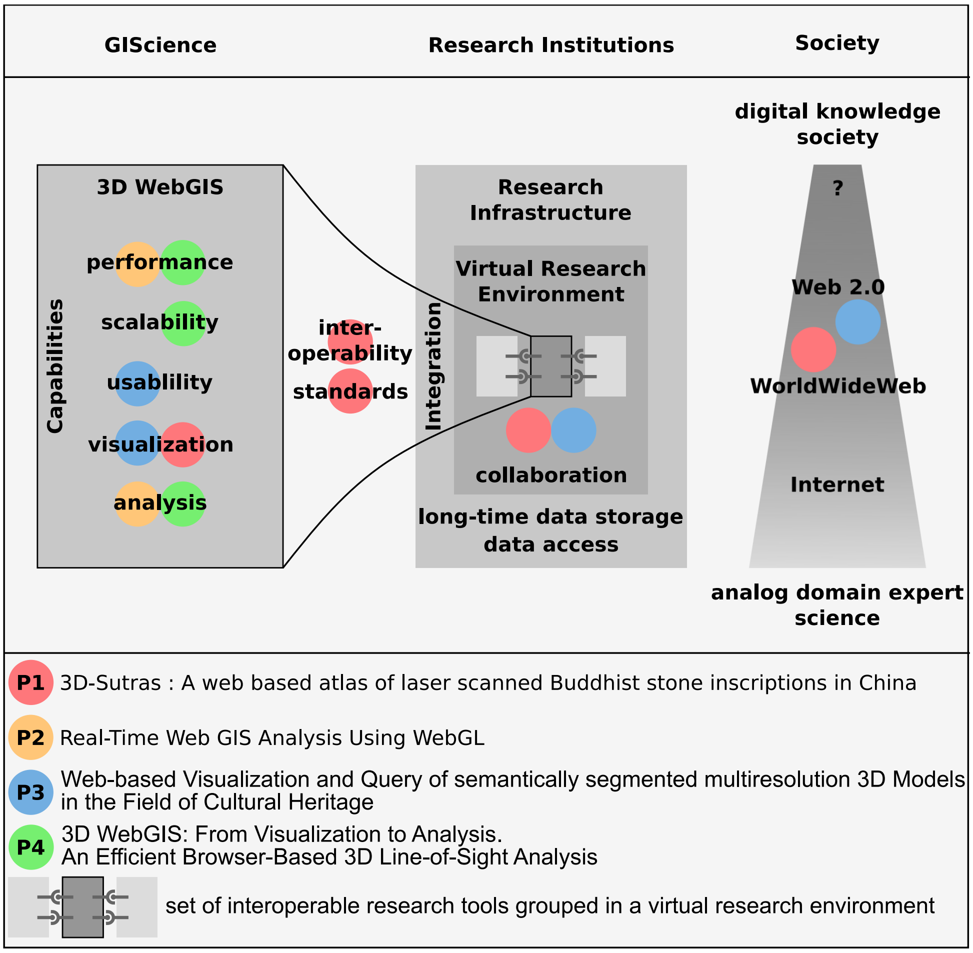


Figure I.1.1: Research contexts and contribution topics of the cumulative publications about the integration of 3D WebGIS components into Virtual Research Environments (VREs) for CH.

I.1.1 Structure and Context of the research

This work presents the results of four cumulative publications which where elaborated in the scope of two interdisciplinary research projects, accomplished in the field of Cultural Heritage. These projects served as case studies to examine the requirements that are related to the work with 3D data in CH-VREs. Furthermore these case studies served to advance and evaluate specific methods to enhance the capabilities of 3D WebGIS components to meet those requirements.

The structure of the research and the area of impact of the four cumulative publications of this thesis is summarized in Figure I.1.1.

One of the two main goals of the research activities of this thesis was to improve the visualization and analysis "Capabilities" of 3D WebGIS in terms of performance, scalability, usability and interoperability. Both case studies started with the intention to create VREs and to use 2D and 3D WebGIS as supplementary tools in conjunction with further, sometimes preexisting, system components. Hence, "Integration" was a key requirement and represents the second main goal of investigation.

The integration of research tools into VREs is important, because VREs can bundle domain specific functionalities that are provided by different remotely located institutions, e.g. for data capture, processing and analysis, documentation, discussion and publication. Being able to access all necessary functions and services at one virtual place, creates an efficient and collaborative workspace for a group of scholars, that intend to work together on a common research topic.

The broader context of this thesis—to advance 3D WebGIS and enable integrated and collaborative VREs for CH—can be located on a higher societal level. The developments of Information and Communication Technologies (ICTs) have paved the path for a transformation from an analogous world, where scientists created differentiated knowledge in largely separated expert domains, to an information society that eventually lead to a digital knowledge society in the future. The knowledge society, how it is envisioned by the UNESCO (2005), is based on access to knowledge which is the decisive factor for a sustainable human development. Therefore, infrastructures and VREs that facilitate the global collaborative production and exchange of knowledge is a step forward on the path towards a digital knowledge society.

The content of this thesis is separated into two parts. Part I (Summary and Conclusions) of this work gives the reader an overview of the conducted research and provides background information to understand the wider context of the research, which then is specifically presented in the original cumulative publications in part II (Publications).

Both research goals—extending the "Capabilities" and "Integration" through standards and interoperability into CH-VREs—guided the selection of specific research questions, which are presented in the following Section I.1.2.

Next to this introduction, the reader will find three Chapters, explaining in more detail, the background of the research with respect to the three levels of impact presented in Figure I.1.1.

To understand the necessity of developing and advancing interoperable web-based research tools like 3D WebGIS the first background Chapter I.2 will describe the situation of the changing world with respect to the impact that Information and Communication Technologies (ICTs) have on the daily work of scientists.

The second background Chapter I.3 will describe how research institutions can cope with this change by developing Virtual Research Environments (VREs), which allow researchers to access tools, services and resources to facilitate the whole research process and allow for collaborative working.

The third background Chapter I.4 will more specifically discuss the roles which 3D WebGIS applications and VREs can play in Cultural Heritage research and which scholarly activities can be supported by 3D WebGIS.

Chapter I.5 gives a detailed overview of the scientific contributions for each of the four publications that constitute the base for this dissertation.

Chapter I.6 will give an integrated synopsis (I.6.1), which relates the outcomes of the four publications with each other. Afterwards the main conclusions I.6.2 are drawn from the results of this thesis.

Finally, Chapter I.7 will give an overview of future research areas and suggests several specific research topics to continue the research on advancing 3D WebGIS in the scope of CH.

I.1.2 Research Questions

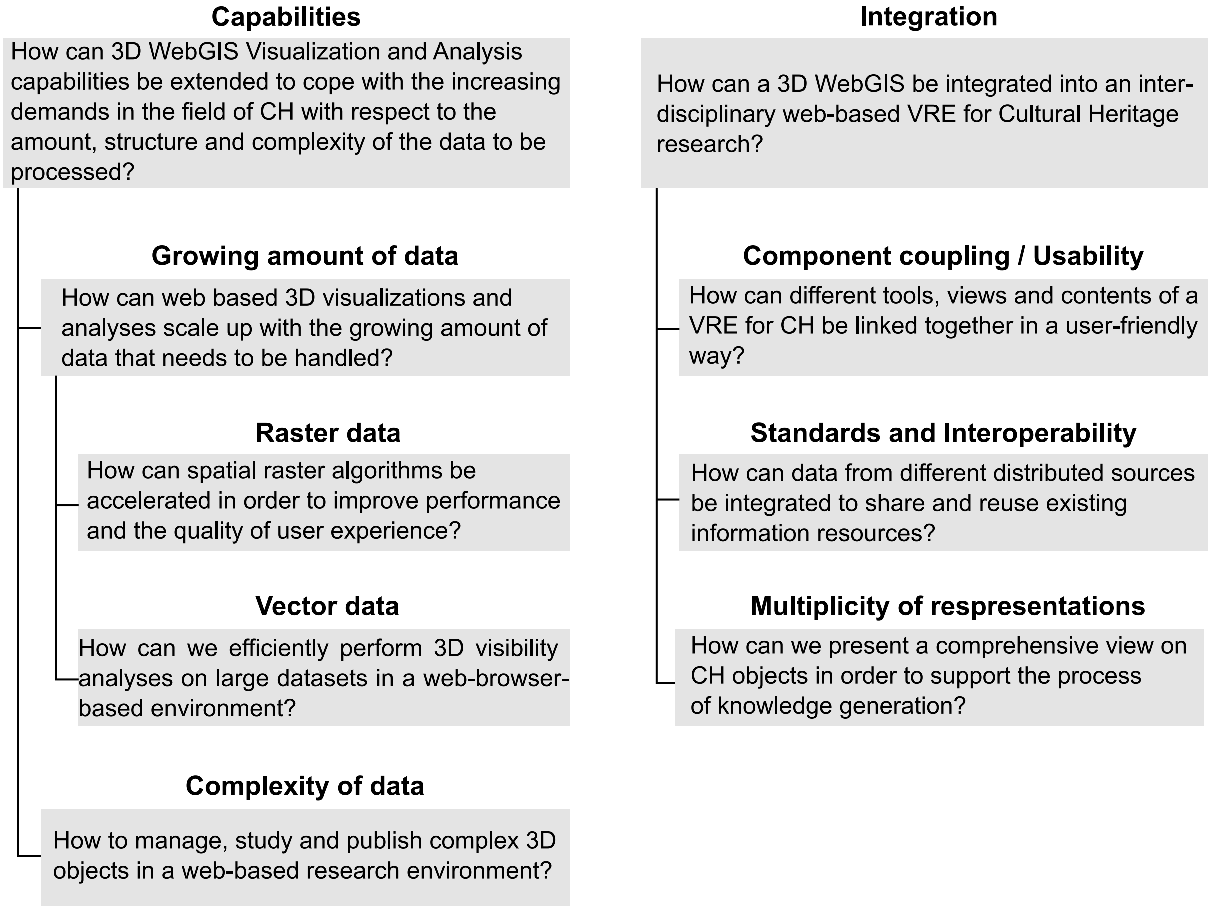
This section will provide an overview of research questions that are subject to the present work. Specific questions which are related to the publications attached in part II are embedded in the context of more general research questions on a more abstract level (Figure I.1.2).

The research questions are associated with the general developments in the area of ICTs and the accompanying transformation of our society towards a knowledge society and the fact of an increasing global scientific community that require information systems that enable the organization of collaborative creation and distribution of knowledge.

Added to this is the fact that especially in CH and archeology, the subjects of research—the finds, artifacts, reconstructions, etc. of a certain site—are often located in collections and museums that are scattered all over the globe.

Hence, internationally distributed researchers are working on globally distributed research subjects.

This calls for research tools that are designed and developed in such a way that they contribute to efficient and effective research conditions. For the work with 3D representations in the context CH this means, that the integration of 3D WebGIS methods into VREs with customized capabilities, which accommodate the needs of CH research is a desirable goal.



Capabilities

How can 3D WebGIS Visualization and Analysis capabilities be extended to cope with the increasing demands in the field of CH with respect to the amount, structure and complexity of the data to be processed?

- **Growing amount of data**

  How can web based 3D visualizations and analyses scale up with the growing amount of data that needs to be handled?

  - **Raster data**

    How can spatial raster algorithms be accelerated in order to improve performance and the quality of user experience?

  - **Vector data**

    How can we efficiently perform 3D visibility analyses on large datasets in a web-browser-based environment?

- **Complexity of data**

  How to manage, study and publish complex 3D objects in a web-based research environment?

Integration

How can a 3D WebGIS be integrated into an interdisciplinary web-based VRE for Cultural Heritage research?

- **Component coupling / Usability**

  How can different tools, views and contents of a VRE for CH be linked together in a user-friendly way?

- **Standards and Interoperability**

  How can data from different distributed sources be integrated to share and reuse existing information resources?

- **Multiplicity of respresentations**

  How can we present a comprehensive view on CH objects in order to support the process of knowledge generation?

Figure I.1.2: Overview of Research Questions

On the one hand, this includes the extension of visualization, analysis and data processing functionality of 3D WebGIS and, on the other hand, the ability to use such a 3D WebGIS in combination with other research tools in order to become part of a user-friendly and adapted VRE. These two subject areas: "Extension of Capabilities" and "Integration", form the basis of the research framework of the present work.

RQ 1: How can 3D WebGIS Visualization and Analysis capabilities be extended to cope with the increasing demands in the field of CH with respect to the amount, structure and complexity of the data to be processed?

Many CH Projects produce large amounts of 3D data during capturing of existing objects, e.g. by different scanning technologies (airborne and terrestrial laser scanning or structured light) or while post-processing the captured data with methods like Structure-From-Motion (SfM), which converts a series of overlapping photographic images into 3D point clouds. Furthermore 3D data is produced when decayed buildings or damaged object are reconstructed, possibly in many variants of interpretation and at their different states and conditions over time. The data that is produced is not only large in amount, its structure in terms of data formats is diverse and it's internal semantic structure can be quite complex. Sometimes 3D models of different resolutions for different purposes are generated. And sometimes different representations and formats are created, e.g. point cloud, surface model, volumetric model, parametrized models, raster data, vector data etc. Choosing a data model that adequately represents the complexity of the internal semantic structure of a recorded cultural asset often is a challenge. These examples demonstrate that there are many aspects that have to be taken into account for the definition of capabilities that a 3D WebGIS must provide. And only in their entirety they lead to the desired goal: a 3D WebGIS suitable to be used in CH research context. The first subquestion to this topic is concerned with the amount of data that has to be processed:

RQ 1.1: How can web based 3D visualization and analyses scale up with the growing amount of data that needs to be handled?

In this context paper II.2 is concerned with the question:

RQ 1.1.1: How can spatial raster algorithms be accelerated in order to improve performance and the quality of user experience?

And paper II.4 is about:

RQ 1.1.2: How can we efficiently perform 3D visibility analyses on large datasets in a web-browser-based environment?

In both publications a re-evaluation of existing geospatial analyses and concepts of data reduction and their adaption to altered contexts has lead to new methods that perform well even with limited resources in a web context. This is an important prerequisite to be able to offer 3D WebGIS applications in future VREs. In Publication II.2 the performance gain and the resulting high responsiveness to interactions are particularly important to ensure a high level of acceptance and user satisfaction. Publication II.4 goes one step further than paper II.2 by not only focusing on performance but also on scalability, which means that an algorithm is not only fast on large datasets but additionally is capable to act on datasets that are larger than the available main memory on the device that has been chosen to perform the processing. One possibility to reach this goal is the partitioning of the processing work into smaller "digestible" chunks.

Performance and scalability are important features of a 3D WebGIS. They enable it to deal with large datasets. But, besides the amount of data, the semantic complexity of the research subjects is a challenge. It should be reflected in the structure of the data and also in the way the user can interact with their research subjects through a sophisticated user interface. The user interface should correspond in its design and functionality to the complex semantic structure such that a high usability can be achieved. Therefore, Publication II.3 handles the question:

RQ 1.2: How to manage, study and publish complex 3D objects in a web-based research environment?

This question is related to the requirements of the "Copán" case study, where individual artifacts from archives, built structures in situ and their parts and surfaces regarding inscriptions and ornamentation should be recorded and investigated. The relevant data was captures by airborne laser scanning (ALS), terrestrial laser scanning (TLS) and photogrammetric methods. Additionally CAD-based virtual reconstructions of temples were made from the various individually recorded objects and object parts. The visualization and analysis of the position and orientation of the objects and their parts in space as well as in relation to other structures and surrounding landscape features should be made available in a 3D WebGIS. These requirements result in a number of possible relationships between the objects, the object parts and their associated representations with respect to geometric resolution, semantic interpretations, and possible reconstructions of different states over time. The information associated with an object may therefore be of high complexity, depending on the semantic and geometric structure, the geographical location, and historical changes. This complexity must be reflected in the underlying data structure to ensure efficient storage and retrieval, effective analysis and visualizations with a high degree of usability. The generated 3D models have been hierarchically segmented according to their semantic properties and each segment was given its own proper metadata. For this purpose, a uniform ontology was defined, reflecting the peculiarities of the Mayan architecture. It defined the semantic structure and decomposition of certain architectural units, such as temples or stone stelae into smallest parts such as single glyphs of an inscription. With the help of the segment's metadata further relationships could be established, e.g. to an externally managed object and image database of the German Archaeological Institute, DAI (Arachne / iDAI.Images Link: https://arachne.uni-koeln.de). Besides the research question for the correct data structure for the management of the data, the question of data presentation arises, which on the one hand should support the research process itself and on the other hand should serve for the publication of the 3D models and the corresponding research findings.

RQ 2: How can a 3D WebGIS be integrated in an interdisciplinary web-based VRE for CH research?

The integration or coupling of software-systems and data is a wide field. There are several approaches and paradigms for software integration like, e.g. Enterprise Application Integration (EAI), Service Oriented Architecture (SOA) or Software as a Service (SaaS). All of these approaches aim to bring together different pieces of software which may be specialized for specific tasks, maintained by different groups of people and even running on different platforms and distributed over different servers at different locations. The idea is to create independently usable functional units which can be made accessible through a common user interface that reflects the business (or science) process chains. These are typical procedures that are repeatedly performed while doing research. A special challenge is that in contrast to well defined processes in economic production the research processes in science are often much less predefined and can differ from research question to research question. Basically each scientific "product" is a unique item and its "production process" is unique as well. Nevertheless it is important to identify those tasks or processes that are repeatedly carried out during the research cycles. Furthermore, the development of appropriate tools for those tasks must assure their interoperability such that they can work together with minimized efforts of transforming their exchanged information. Integration of 3D WebGIS comonents into VREs is, what Publication II.1 and II.3 are dealing with. To get closer to an answer of RQ 2 it is subdivided into three further RQs:

- **RQ 2.1:** How can different tools, views and contents of a VRE for CH be linked together in a user-friendly way?
- **RQ 2.2:** How can data from different distributed sources be integrated to share and reuse existing information resources?
- **RQ 2.3:** How can we present a comprehensive view on CH objects in order to support the process of knowledge generation?

RQ 2.1: How can different tools, views and contents of a VRE for CH be linked together in a user-friendly way?

What does user friendly linking mean? User-friendliness or Usability means efficiency, effectiveness and satisfaction while using a system (ISO 2018). This, in turn, means that by finishing the development of a VRE, all of its subsystems and tools know how to communicate and collaborate with each other in such a way that they support the researchers' workflows. During the design phase of a VRE, a selection of tools has to be created which will be used and together form the VRE. This means, first of all, that within an interdisciplinary executed requirement analysis, the work processes are identified, the required data and which semantic logic the research objects and their representing data should follow. The semantic structure of the research objects and the identified work processes can then be transferred to the application logic, which determines how strong the different components need to be linked with each other. Different building blocks of a VRE can be coupled more or less tight or not at all, always depending on how the work processes take place. A so-called loose coupling has the advantage, that only minor dependencies exist between the components. Thus, modifications of individual parts are easier to carry out. As new methods and processes are at the core of scientific work, flexible systems that can accommodate new requirements and thus adapt over time are very important. Only through the adaptability of the systems, their usability and their contribution to the innovative development of disciplines can be maintained.

RQ 2.2: How can data from different distributed sources be integrated to share and reuse existing information resources?

We have argued that the way how VREs are composed is highly dependent on their purpose and that flexibility of the systems is crucial to be able to react on upcoming new requirements. Another topic related and contributing to flexibility is interoperability and open standards. Interoperability can be reached when participating components are able to communicate through a common language, thus sharing a common interface. This could be e.g. one component requesting a service action from another component or the exchange of data whose format and semantic structure is understood by both of them. The standardization and open-specification of such interfaces increases the re-usability of components in different contexts and thus reducing development costs. Furthermore it makes it much easier to integrate data from different and possibly remote sources into several different client applications. This means that the same data source could be used by different scientists in different functionally and methodologically specialized tools to perform domain specific analysis or visualizations. Open standards are an important prerequisite for creating interoperable systems. All four publications of this work use and sometimes extend open standards. Since there was no official 3D geodata standard for visualization until 2017—since then the OGC 3DPS (3D Portrayal Service) exists— the experimental use of a draft version (OGC W3DS) was used and adapted in publication II.1,II.3 and II.4. Missing functions in the draft version were identified and had to be supplemented by own solutions. Open geodata standards have a long tradition, especially interfaces and formats for the exchange and visualization of 2D geodata exist since almost 20 years and are supported by common commercial (e.g. ArcGIS ®) and open-source GIS software (e.g. QGIS ®). This is different for the scope of 3D geodata, where the standardization process took much longer (e.g. OGC 3DPS). According to data formats there is no single universal format that has prevailed. Instead, there are numerous specialized data formats for specific purposes, some of which have also achieved the status of an official or de facto standard. To reach the goal of an integration and interoperability of 3D WebGIS tools in the context of a CH-VRE developers must—additionally to the geospatial standards—recognize data formats, ontologies and interfaces from the area of CH. One important standard, which took over 10 years to develop is the CIDOC-CRM Ontology (a conceptual reference model to describe semantic concepts and relationships for cultural heritage documentation). This model has been adopted as ISO Standard in 2006 and extended in 2014 (ISO 2006; ISO 2014). For machine-readable documentation of texts (e.g buddhistic stone inscriptions, their transliteration, translation and interpretation) the Text Encoding Initiative is maintaining the TEI de-facto standard (TEI Consortium n.d.). Further initiatives try to set scientific quality standards, especially when it comes to 3D Visualization of reconstructed CH goods. For this the London Charter (Denard 2009) defines guidelines to ensure transparency in conveying information in the sense that it must be clearly visible what parts of a visualization is based on evidence and what is based on interpretation. This is intended to avoid the problem that hyperrealistic 3D visualizations are perceived as true and to give scholars the possibility to critically discuss specific parts of such presentations. The ability to attach additional information to 3D model parts is crucial for this and has been solved in publication II.3 through a semantic segmentation approach. To sum up, it is important to note that only the joint support of standards from both areas—geoinformation and CH-information—enables efficient and effective integration of 3D WebGIS into a geospatially enabled CH-VRE. The openness of the used standards is not only important for the current interdisciplinary collaboration but yet as important for the secure access and use of the data in the future.

RQ 2.3: How can we present a comprehensive view on CH objects in order to support the process of knowledge generation?

The third subquestion brings up the topic of the manifoldness of medial representations that research objects can have and which when supported inside a VRE-component can help researchers to develop a better imagination. The main goal of information systems is to facilitate access to information in order to derive knowledge which enables a user to prepare informed subsequent actions. In case of physical tangible CH objects, an information system can at most contain representations of the original. Any such representation is lossy compared to the original. But some characteristics are represented better in one media type and other aspects in another medial form. Each media type has its strengths and weaknesses. Presenting an object in multiple media formats is likely to convey a more complete picture of the original and thus helps to generate knowledge in the perceivers mind. The following list indicates different reasons why it might be necessary to store a multitude of representations for just one semantic entity:

- actual structural changes of the object happened over time (geometric object states)
- changes of object properties, e.g. surface color, surface temperature, humidity, decay, etc. over time (attributional object states)
- the existing knowledge about the object has changed over time (updated versions of object states)
- different interpretations may lead to different hypothetical representations, which might be used as arguments in a discourse (hypothetical states and their updates)
- emphasizing presentation of a certain property, e.g. surface map of decay for restoration purposes
- customized representations for different target groups
- different resolutions and levels-of-details for scale dependent visualizations and contexts (architectural, site, city, landscape)
- transformations for technical reasons to fit requirements of targeted output devices (e.g. mobile vs desktop)

Each representation owns its proper communication goal. In order to fulfill this goal in the best possible way—to convert data into information and information into knowledge—a suitable form, respective a suitable medium has to be chosen which can adequately convey the intended information. To be able to deeply understand a certain CH object, its peculiarities and relationships, and ultimately its meaning, an information system like a virtual research environment must be capable to support and connect multiple types of media and thus present its content in an integrated multimedia fashion. The term multimedia in its everyday usage is heavily occupied by consumer electronics technologies, but here it is meant literally as diversified mediation of information between machine and human and vice versa. Interactive 3D models are just one media type among many. Due to its graphical properties it suits quite well as a user-interface metaphor to link to further related information and representations of different media types. This approach was exploited in Publication II.3 in conjuction with a semantic segmentation and hierarchical ontology. The case study reflected in Publication II.1 explicitly pursued the goal to develop a multi media atlas. Therefore, spatial and non-spatial data was linked through the means of a 2D WebGIS, which facilitated direct access to images, interactive 360° panorama views, different textual representations and georeferenced 3D scenes. The intention was to create a holistic understanding of the presented cultural heritage and its spatio-temporal context.

I.2 Fundamental changes in research practices, workflows, scholarly communication and organization through the adoption of Internet, WWW and Web2.0

The transition from the industrial society towards an information- or knowledge society had and has an ongoing impact on how science works. A driving force in this process are the developments in Information and Communication Technologies (ICTs), which have a strong impact on many aspects of our daily lives. Likewise for the economy, politics and other areas they bring fundamental changes for the sciences as well. They change the way research takes place, how researchers do their daily work and how they approach their research subjects and communicate with colleagues, students and the public (Nentwich 2003; Nentwich and König 2012; Gross and Harmon 2016). This change is known as the "Digital Revolution" or "Digital Transformation" which leads into a so called "Information Age" or "Digital Age" (Stengel et al. 2017) and further to a knowledge society (UNESCO 2005). In the context of science, terms like "Cyberscience", "Digital Science" or "Digital Humanities" etc. exist. The trigger for these changes are the ICTs, especially the widespread use of computers and their interconnection into networks. These networks allow to share computing resources, data, and to perform instant communication and collaboration. Major milestones on this road of "Digital Transformation" are the introduction of the Internet in 1969, the invention of the WorldWideWeb (WWW) in 1989 and the evolution of the WWW towards the Web 2.0 since the early 2000s. In combination with the mobilization of user devices those technologies evolved to a social space where user generated content and social interactions between users on Social Media platforms are predominant.

Nentwich (2003) and Nentwich and König (2012) have examined the impact of ICTs, especially by the Internet and the Web 2.0 on science. The first study from 2003 provides a technological overview and assesses the impact of Internet on science. The second study from 2012 is focused on Web 2.0 phenomena and their impact on science. What we can learn from both studies at this point, are the activities taking place in a research cycle which are involved when it is said "many aspects of a researchers daily work are affected". In a model of "scholarly activities and framework conditions" Nentwich (2003) partitioned those scholarly activities into three interconnected spheres and relates them to a framework of institutional settings (I.2.1). These three spheres encompass "Knowledge Production", "Communication (Knowledge Processing)" and the "Distribution of Knowledge". These are not meant as a strict sequence but rather as activities scopes happening in a forth-and-back in cycles.

The sphere of **"Knowledge Production"** includes core activities of research, like "information gathering", "data processing and analysis" and "data management". The form of all of these activities have changed dramatically. Questionnaires are often completed online, research

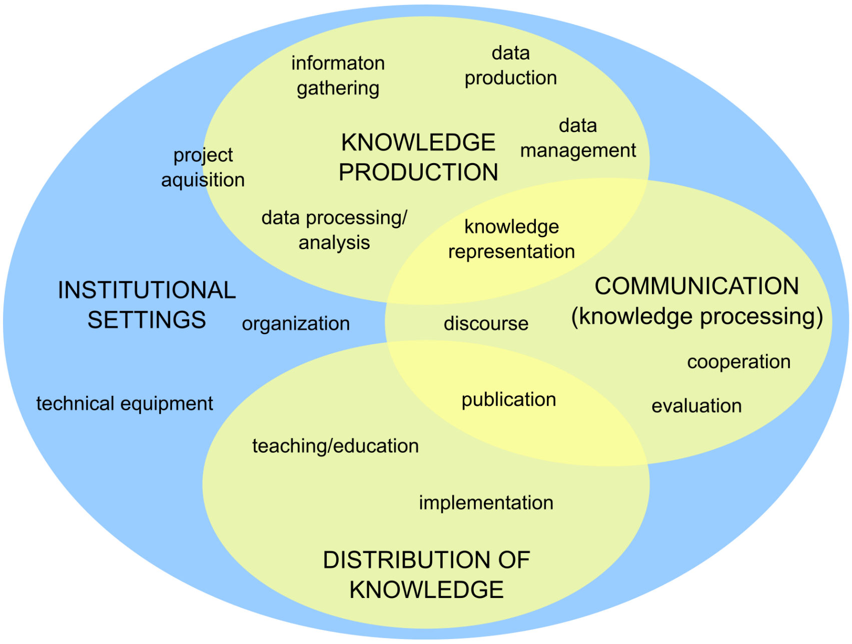


Figure I.2.1: Types of scolarly activities and framework conditions. Source: Nentwich (2003)

databases can be accessed online, lots of publications can be accessed online (often times free of charge as Open-Access publications), observations are made remotely by using sensors which are connected to communication networks like mobile networks or the Internet. And even data that Internet and mobile phone users produce themselves may be accessed by researchers to gather information, may it be produced intentionally as Volunteered Geographic Information (VGI) or unintentionally by just using services like Twitter that besides transmitting a message, stores spatial traces of those messages as Ambient Geographic Information (AGI) (Goodchild 2007; Stefanidis et al. 2013).

Data processing and data analysis is nowadays almost exclusively performed on computers. In addition to the growing power of the researchers PCs the increasing amount of automatically created data has lead to techniques such as distributed computing and cloud computing, which allow for a horizontal scaling[1] of computing resources like CPUs or storage volume.

In the field of data management solutions to share data between project partners are available e.g. web applications like wikis or groupware systems. Long term storage of data beyond project lifetimes can be achieved through the use of data repositories. These also allow to publish data together with their metadata and provide permanent Uniform Resource Identifiers (URIs) that make them globally accessible and hence citeable and reusable.

The **"Communication"** sphere is about knowledge processing among researchers. The produced knowledge has to be discussed between researchers personally, in seminars or at conferences. For all of these situations means have been developed. Communication can take place instantly or with a timely delay, it can be a one-to-one or a one-to-few or one-to-many

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[1] Horizontal scaling means adding computational power and memory by combining several physical computers to one big virtual computation system. In contrast, vertical scaling means putting more resources (RAM, CPUs, Disks) into one physical computer.

Table I.2.1: Typology of electronic people-to-people communication tools in academia

	Cooperation	Publishing
One-To-one	E-Mail E-conferencing tools (bilateral type) chat tools	-
One-To-many/few	Mass E-Mail E-conferencing tools (lecture type)	E-newsletters Homepages Self-publishing
Few-to-few	Discussion lists E-conferencing tools (seminar type) E-teaching tools Groupware, CMS Chat tools	(Discussion lists: skywriting) Project-specific working paper series
Many-to-many	Distribution lists (newsgroups) Link collections Shared databases Software sharing	E-(pre-)print series E-journals Frequently asked questions (FAQs)

Source: Nentwich (2003)

communication or it can be communication for the collaboration of groups at a distance. Table I.2.1 summarizes this in a topology of communication tools in academia.

Finally after discussing and evaluating the knowledge (knowledge processing) between researchers, the newly created knowledge must be distributed. **"Knowledge Distribution"** is represented by the third sphere in Nentwich's model. On the one hand this means publication of the relevant research results to other researchers and on the other hand the knowledge might be integrated in the curriculum of study programs for teaching or it may be implemented as product or advice to decision makers.

Scientific publishing has undergone profoundly changes since ICTs brought the Internet and the WWW to scientists and publishers. Even if the main function of the digital article remains the same as the one of printed articles—explaining research results by means of scientific argumentation—its form, accessibility and interactivity extended a lot (Gross and Harmon 2016). Many Journal publishers allow the authors to add supplementary material like datasets, 3D models or explanatory videos for the replication of experiments. The Digital Article is characterized by being extensively linked internally, linked to external referenced literature and their authors information and has embedded interactive items like tables, charts, maps, 2D/3D animations and rotatable models (Gross and Harmon 2016).

An important and ongoing change in scholarly publication habits is the improvement of accessibility to scientific knowledge by following the conditions of Open Access. The idea of Open Access goes back to an initiative of scientists—the Budapest Open Access Initiative (BOAI)—who declared the promotion of free and unrestricted access to research results as their goal (BOAI 2002). An extension to the BOAI declaration was made in 2003 in the "Berlin

Declaration on Open Access to Knowledge in the Sciences and Humanities" which included the access to Cultural Heritage stored in archives, libraries and museums. Many important german research institutions and cultural heritage organizations have signed the declaration and are working on the fulfillment of the ideas of open access (Max-Plank-Gesellschaft n.d.). The realization of the ideas of the Open Access movement would be impossible to imagine without the existence of the possibilities of communication and reduced costs of electronic publishing.

Further changes in the communication of research results are related the Web2.0 and its possibilities for individual researchers to directly communicate with colleagues and the public and to relate to other scientists with similar interests. Personal websites as publication archives, science blogs and scientific social networks are made possible by the combination of web technology and open access publication policies that allow these ways of knowledge dissemination.

Web technology and the changing view regarding publicly financed scientific outcomes as public goods are trends that fit well to the ideas of Citizen Science. A phenomenon where at different grades of participation citizens from outside of the traditional scientific community take over certain tasks during the research process. For the scope of geographic information See et al. (2016) give a detailed overview. Although Citizen Science existed long before the breakthrough of the Internet, the Web2.0 has stimulated its extension to a wide field of application domains and encouraged a large amount of volunteers to participate.

To sum up, ICTs have brought more and more actors together that are related and involved in the search of new insights to protect natural and cultural resources worldwide or to participate in the planning of our future living spaces. Researchers, engaged citizens, planners and many more stakeholders and desicion-makers need web-based tools to share and collaborate. Among these tools WebGIS in general and 3D WebGIS can play an important role as media type for the communication of space related information.

I.3 Virtual Research Environments as facilitators in a changing world

As we saw in the last chapter, we live in a changing world. A world with an increasing number of scientific actors, publications and complex research topics, often concerned with global phenomena. Topics such as climate change, food security or sustainable development can no longer be handled by individual researchers, institutes or disciplines alone. Remote and interdisciplinary cooperation is essential for this. Especially in the field of cultural heritage the research topics are often influenced by global phenomena. Conflicts, climate change and environmental pressures are threatening heritage sites around the world. On the other side researchers themselves have contributed to the global dispersion of artifacts and the knowledge about it by taking them home into archives and collections from excavation expeditions—in the case of the Maya Site of Copán, Honduras, this has been the case for more than 100 years. In this context, the possibilities offered by the Digital Transformation can be seen as an opportunity to at least virtually make knowledge and cultural assets accessible to research and the general public. Applied properly, the technological developments that have come along with the Digital Transformation can help to master the challenges of distributed and ever-increasing amounts of data. In particular, progress has been made in the areas of database management systems (DBMS) and structuring of information, networking and provision of knowledge using the Internet and distributed information systems, in the field of communication and visualization of data, information and knowledge through a variety of media formats, and in the capabilities of more powerful graphics processing units that can be used for parallelized data processing. Especially the work with 3D data generated by CH projects is demanding with respect to storage, processing, analysis and publication. These requirements can be fulfilled by VREs which are accessible and managed in a sustainable way, kept up-to-date with ongoing developments and maintained beyond the end of project lifetimes to make content searchable and reusable for the future. Supporting all phases of research is the idea behind the term Virtual Research Environment (VRE).

The concept and understanding of what a VRE actually is has developed over a certain period of time. In 2004, the Joint Information Systems Committee (JISC) in the United Kingdom started to explore the concept and context of VREs (Joint Information Systems Committee 2016). Fraser (2005) provides an overview of various JISC VRE projects and the understanding of VREs at that time. The potential of digital support for research processes was also recognized in Germany, so that in 2008 the priority initiative "Digital Information" (also known as Alliance Initiative) was founded by the Alliance of German Science Organizations. The aim of this initiative is "... to design a research and development strategy to help scientists build up discipline-specific and interdisciplinary networked digital research infrastructures called 'Virtual Research

Environments' (Allianz-Initiative 2008, translated by the author). In the mission statement "Leitbild 2013-2017" (Allianz-Initiative 2013) the Alliance Initiative has developed its own definition of VREs [translated by the author]:

> A Virtual Research Environment (VRE) is a work platform that allows collaborative research by multiple scientists in different locations at the same time without any restrictions. In terms of content, it potentially supports the entire research process—from collecting, discussing and further processing the data to publishing the results—while being technologically based primarily on software services and communication networks. Virtual Research Environments are essential components of modern research infrastructures and play a crucial role in the productivity and competitiveness of research.

An overview of the discourse about VREs can be found in Candela et al. (2013) and Bender (2016). The latter summarizes that VREs are a combination of information-, documentation- and collaboration systems. The abstract goals of efficiently supporting researchers and their various work processes are thus clearly defined. But what does this mean in a specific case? Depending on the research question, disciplines and composition of the user group, VREs can be very different in their design. The goal must therefore be to provide individual components as reusable infrastructure in the form of services. Generic and commonly needed components should then be individually linked to the specialized toolset of specific research areas to ensure the best possible working environment during the research phase, as well as sustainable maintenance of the generated knowledge after the end of the active period of a research project. The individual research infrastructures and services can be provided by different organizations at different levels. It would be sensible to locate general functions centrally at a high level, e.g. the storage of research data and their long-term archiving, as well as systems for searching and retrieving this information. In contrast, highly specialized services and tools should be administered and, if necessary, improved and further developed by the local research groups and their research institutions until matured and usable for a broader audience.

The research, development and deployment of research infrastructures (RIs) as a prerequisite for the compilation of VREs in the area of Digital Humanities took place at roughly the same time as the two projects "3D Sutras" (II.1) and "MayaArch3D" (II.3), which provided the case studies for this work. Since then, many RIs and VREs have been developed at the national, EU and global level. For the field of Digital Humanities, DARIAH-EU[1] with its German counterpart DARIAH-DE[2] deserve special mention. It has been sponsored since 2008 and will be merged in 2019 with the project CLARIN-D[3]—a linguistic RI— into CLARIAH-DE. Numerous different tools for storing, analyzing and visualizing different types of data are provided, but the field of geodata is only weakly covered. A 2D geobrowser enables the visualization of own datasets. The display of spatio-temporal 2D data sets is possible, too. However, the area of 3D WebGIS is completely missing. Another EU-funded project is ARIADNE, a network of

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[1] `https://www.dariah.eu/`

[2] `https://de.dariah.eu/`

[3] `https://www.clarin-d.net/de/`

archeology stakeholders dedicated to develop infrastructure for the management and integration of archaeological datasets at the European level. ARIADNE+ has entered a new 4-year funding period since the beginning of 2019 and is currently the most advanced german RI in terms of 3D WebGIS in CH. Two services deserve special mention: "ARIADNE Visual Media Service", which among other datatypes allows uploading and visualization of 3D models, and the "ARIADNE 3D Terrain Service", which allows large digital terrain models and overlays to be uploaded to a cloud storage. The data can then be automatically preprocessed and optimized for display in a web browser. In addition, annotation layers can be created to locate text, images and other media inside the terrain model. Part of the ARIADNE network is the German Archaeological Institute (DAI), whose infrastructure was also used in the project MayaArch3D for parts of this work. Currently a European Research Infrastructure for Heritage Science (E-RIHS) is being planned which will integrate existing research infrastructures. According to the ESFRI Roadmap 2018, it should be available by 2021 (Striova and Pezzati 2017; ESFRI 2018). All this demonstrates that, on the one hand, the will and the demand exist to build up the infrastructure for virtual research environments and to develop corresponding tools. However, it also shows that there is still great potential for improvement in the area of WebGIS and particular 3D WebGIS for CH VREs. This work exemplifies some of the possibilities how research tools for future research tasks in CH VREs can be designed by implementing new methods as proof of concepts.

I.4 The role of 3D WebGIS in knowledge-production, -communication and -dissemination in the context of Cultural Heritage

In the chapter before we have seen that there have been made great efforts by national and international organizations to provide flexible research infrastructures (RIs) for science in general as well as for Digital Humanities and CH. While it is still an ongoing process to find out which composition of components and services is needed for VREs that optimally support the research tasks of different disciplines and research teams, there is also a need of understanding what tasks and activities 3D WebGIS components can support in the research process and how. Which are the functional roles that a 3D WebGIS can take over to facilitate scholarly activities in the context of CH?

The roles that a 3D WebGIS can take are manifold. They can be derived from the activities in the various research phases and the respective communication situations which may arise during those activities. The communication situation is determined by the question of who communicates with whom, where and how. Based on the activity model of Nentwich (2003) I.2.1, a synoptic overview will be given which relates the activities and their outcomes, as well as the possible communication contexts in which the activities take place. As a result, various roles that a 3D WebGIS can play in the research and communication processes will be derived.

Before describing the details of each activity, it is important to understand what research subjects are being investigated in the area of CH in order to understand what kind of information could potentially be handled using a 3D WebGIS. Fless et al. (2016) created a figure I.4.1 about those. They distinguish between tangible and intangibles on one side and immoveable/outdoor and movable/indoor CH resources on the other side. Between material things and immaterial concepts, people and arts are included as living heritage.

It is in the nature of things that 3D technologies in CH are mostly used for tangible resources. The progressive development of capturing methods in this area has also contributed to this. However, immaterial concepts, such as the spread of cultural or religious ideas or even movement patterns of culturally significant personalities can also be modeled and displayed in geographic information systems.

In the phase of "Knowledge Production" (Figure I.4.2) different activities take place, all of which contribute to the production of knowledge. However, their results differ in quality. First of all, 3D primary data from tangible resources can be captured using sensor-based capture methods. Numerous technologies are available for this purpose (e.g. ALS, TLS, SfM). Such a recording e.g. using a terrestrial laser scanner or a drone with camera equipment requires prior planning. With the help of a web-based 3D GIS this can happen collaboratively with participants

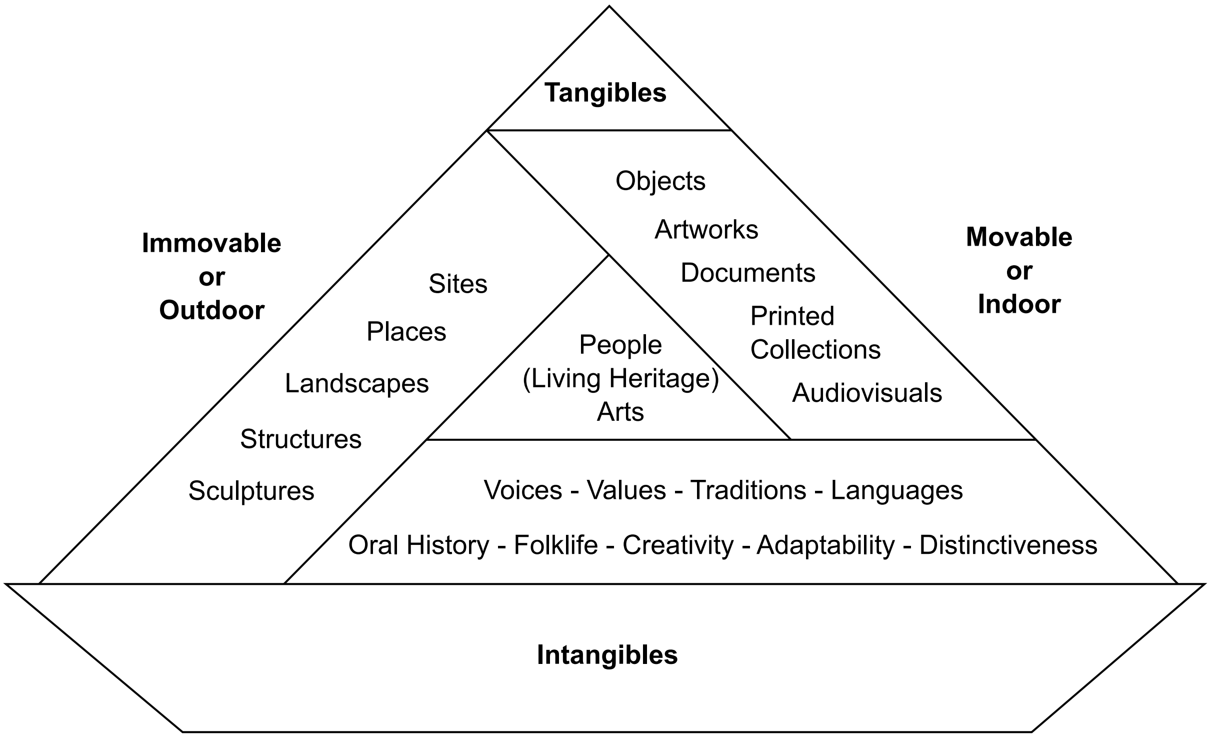

Figure I.4.1: A holistic representation of cultural heritage resources. Source: Fless et al. (2016)

who work in different places at their respective institutions. Thus, during planning, all survey relevant information, e.g. adjacent residential areas or roads, can be collected and shared by each other. Additional 3D datasets may be created during the planning by a simulation of the capture process. Such simulations may improve the capture quality and efficiency in the field and may be supported by simulation software like Helios for laser scanning recordings (Bechtold and Höfle 2016). Later, while performing data collection in the field, it is important to check the recorded data as quickly as possible, preferably in real-time, so that the survey team can react quickly and minimize the precious time required for repeated measurements. The second important activity during data acquisition is the documentation of the recording itself. This is especially true where invasive methods are applied, such as archaeological excavations which carry a risk of damage or destruction. Therefore, normally the entire excavation process is recorded in the form of 3D excavation layers. This allows for a analysis and exact reconstruction of the spatial configuration of the individual finds afterwards. Another beneficial feature of a 3D WebGIS that is distributed over the Internet is to share 3D information during the excavation with remote experts. This can help to make difficult decisions about how to proceed with the salvage of threatened finds. Another activity is monitoring, where repetitive recording takes place over a longer period of time. Often, sensors and gauges collecting 3D data are firmly installed in place to monitor slow processes, such as subsoil or masonry movements of a building. These data can also be transmitted via Internet and evaluated independently of location by experts using a WebGIS.

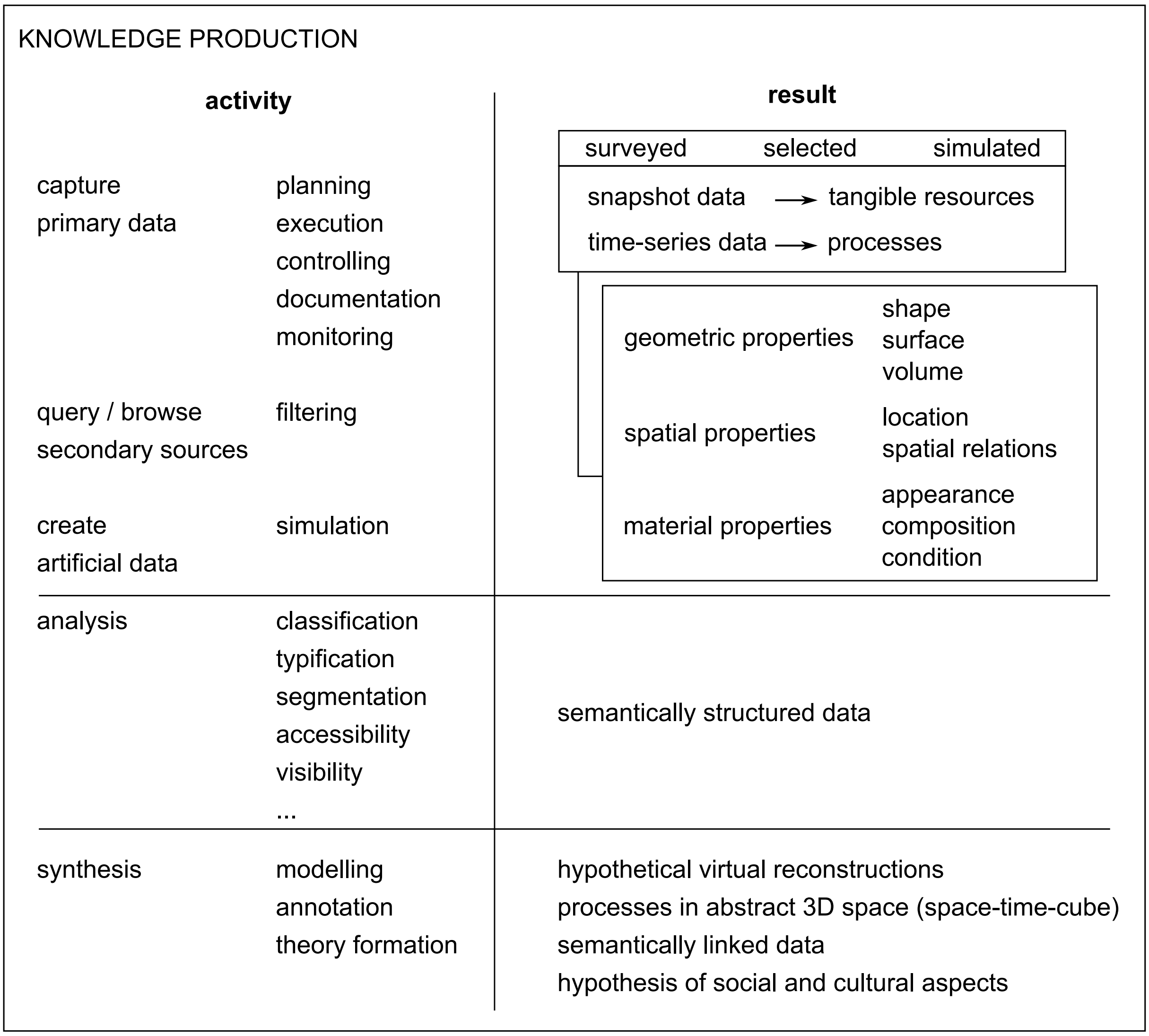

Figure I.4.2: Knowledge Production in the context of Cultural Heritage.

Another form of information retrieval is the query of secondary sources by means of an information system, e.g. a museum database or repository for 3D CH assets. In addition to filtering for textual properties, a geoinformation system offers extended possibilities of selecting according to spatial or geometric properties. Web-based access to such a system allows the stored information to be incorporated into VREs providing access via a 3D WebGIS interface. In this context, a segmented or annotated interactive 3D model can also play the role of a visual user interface by using spatial properties for the queries as an organizational principle. This makes the exploration of data very intuitive. An example of this can be found in Publication II.3.

As a result of capture, query, or simulation, the researcher receives data that can be analyzed, interpreted, and synthesized to new knowledge. Whether sensored by technical equipment, selected through spatial, temporal or other properties or simulated, these data represent a specific temporal state or a temporal process of change of the examined objects. By analyzing this partly unstructured and noisy data it is converted into semantically structured data as a result of classifications, typifications or segmentation according to geometric, spatial, material or other recorded characteristics. In the synthesis of this structured data, new hypotheses, theories, and knowledge can emerge that can be modeled, e.g. by hypothetical virtual reconstructions, which in turn again generates new data that can be experienced and communicated using a 3D WebGIS.

This newly created knowledge can only have its effect by being communicated. In the phase of "Knowledge Dissemination" (Figure I.4.3), for scientists this means, first and foremost, the publication of research results in scientific journals or books. Some publishers allow the publication of 3D models as supplementary material, which can then be viewed or downloaded in the online edition of the article (Elsevier n.d.). However, these are usually simpler 3D viewers, true 3D WebGIS applications in this context are unknown to the author. In addition to the publication through scientific publishers, the results are often made available as 3D assets in digital archives. This is beneficial for scientists but also for many other target groups, e.g. in public education for teachers, students and tourists. The results of the "Knowledge Production" in CH are also of great importance to CH management, who are in contact with city planners, construction and conservation companies and many other stakeholders. They can use CH data and 3D WebGIS also as decision support systems. Last but not least, publicly shared 3D models can be used economically, for example, for the 3D reproduction of art historical objects and motifs to be traded on the market.

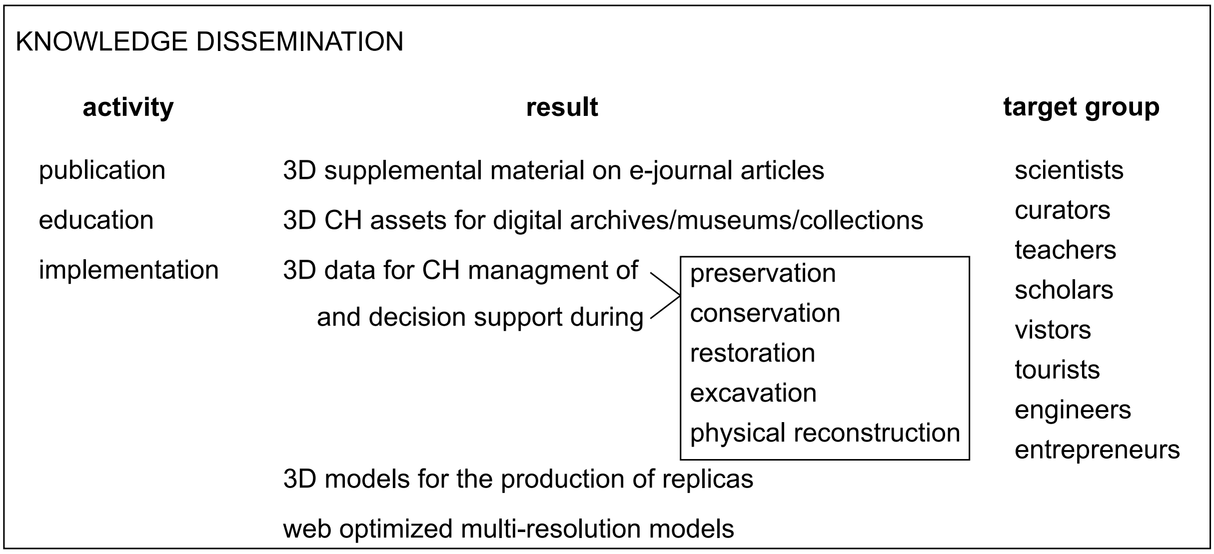

Figure I.4.3: Knowledge Dissemination in the context of Cultural Heritage.

All actors within the process of Knowledge Production and Dissemination must communicate with each other about CH resources. A web-based 3D GIS can support these very different kinds of communications between scientists themselves, between humans and computer systems and between all other user and target groups to convey 3D information in its most natural way, as 3D visual impression. But its not only the information needs of the different actors that are supported. The web-based nature makes a 3D WebGIS independent of operation systems and thus provides the flexibility to be used in a wide range of communication devices in completely different usage contexts (Figure I.4.4).

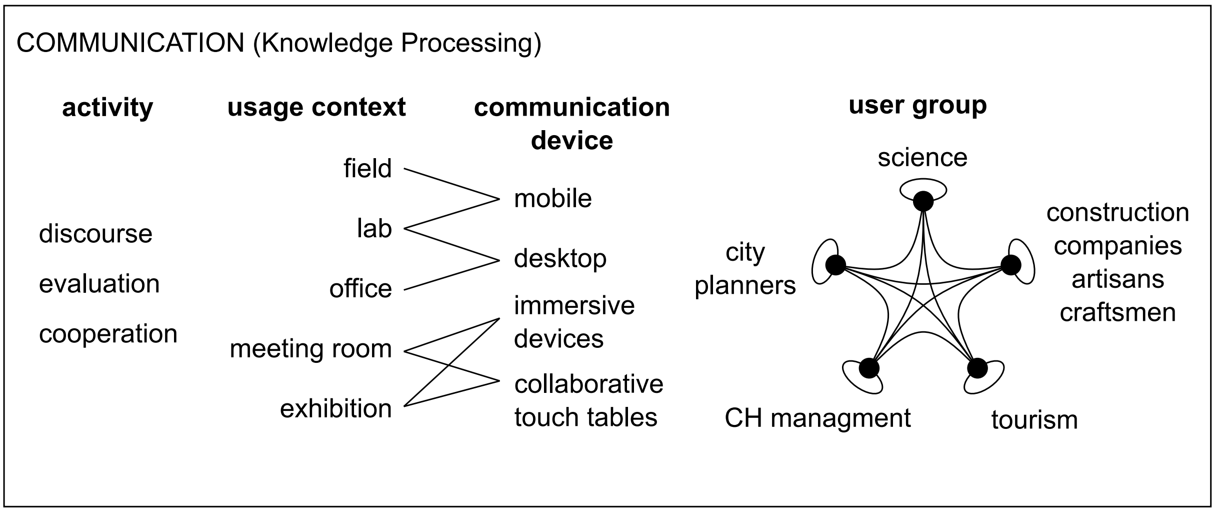

Figure I.4.4: Communication in the context of Cultural Heritage.

To conclude 3D WebGIS can play many roles in "Knowledge Production" and "Knowledge Dissemination" as a communication facilitator. It can be used outdoors in the field as well as indoors in the labs and offices of sometimes remote working colleagues. It can take over the function of a decision-support-system during excavations but also for CH management in contact with city planners and conservation companies. It can be a visual user-interface to interactively express queries for related information, documents, and linked data. It can be part of a documentation system or CH content management system. Furthermore it can serve as base of discussion in meeting rooms or exhibitions using collaborative touch tables or other immersive devices. And finally it can be a source of infotainment for visitors of museums aiming to foster the understanding and appreciation of our current culture by better understanding our past. It can be said, that 3D representations and web-based geoinformation systems can help raising buried treasures from the real world and from magazines of archives and museums.

I.5 Scientific Contributions

In the following chapter the main contributions of the four publications are discussed in the context of their origination and the respective RQs formulated in Section I.1.2. The detailed results are to be found in the original published articles, attached to this work in Part II.

I.5.1 Integration of 3D WebGIS into an Interdisciplinary Multimedia Cultural Heritage Virtual Research Environment: The case of "3D Sutras"

Publication II.1:
M. Auer et al. (2011). ‘3D-Sutras: A web based atlas of laser scanned Buddhist stone inscriptions in China’. In: *Online Proceedings 2011 of the 14th AGILE International Conference on Geographic Information Science - Advancing Geoinformation Science for a Changing World*, p. 8
RQs: 2.1, 2.2, 2.3

Publication II.1 of this work was produced during the research project "3D-Sutren – Interaktive Analysewerkzeuge für einen Web-Atlas gescannter Sutratexte in China" (engl.: 3D Sutras - interactive analysis tools for a web-atlas of scanned Sutra texts in China). The aim was to create a VRE to document, analyze and archive Buddhist stone inscriptions from various sites across China. It was conducted from 2008 to 2011, a phase where Web 2.0 already started and was characterized by user generated content (UGC) platforms—like Wikipedia [1]—and services for remixing content of different sources into mashups (e.g. Google Maps®). Social Networks were still in its infancy, at least in Europe. Some of the important geospatial standards of the Open Geospatial Consortium (OGC) for presentation and exchange of geodata were already in place (OGC WMS, OGC WFS, OGC WCS). The nowadays most important building block of web 3D applications, the WebGL Standard (Khronos Group 2011) was not yet available, so that the 3D spatial data infrastructure (SDI) developed for the interdisciplinary research platform for documentation, interpretation and presentation can be seen as a pioneer project. In its interdisciplinary layout it revealed the insight that standardization across disciplines is of crucial importance to integrate data and tools of different research domains into one virtual research space. Further, an interdisciplinary exchange of methods (e.g. terrain analysis methods to enhance readability of carved stone inscriptions, the graphical layer concept of GIS as interactive

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[1] `https://www.wikipedia.org/`

visualization tool for graphical annotation of inscription texts) opened up new potential with respect to access, organization and perception of data. The VRE that was developed in close connection with the later users demonstrated the importance of integrating and linking tools and content by loose coupling of the components, such that the current state of one component was used to initialize another component showing the related context right away. The multi-media approach presented in publication II.1 has proven advantageous for the comprehension of a CH topic that relates to multiple scales. At first there are the inscriptions themselves which where scanned with sub-millimeter resolution to be able to analyze the geometric properties of each symbol of the texts, a special text reading tool used these properties to enhance the readability of sometimes eroded surfaces. A single Sutra text could be separated into several chapters and annotated with additional information, the delineation of the chapters could be visualized using an OGC Web Map Service and a Web Map Client in a completely new way. Instead of geographic coordinates, the cartesian coordinates of the text image could be used to reference overlays and apply the GIS-typical layer concept for organizing and visualizing corresponding textual information. The next scale to support was the direct spatial surroundings of the inscriptions, some of which where located inside stone caves, these were represented as interactive 360° panoramic views. Then the spatial relations between the caves on a inscription site constituted the next scale to be presented, analyzed and understood. This could best be presented as multi-resolution 3D scene and alternatively as cave map in a 2D WebGIS view. Finally the relations of the inscription sites across China made up the macro scale which was presented together with additional context data in an interactive 2D Map.

I.5.2 Visualization of Complex data, Multiplicity of Representations, Interoperable Standards and Usability: The case of "MayaArch3D"

Publication II.3:
M. Auer et al. (2014). ‘Web-based Visualization and Query of semantically segmented multiresolution 3D Models in the Field of Cultural Heritage’. *ISPRS Annals of Photogrammetry, Remote Sensing and Spatial Information Sciences* II-5, pp. 33–39. DOI: `10.5194/isprsannals-II-5-33-2014`
RQs: 1.2, 2.1, 2.2, 2.3

Publication II.3 was created in a similar but slightly different context than publication II.1. It was an outcome of the interdisciplinary project "MayaArch3D - Ein webbasiertes 3D-GIS zur Analyse der Archäologie von Copan, Honduras" (engl.: MayaArch3D - a web-based 3D-GIS for the Analysis of the Archaeology of Copan, Honduras). This project took place from 2012-2015, a time where the important standard WebGL (Khronos Group 2011) was freshly published and at least partial support of the major browser manufacturers was implemented. This new standard played an important role for the development of the different 3D components of the virtual research environment. The overall goal of the project was to find solutions to manage, publish and study 3D data from heterogeneous quality and sources in an integrated way. A 3D single object viewer for artifact details, a 3D scene viewer for details of the archaeological site and it's surrounding landscape with information to hundreds of reconstructed buildings and structures, like temples and stelas, was combined with a 2D WebGIS component for an even wider context with information on all known Maya settlements in Mesoamerica and other maps of the site. All three GIS components were connected to an archaeological database, where the involved scientists could enter a vast amount of details on any kind of archaeological entities which were modeled in an ontology as extension of the standard model of the German Archaeological Institute (DAI). For this linkage of information of the archaeological database to the 3D models a solution for the user interface had to be found. The challenge was the complex semantic hierarchy of information which had to be attached to parts or segments of a 3D model and also hierarchically to groups of segments which together form a higher entity in the ontology. For example a glyph is part of a text which is part of a stela side, which itself is part of a stela etc. and each of these levels have their own database entries. Publication II.3 describes a solution for the storage, query and presentation of such complex data.

I.5.3 Performance & Analysis: Geospatial raster processing speed-up through browser-based parallelization

Publication II.2:
M. Auer (2012). 'Real-Time Web GIS Analysis Using WebGL'. *International Journal of 3-D Information Modeling* 1 (3), pp. 49–61. DOI: `10.4018/ij3dim.2012070105`
RQ: 1.1.1

It's a general aim to reduce waiting times in web-based applications to improve user-experience. Beyond that, a massive acceleration of geospatial processes does not only improve the responsiveness of a WebGIS application but allows to come close to a real-time WebGIS. At the same time it allows to bring functionality to the web, that before were only available to desktop applications and thus enabled their potential integration into VREs. Publication II.2 demonstrates how existing methods can be rearranged and evaluated in a new technological context and how this can lead to a completely new usage and user experience. As an example to demonstrate the approach of WebGL-based parallel spatial raster analysis, a well-known hillshading algorithm by (Horn 1981) is reimplemented as a fragment shader program as part of the programmable WebGL rendering pipeline (Khronos Group 2011; Khronos Group 2010). The result of the proposed method was evaluated by a comparison of the conventional sequential computation and the proposed parallel computation and was tested on different mobile and desktop browser environments. The method yielded acceleration factors between 25 and 100 depending on the browser environment.

I.5.4 Performance, Scalability & Analysis: 3D vector-based Line-of-Sight analysis on large datasets in a web-browser environment

Publication II.4:
M. Auer and A. Zipf (2018). ‘3D WebGIS: From Visualization to Analysis. An Efficient Browser-Based 3D Line-of-Sight Analysis’. *ISPRS International Journal of Geo-Information* 7 (7), p. 279. DOI: `10.3390/ijgi7070279`
RQ: 1.1.2

Publication II.4, like publication II.3 was an outcome related to the project "MayaArch3D". While in publication II.3 the main topic was about the storage, transmission and user-friendly query of complex semantically segmented multi-resolution 3D models, the focus of this publication is the enabling of 3D WebGIS applications to be used as real online analytical tools and not just as visualization containers of prepared content. There are two main problem areas to be solved for that. One is improving the timely performance of an analysis, which is especially important in the web context where users are used to retrieve instant results and the second is scalability. Scalability means that the consumption of memory resources should be—in the best case—independent of the size of the input and output datasets such that the application can run on differently powered client hardware without crashing. This second problem area is again particularly important in the web context, because a supplier of such web based analysis software is unable to know beforehand under which circumstances it will be executed. A new holistic perspective on the problem scope is presented in Publication II.4 which opens up new possibilities for optimization. Rather than focusing on the optimization of the visibility algorithm itself, the whole situation which arises from the application of the algorithm in a web context, is taken into account. By adapting the analysis logic to strategies known to work for large datasets in visualization, like compression, tiling, streaming and caching it could be demonstrated that the main problems of performance and scalability could be solved for a browser-based 3D Line-Of-Sight analysis. The motivation for solving this specific Line-Of-Sight analysis is the need for further and more complex visibility analyses in which the Line-Of-Sight analysis can be used as a building block, e.g. for testing a visibility based communication network that might have existed in the ancient Valley of Copán, Honduras.

I.6 Synopsis and Conclusions

The aim of this study was to advance 3D WebGIS as a means of visualization, analysis and communication between humans themselves and their machines. Further it was concerned with the integration of highly customized 3D WebGIS applications into Virtual Research Environments (VREs) for Cultural Heritage (CH). Two interdisciplinary research projects served as case studies for this thesis.The first project aimed for the creation of a VRE for the documentation, analysis and publication of Buddhist stone inscriptions—the Stone Sutras. The second project likewise focused on the establishment of a VRE for the archaeological study of the Maya ruins of Copán in Honduras. In both cases multiple types of media formats were used for the documentation of the CH resources. 3D representations as digital assets where just one of them among textual documents, images, drawing, maps and others. Georeferencing—the anchoring of 3D representations in a spatial reference system—extends the possibilities for visualization, analysis and combination with additional spatially referenced information and the communication about them. This is what a 3D GIS facilitates. Bringing this functionality into the Web further extends the possibilities of working with, and sharing of, 3D space-related information. It opens up new ways of collaboration, efficient workflows, knowledge dissemination and public outreach.

Four publications have been presented which contributed to the two major research topics of this thesis: "Integration into VREs" and "Extension of Capabilities" of 3D WebGIS applications in the context of CH. The individual research questions (RQs) are presented in Section I.1.2. The contributions of the individual publications to those RQs can be found in Chapter I.5. This chapter is dedicated to give an holistic view on the thesis' topic by relating the outcomes of the single publications with each other in order to derive a synoptic summary. Finally, the chapter is closing with the main conclusions of the thesis.

I.6.1 Synopsis

In this section, the most important findings of the four publications are being put into relation with each other and presented in an integrated synopsis.

Publication II.1 sets the baseline for the succeeding publications. It demonstrates the basic structure of a VRE for CH. This structure is characterized by flexibility, sustainability and openness to innovations. It combines spatial and non-spatial data and software tools to integrate the strengths of different disciplines involved in CH research. It makes use of a rich set of media types, including 3D WebGIS, to support the communication of the varying characteristics of CH assets and their spatial and historic context. It was designed to be distributed over the World Wide Web, encouraging international cooperation and collaboration.

To be flexible in terms of integration and exchange of functional entities, the VRE is implemented using a 3-tier-software-architecture. This architecture pattern reduces dependencies between components of the application such as persistent data stores (e.g. database), data access and processing services (e.g. map service) and the application client (e.g. fat client including application logic and presentation layer).

Conformity to standards and openness to innovations are somewhat contradictory to each other. On the one hand it is a good practice to follow established standards because they enable interoperability between software components of different provenience. For example using a well known data format increases the possibilities to use one and the same source again and again in different software and in different research contexts. Using the same standardized way to describe CH assets, e.g. using the Dublin Core Metadata Standard (ISO 2017) or the CIDOC-CRM Ontology (ISO 2006) enables the merging of decentralized managed archives into centralized queriable entrypoints for multi-database searches across thematically affiliated institutions. So building upon standards is an important and useful strategy but on the other hand it hinders the use of cutting edge technologies that might provide new ways of knowledge production but doesn't fit to the established standards. In the end, it comes down to a trade-off between the two goals. This conflict can be alleviated somewhat by trying to provide transformation procedures to at least archive and document the outcomes and the access to the innovative tools in standardized ways such that the innovations can be tested and evaluated by the research community. If considered as useful and adopted by the community such innovations might be standardized in the future.

Following this conception, the VRE for the project "3D Sutras" combines standardized data formats from the geospatial domain as well as from the Digital Humanities. Equally, it integrates database management systems (DBMS) from both domains. And, it mixes data and software from both domains to provide new functionalities in unexpected ways.

However, at this stage the VRE uses the 3D WebGIS component mostly as a means of visualization, integrated by being linked from other tools and views of the application. The central point of access and content organization is the 2D WebGIS component II.1.3. Nevertheless, the presentation of the spatial context of the Buddhist Stone Sutras, in its most intuitively way, as virtual 3D scenes, enriches the portfolio of knowledge representations for their study and documentation.

Publication II.2 is dedicated to the acceleration of geospatial raster algorithms using the parallelization possibilities provided by the graphics processing unit (GPU) of a computers graphics card. This has become possible through gaining direct access to GPU-processing from within a web-browsers programming environment in a standardized way by the introduction of the WebGL Standard in 2011 (Khronos Group 2011). The WebGL Standard defines an API (Application Programming Interface) for web developers, which allows to define so called shader programs, which can be transfered from a website to the graphics card and will be executed in specialized processors, which are highly optimized for graphic operations and pixelwise parallelization. The capabilities of such shader-based computations were exploited to demonstrate the browser-based real-time computation of a hillshade algorithm. The possibilities opened by the presented method is directly related to publication II.1 and the VRE for "3D Sutras". For the involved researchers of the the project "3D Sturas" a special text reading tool was developed and integrated into the VRE by project partners from i3Mainz[1] (Schmidt et al. 2010). This text reading tool aimed for the improvement of th readability of the encarved sutra texts, that were scanned and transformed to a rasterized digital elevation model (DEM). Several algorithms, originally developed for terrain analysis (hillshade, waterfilling, height based color classification), were implemented for an interactive visual analysis of the 2.5D text surface. The realization of this tool required a lot of effort. An external application had to be implemented requiring additional software installation for the users and a laborious preprocessing of the data was necessary to achieve real-time responsiveness. With the approach of publication II.2 this effort could be massively reduced. No extra sofware or plugins needed, no special preprocessing of surface properties (normal vector pixel encoding) for real-time performance and completely integrated into the web application in a standardized way. These are the benefits a future realization of a similar tool would gain from the results of publication II.2.

Another relation can be drawn from publication II.2 to the project "MayaArch3D" and its 3D WebGIS component. Although not part of the publications in this thesis, the concept of shader-based geospatial analysis was applied by the author to develop two 3D orientation analyses. These can be used to determine either the orientation of 3D surfaces towards compass directions or towards a user-defined target point. Both analyses have been implemented and integrated into the MayaArch3D-VRE, presented at the AGIT Conference in 2016 (Auer et al. 2016) and made publicly available as open-source software included into the GIScene.js[2] 3D WebGIS framework.

The topic of **publication II.3** is related to the VRE created for the project "MayaArch3D". The basic concept for this VRE was similar to the one for "3D Sutras", presented in publication II.1. Namely, a web-basesd composition of tools to support the scholarly activities. This time the activities of an international team of archaeologists, who were concerned with the CH of the ancient Maya city of Copán, Honduras. However, the requirements regarding the handling of 3D data were far more ambitious, more diversified and had to be adjusted towards archaeological issues. A major concern of the project was the documentation, analysis and publication of built structures, like houses, temples, stone stelas and altars. Like in the "3D Sutras" project the range of scales in which the archaeologists operated was large. From landscape, over settlements, single built structures of varying types, up to structure parts above and below surface and single inscriptions and sculptured motifs. 3D models of different Levels-of-Details have been created and segmented according to semantic entities. Some of the structures were additionally reconstructed as hypothetic 3D models. To handle the storage, transmission, query and visualization of such complex multiscale and multirepresentational data, new methods had to be developed. As pointed out before, for the implementation of a VRE, sustainable standards-based solutions should be preferred where possible, but this must not lead to a denial of novel approaches. Scientists working with VREs must be able to keep up its innovativeness

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[2] `https://giscience.github.io/GIScene.js/`

by allowing them to integrate customized solutions where needed. The flexible service based 3-tier architecture presented in publication II.1 enables this flexibility here, too. In our case only a combination of the OGC candidate specification W3DS (Schilling and Kolbe 2010) and custom service implementations to request 3D models and related archaeological properties by an object identifier could finally provide the necessary functionality for the query and visualization of semantically segmented multiresolution 3D models. In the meanwhile, in 2017, a new standardized OGC service specification—the OGC 3DPS—has been accepted and published (Hagedorn et al. 2017). It provides exactly the missing functionality for querying 3D data by object identifier. It replaces and extends the older W3DS candidate specification such that a future VRE can be realized in more sustainable and standardized way.

The visibility analysis presented in **publication II.4** efficiently computes the Line-Of-Sight between two points in 3D space, considering potential obstacles from multiple 3D layers. It is, like the raster analysis method from publication II.2, an enhancement of the analytical GIS capabilities for the Web. Instead of browser-based raster data analysis, this approach of publication II.4 extends the capabilities in the area of vector data analysis in 3D space. The methodology of both publications are evaluated using examples—Hillshading and Line-of-Sight—but are not restricted to those. Rather than their specific implementation, it is the way how they are implemented what represents the decisive contribution. Both concepts can be transfered and used as basic strategies to implement further efficient geoalgorithms. Hence, publication II.4 complements the capabilities of 3D WebGIS and paves the ground for future research.

Publication II.4 also relates to publication II.1. Its efficient implementation partly relies on strategies for large data visualization already used in the 3D component of the "3D Sutras" VRE. Adapted to the needs of the Line-Of-Sight analysis those strategies contribute to the performance and scalability of the algorithm. The adapted strategies include data partitioning (tiling), client side data caching and asynchronous concurrent loading (streaming). Publication II.4 optimizes the loading strategy to avoid superfluous and slow data transmissions and uses data partitioning to reach scalability in the sense of a constant consumption of memory.

I.6.2 Main Conclusions

The achievements presented in this thesis and its four publications were targeted to advance 3D WebGIS applications in two main aspects. First, the "extension of capabilities" to fit the needs of interdisciplinary partners from different fields of CH and more generally to develop and evaluate methods that allow to efficiently perform spatial analyses under the special conditions given in web-based, distributed architectures. Second, the "Integration" of such 3D WebGIS applications into a composition of interrelated tools and services that together make up what is referred to as VRE. The combination of the presented results in both areas enable the establishment of integrated browser-based 3D WebGIS components for CH-VREs to support different interdisciplinary and collaborative scholarly activities in an open, flexible and sustainable way.

I.6.2.1 Why do we need VREs and why do CH researchers need 3D WebGIS to be integrated in their VREs?

The background for the first question—Why do we need VREs?—was discussed in Chapter I.2. Fundamental changes in society and science have been caused from various influencing factors. One main driving force are the developments of ICTs. Especially the developments that came along with the availability of the Internet created a new virtual social space, where people and particular scholars can act and interact with each other. This way, more and more data is being collected and shared and needs to be transformed into knowledge to make use of it. Besides dealing with more data, more globally distributed actors participate in research. Partly because of the economic development of highly populated countries like China and India, which invested heavily in science and education and appear as new serious actors on the previously western dominated stage of science (The Royal Society 2011). A third factor is the growing number of urgent global phenomena in environmental, social and economic areas, that also cause pressure on the preservation of CH, and that call for solutions based on global collaboration. To sum up, it's globally distributed research scopes, globally acting scientists and globally distributed data that must be brought together and VREs are a possible solution to create a common and efficient workspace to access, process and publish the necessary information to create new knowledge.

The answer to the second question—Why do CH researcher need 3D WebGIS to be integrated in their VREs?—is straightforward, while its conceptual and technical implementation is not. CH sites and objects do have a spatial context and their physical bodies are inherently 3-dimensional. 3D models in CH fulfill several important functions, e.g. as means of documentation for a future restoration in case of damage, as means for monitoring of slow processes and forecasting of damage risks, for the documentation of context and origin of finds during excavations, for measuring and analyzing remotely and without physical contact to the original and as representations to share virtual access to the public or create physical replications. Thus, creating records of CH sites and objects which include 3D representations is a useful complementation to the previously existing documentation methods. Things of cultural importance have been created somewhere, sometimes they have moved to other places by trade or spoils of war. Finally, they have been found again (or not yet) and brought to other places for examination, conservation or exhibition. Immovable CH like settlements, buildings or building parts own a spatial configuration and may have intentional spatial relations between each other, which may give insights into social values and organization of long-lost cultures. These examples already show that geographic issues are an important part in the search of understanding the past and thus it is important to have appropriate tools, like 3D WebGIS applications, to work with.

I.6.2.2 Conclusions about advancing 3D WebGIS for CH

Strenghten the support of geographic research tools in CH VREs

The implementation of open, flexible and interoperable 3D WebGIS for CH does not only depend on the software itself and the software architecture, but on the available infrastructure on which the system may be deployed. Chapter I.3 describes in more detail the developments of RIs und VRE in the context of CH. Nevertheless, it is worth to conclude at this point that even though great efforts have been made by national and EU wide initiatives, we are far from the goal where every outcome of new CH research projects is long-term archived and accessible for collaboratively driven geographic analysis. The support for geographic analyses and 3D support inside the existing VREs like CLARIAH-DE is only weakly covered. The ARIADNE+ network is providing a 3D model upload to a cloud storage and a basic 3D terrain service for visualizing and overlaying of other GIS layers. But this can only be the first steps, there is much room for improvement in the sense of "Integration" and "Capabilities" of 3DWebGIS in CH.

Standardization paves the way for the diffusion of innovation
Building a VREs components upon open standards is an important and useful strategy to establish interoperability, improve the re-usability of contents and reach flexibility for the extension with future and legacy components. On the other hand it hinders the use of cutting-edge technologies that might provide new ways of knowledge production, but doesn't fit to the established standards. Considering this contradictory conflict of aims a trade-off strategy helps. The goal to develop innovative methods in science must take precedence over the aim of making them easily connectible. The conclusion is, make innovations first and publish their concept and evaluation. The scientific discourse and the adoption of pioneer practitioners will prove its usefulness and practicality. Only then, the long and sometimes tedious way of standardization makes sense and should be implemented as an open and inclusive process that leads to an open and widely accepted standard. Such a validated standard will then have the ability to diffuse the innovation to a wider audience of users in an interoperable way.

Step back and rethink. Coping with the growing amount of data
The progressing developments in ICTs have brought a significant increase of capacities for electronic devices that capture, process, store and display CH data. Still there are deficiencies when it comes to the ubiquitous availability of data and information for the scientific use, e.g outdoors in the field or in the office. To provide reliable web-based research environments that support all sorts of scholarly activities new strategies are needed. For the case of spatial analysis in 3D WebGIS applications this thesis provided two solutions. For raster analysis (II.2) and for 3D vector based analysis (II.4). Both approaches improve the performance of the computation but tackle the problem with different strategies. The approach for the raster analysis is *acceleration through parallelization* which increases the performance by distributing the processing load to more resources, that became available through the WebGL API (Khronos Group 2011). A different approach was followed in the 3D vector analysis for a Line-Of-Sight computation. Here the strategy was *acceleration through reduction of data*. In this case, stepping back and taking a holistic view on the problem to be solved, opened up new potential for savings at data transmission and processing. In combination with a redesigned usage of visualization strategies the goals of performance and scalability could be achieved. In short, more efficient usage of existing resources and reduction of data usage to the really necessary can help to cope with the growing amount of data in the future.

Making complex things look simple. Usability and Human-Computer-Interactions
When designing tools that mediate information between computers and human users, it is of utmost importance to take care of the way how this communication takes place. A combination of visual, textual and behavioral signals control the attention of the user and gives him hints for possible actions. A good User-Interface design can increase the efficiency of the communication especially on complex issues. In II.3 a complex data model has been introduced to fulfill the requirements that were given by the complex nature of Maya architecture and demands of archaeological documentation. It supports hierarchical relationships, multiple resolutions and multiple representations for each digital record. The challenge was to find a way to visualize and query this non-standardized complex data model. Therefore two interfaces have been designed. One for the communication between computers in form of a Web API, which is served by a custom Geometry-Service. And a second interface to alleviate the communication between humans and the information system, which visually and interactively translates the hierarchical data structure to the users and enables them to query additional attributive data using the semantic structure of the given object. To conclude, to make 3D WebGIS an accepted and usable tool for a broader often interdisciplinary group of users, a well designed appearance and behavior of the system is just as important for a success as the sophisticated technical solutions in the background.

It's all about communication
As an essence it can be said, that it's all about communication. Human–Human, Human–Computer, Computer–Human, and Computer–Computer. All participants must be enabled to find a language to understand each other. There is no universal language for all because some things can expressed better in one language than in another. But at the point, where one system meets the other, the language must be properly translated to ensure that we—the Humans—can transform Information into Knowledge. This is not only true between humans and machines, but also between scholars of different disciplines.

The contributions of this thesis are a step forward in this endeavor and to advance 3DWebGIS as a beneficial research tool for the understanding and protection of CH.

I.7 Future Research

This thesis has revealed new insights in different aspects of 3D WebGIS, especially in the two areas "Extension of Capabilities" and "Integration into VREs". Nevertheless, it covered only a part of the manifold research topics that exist in relation to 3D WebGIS in CH. An overview of the research challenges of WebGIS in general has been given in Section II.4.1.2 of publication II.4 and is applicable to the more specific research topic of 3D WebGIS in a similar way.

The following compilation of research areas and suggestions for future research are based on the main topics that were identified:

Context of WebGIS usage: Future research should concentrate on the differences in the requirements that come along with the usage of 3D WebGIS for different scholarly activities. Gaining a deeper understanding of the specific work processes of each activity listed in the Figures I.4.2, I.4.3 and I.4.4 of Chapter I.4 would help to answer the question "How to efficiently support specific requirements in the work processes of scholarly activities in CH?"

Usability: This is an ongoing research topic. The question "How to improve Human-Computer-Interactions to improve effectiveness, efficiency and user satisfaction for 3D WebGIS applications?" should accompany any new developments of systems that are targeted to be used by humans.

Speed: The improvement of performance and efficiency of every part of a distributed system like a 3D WebGIS is a general research goal. Yet it is important to keep in mind, that a positive user experience depends to a high degree on the overall performance of a system. A bottleneck in one layer of the system architecture can have negative effects on the performance of the entire system. Especially in a multi-layer architecture like 3DWebGIS bottlenecks constitute a problem and need to be investigated. Therefore, for future research it is important to identify these issues by applying a systematic and holistic view. The key challenge in this context is that the location of the bottleneck can be different for every function that is provided by the system to the user.

Capabilities: The extension of capabilities is a major concern of this thesis. Two methods for client-side raster and 3D vector analysis have been presented and evaluated using examples of *Hillshade* and *Line-Of-Sight* computations. Those methods have great potential to be used as basic concepts for further research and developments of analysis methods. Especially the 3D Line-Of-Sight analysis has the potential to be used to compose complex visibility analyses for CH research. Any combination of relations between 3D Point,

3D Line, 3D Surface is conceivable. In many cultures, including the old Maya Culture, the visual prominence of built structures is an important property which helps to asses social structures that once may have existed. Sometimes the power and influence of the personalities that are related to buildings or of the gods to whom temples are dedicated are reflected in their visibility. In this context, a method that tells CH researchers *who could see what from where* would be of great use. Another research area that can be assessed by 3D visibility analyses are visual communication networks that are linked by prominent landscape features or built structures, which may have been used to transmit information along defense lines or from peripheral locations to a center of power.
Future research effort should also be put into 3D accessibility analyses for interactive usage in a 3D WebGIS. The movement of people in a cultural space was sometimes restricted by natural or intentionally built barriers. So for the study of past social structures the inclusion or exclusion of certain areas and the possible pathways that certain groups of people used give researchers another hint to build plausible theories.

Adaptiveness/Portability: Like the topic of Usability, this area requires an ongoing research effort and is largely a technology-driven area. "How well does an application work on different devices, mobile or stationary, outdoors in the field, with or without access to Internet or mobile network, on different operation systems, etc.?". Nevertheless, it is important to keep up with the latest developments. Otherwise, there is a risk to miss out new potential for innovative and beneficial methods that can only applied in new contexts.

Re-evaluation of existing methods: Recent developments of web and geo-standards that might have an impact on multiple of the above mentioned areas are worth to be examined. They may provide potential for a re-evaluation and improvement of existing 3D WebGIS methods. These are: the new OGC 3DPS standard (Hagedorn et al. 2017) that defines an extended set of 3D rendering and dissemination functionalities, the W3C WebAssembly standard working draft (W3C 2018) for increased code performance in browser environments and the OGC 3D Tiles community standard (Cesium and OGC 2019) that was designed for streaming and rendering of massive 3D geospatial content, including photogrammetry, 3D buildings, BIM/CAD models and point clouds.

The research agenda for 3D WebGIS in CH is far from being exhausted. The future research will be as interdisciplinary and exciting as the topics that will be explored by the various disciplines involved.

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Part II

Publications

II.1 3D-Sutras : A Web Based Atlas of Laser Scanned Buddhist Stone Inscriptions in China

Abstract

An important cultural heritage is located in the Chinese providence of Sichuan: about 1000 years ago, Buddhist stone inscriptions have been carved into rock – the Stone Sutras. Archiving the current state of the inscriptions, their transcription and translation into digital assets, their interpretation and provision to the public and scientific community are of a major interest to an interdisciplinary research team of art-historians, geodesists and geographic information scientists. This paper describes the innovative architecture of a Spatial Data Infrastructure (SDI) which combines standardised geospatial OGC Web Services (OWS) with an existing XML document system providing art-historic and text-scientific information. Further a web-based interactive atlas system for analysis and multimedia presentation in 2D and 3D has been realized as a sustainable solution helping art-historians and text-scientists to examine Buddhist stone inscriptions in the future. Innovative aspects comprise in particular the adaptation of the data pre-processing to enable the portrayal of terrestrial laser scan (TLS) data of relevant sites by a Web 3D Service and furthermore the integration of standards across different domains, including GIS analysis functions relevant for historians and archaeologists through several Web Processing Services (WPS).

Keywords: Archaeology, Stone Sutras, Spatial Data Infrastructure, 3D-Visualization, Laser Scanning, Web Atlas

II.1.1 Introduction

Around thousand years ago, people in the province of Sichuan carved Buddhist texts into the surface of niches and little manmade caves of stone. These texts, the Stone Sutras, are an important cultural heritage of China exhibiting the religious history and the development of Buddhism, its growth and its adaptation into the Chinese culture. More than 80 Sutras with a total number of over 600,000 characters are located at six different sites in the Chinese province of Sichuan (Schmidt et al. 2010).

An interdisciplinary research team of art-historians, geodesists and geographic information scientists developed a sustainable information system for the documentation, interpretation and presentation of the stone scriptures. For the documentation of the texts different Terrestrial Laser

Scanning (TLS) technologies have been used to create three-dimensional virtual models of the carved stone surface and the surrounding environment at the archaeological sites (Schmidt et al. 2010). To provide all the necessary information for text-scientific work over a web application, a Spatial Data Infrastructure (SDI) has been developed to complement an existing XML-Document service[1] which stores and provides textual historic information with a spatial component, thus enabling new possibilities of visualisation and analysis. The visualization component is based on standardised geo web services. The interactive 2D map enables to geographically browse the available information about the archaeological inscription sites, the historical infrastructure connecting the sites, time dependent information about the development of the area of power of the Tang Dynasty from 669 to 820 AD and temporal information about the itineraries of Buddhist monks involved with the sutras and the province at the specified time. Additionally a 3D visualization component based on the Web 3D Service[2] (W3DS) is embedded in the system in order to give the user a virtual model derived by high-resolution terrestrial laser scanning and other modelling techniques (e.g. manual 3D reconstruction based on field investigation) enabling a realistic exploration of the archaeological inscription sites.

The presented work is related to a pre-existing project within a similar scope described by Arnold (2008). In this project stone sutras in another province of China (Shandong) had been archived by means of photographs of the stone sutras and their respective rubbings. Rubbings are handmade copies of the inscription surface created by pressing thin wet paper on the surface and carefully dyeing the paper by manual tracing of the stone inscription (Ledderose 1981). In the project, described in this paper, these types of artefact representations are supplemented by 3D models of the stone sutras derived from TLS data. The archive of the former project has been built up using the TEI format to encode the text transcripts with annotations, comments and references. TEI is a relevant XML standard in the humanities, social sciences and linguistics from the Text Encoding Initiative. This underpins that all parts of the project use open standards to ensure sustainability, flexibility and independence from software providers. TEI is also used to store metadata about the inscriptions and their corresponding archaeological sites. The metadata contains geographic references which enables a geographic visualisation of the data. This already existing database was the base of the system presented here and had to be integrated. Bingenheimer has shown in several projects the potential of using TEI with place references as a source for mapping applications, e.g. in his 'Spatio-temporal & image database of Buddhist Temples in Taiwan'[3] or the visualisation of 'Biographies of Eminent Monks' (Bingenheimer et al. 2009; Hung et al. 2010). Mainly this is done by an XML transformation from TEI into KML[4] and then visualized with the help of the Google Maps API or Google Earth. This setup works well for its purpose but as in our project the aim was to integrate a greater number of different geographic themes at various scales and the possibility of data management, visualisation and in particular analysis another approach had been chosen – the setup of an standards based SDI.

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[1] http://exist.sourceforge.net/ - An Open Source Native XML Database

[2] The Web3DService is actually an OGC discussion paper which aims for future standardisation (Schilling and Kolbe 2010)

[3] http://buddhistinformatics.ddbc.edu.tw/taiwanbudgis/

[4] KML – The Keyhole Markup Language is also an OGC Standard since 2008

Corns and Shaw (2010) emphasised the importance of developing SDIs with open standards and formats as Service Oriented Architecture (SOA) in the domain of archaeology and cultural heritage where up to now mainly areas related to environment and security are involved. With this approach it is possible to re-use and share the collected geodata with other research projects in a flexible, interoperable and future-oriented way. Within this project we combine for the first time SDI technology not only for the visualization and management of archeological 2D geodata, but also 3D spatial data from different sources, dimensions, scales and qualities and even provide OGC-based spatial analysis functionality for them. To our knowledge all these have been integrated for the first time with open text related standards relevant for the Humanities from the TEI initiative.

The main objective of this contribution is to introduce a new concept for a web-based SDI covering a large diversity of geographic data in terms of spatial and temporal scale, domain, purpose and presentation and even interactive analysis. This new concept uniquely integrates spatial data sources such as from high resolution sub-centimetre 3D laser scanning data via photograph panoramas and map of the caves up to historical boundaries and road network of the Tang Empire. It is aimed at providing a flexible and interoperable atlas for interdisciplinary scientific exploration of stone inscriptions fully based on open standards and web services.

II.1.2 Atlas Components

II.1.2.1 Overview

From a user's point of view the Web Atlas consists of five major components: 1) textual description of all inscription sites, 2) inscription catalogue with metadata of the texts, 3) reading tool to explore the inscriptions in different ways, 4) search module to query the inscription database and 5) innovative multimedia map combining geographic 2D/3D visualisation with 360° panoramas, annotated photographic pictures and GIS functionality for measuring, searching and analysing (Fig. II.1.1).

The following sections will describe the conceptual layout of the 2D/3D-Map component which is composed of the 2D-Multimedia-WebGIS and an interactive 3D-Scene-WebViewer.

II.1.2.2 2D Multimedia WebGIS

The 2D map component plays a major role in the overall atlas system. It serves as an entry point to the end-user for exploring the theme of Buddhist stone sutras in China but also as an interface for navigation through the website. It shall provide a geographic overview of the broader context of the time when the inscriptions arose. This context is depicted with the help of different selectable base maps, which can be overlaid by diverse themes such as the historical-political development, information on historical infrastructure like the historical road network of Sichuan or the distribution of important monasteries in the time of the Tang Dynasty. A user interface

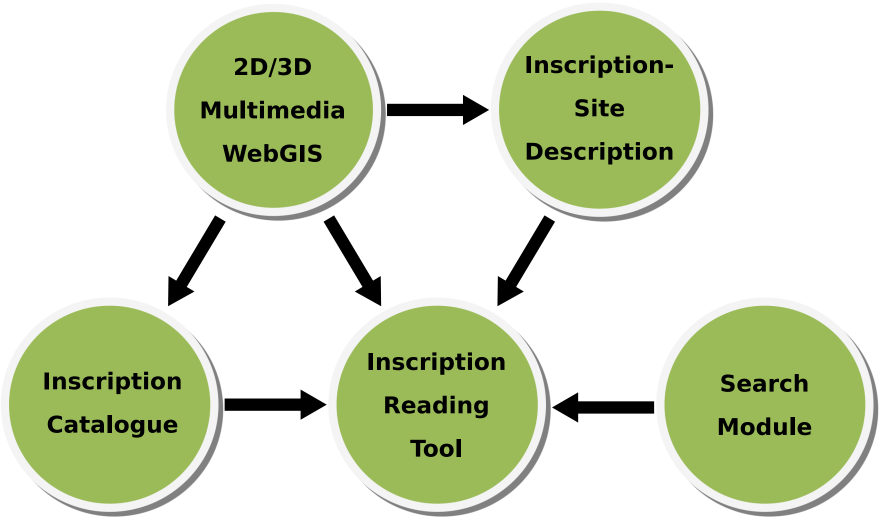

Figure II.1.1: Components of the web-atlas

particularly designed for this purpose allows browsing through time where temporal datasets are available.

Besides the function of giving an overview, the 2D map provides detailed information about the different inscription sites. Especially for the largest site 'Wofoyuan', where there are 125 cubic caves and niches with texts and sculptures (Lee 2009), the map offers a site-plan with all caves, their function and status of completion. Additional information to each text-cave is linked in form of 360° flash-panoramas and annotated pictures which show the distribution of the sutra paragraphs on the cave walls.

To complete the atlas functionality of the map application, several tools have been added to provide interactive exploration and analysis possibilities. For example, the user can measure distances and areas or pick coordinates and export them as XML. Additionally there are possibilities to perform GIS analysis on selected datasets. For instance, to analyse the possible routes a monk may have chosen from a monastery to an inscription site, it is possible to make a network analysis and calculate isometric distances on the historic road network. Therefore, the user can define the starting point and mean daily travel distance. The visualised result allows investigation of the patterns and conclusions about how far someone could travel over a certain number of days on the historic routes (Fig. II.1.2).

The 2D map component has been developed using the open source JavaScript library OpenLayers[5] for map display and interactive drawing functions. The user interface, i.e. the collapsible toolpanels, buttons, floating windows, time-sliders etc. is done with the ExtJS[6] library. Some special parts of the user interface like the layertree are taken from the JavaScript library GeoExt[7], which itself uses the classes from ExtJS and Openlayers and extends them. For the analysis

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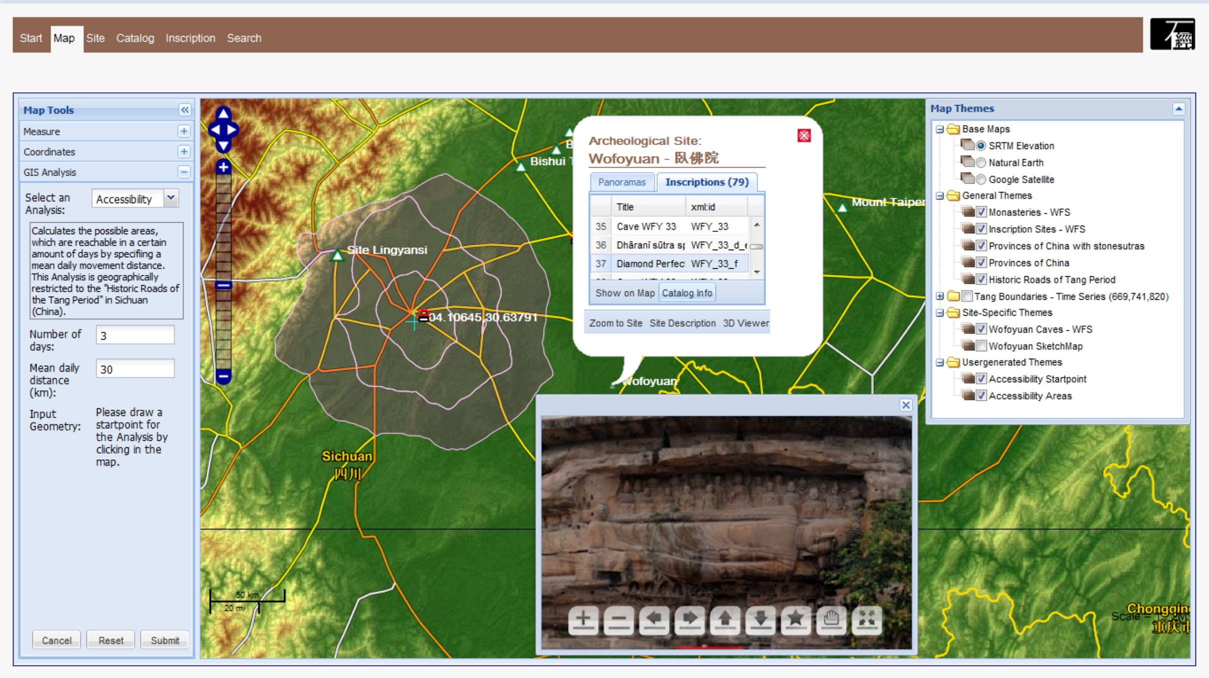
[5] http://openlayers.org/
[6] http://www.sencha.com/
[7] http://www.geoext.org/



Select an Analysis: Accessibility

Calculates the possible areas, which are reachable in a certain amount of days by specifiing a mean daily movement distance. This Analysis is geographically restricted to the "Historic Roads of the Tang Period" in Sichuan (China).

Number of days: 3

Mean daily distance (km): 30

Input Geometry: Please draw a startpoint for the Analysis by clicking in the map.

Archeological Site:
Wofoyuan - 臥佛院

	Title	xml:id
35	Cave WFY 33	WFY_33
36	Dhāranī sūtra sp	WFY_33_d_e
37	Diamond Perfec	WFY_33_f

Figure II.1.2: 2D web GIS client with analysis tools, 360° panorama views and info popup

function the OpenLayers extension from pyWPS[8] is used in combination with ExtJS-Forms to deal with the user interaction and communication with the underlying pyWPS.

As mentioned above the map also serves as central component for website navigation. The user is linked from a chosen feature to other Atlas parts and can get the inscription site description, an interactive 3D-Scene of the current site or can directly move to the inscription reading section (Fig. II.1.3). The linkage is done via a popup-cloud which appears once an object has been clicked. This popup contains several nested panels with context information. Depending on the information type, the user interface provides different paths to the context information, e.g. the user selects an inscription text of a list and can directly go via the meta information from the catalogue to the reading tool. Such it is possible to perform a spatial query of the inscription texts by searching related items in the map. Other options are e.g. to open an interactive 360° panorama of chosen site or cave or explore an annotated picture of the cave walls with the distribution of the texts and their chapters.

II.1.2.3 3D Scene Viewer

Besides the 2D web GIS client, the map component also contains a 3D scene viewer which is embedded in the atlas system. It is derived from the XNavigator[9] application which is used e.g. in the OpenStreetMap-3D[10] project (Over et al. 2009) and the city information system

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[8] http://pywps.wald.intevation.org/

[9] http://koenigstuhl.geog.uni-heidelberg.de/xnaviwiki/doku.php

[10] http://www.osm-3d.org

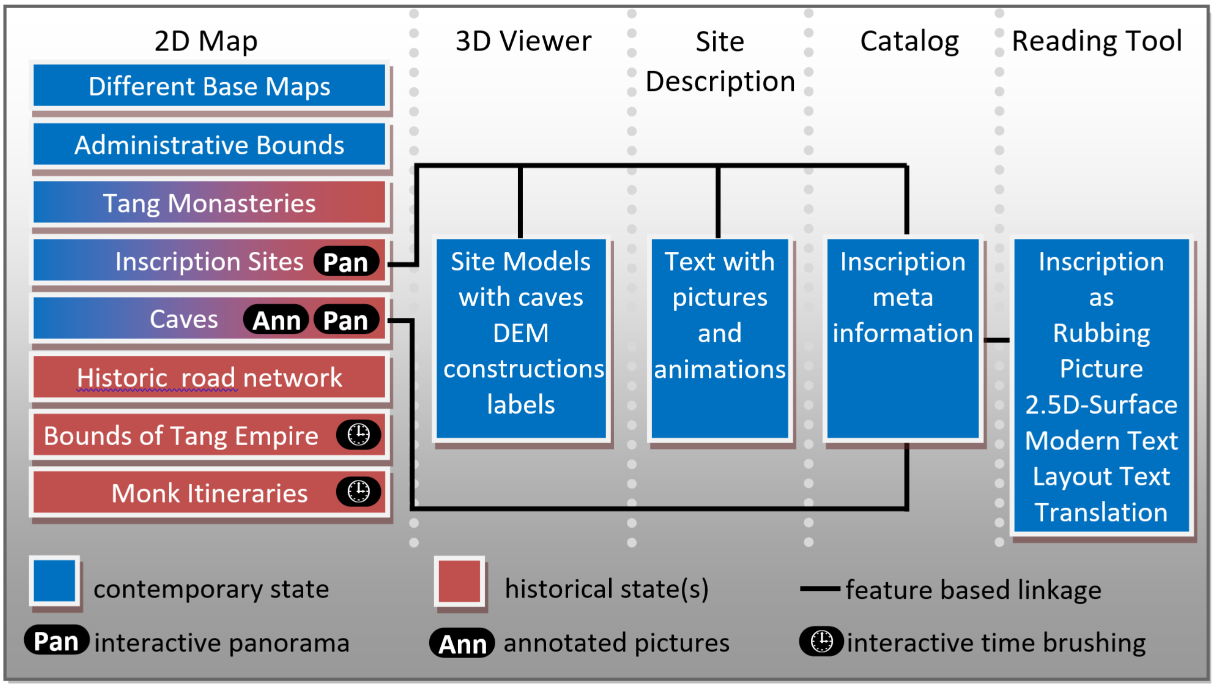

Figure II.1.3: Atlas Component content with historical state of the data, additional related media and interactions, feature based linkage between atlas parts

Heidelberg-3D[11]. This VR-presentation system provides a realistic view of the inscription sites. It aims at enabling a documentation of the archived actual state of the inscription sites measured by TLS and manual 3D reconstruction based on field investigation (Fig. II.1.4). With the help of the 3D impression the user can develop a mental image of the situation which may be helpful for interpretation of the Buddhist texts, their positions on the site and their possible spatial relationships.

To enhance the usability and consider the different grades of experience of the users, the 3D system provides two modes of navigation. Using the free navigation mode, the user can 'fly' to any preferred position in the scene to get certain visual perspectives. By using the guided navigation mode, a less experienced user can quickly get to some predefined viewpoints without the need for 3D mouse or keyboard navigation.

Like in a common 2D web application, the 3D system also provides selectable layers. Therefore, different types of objects like building constructions, vegetation, or labels are grouped together. By turning off visual obstacles or turning on virtual annotations the user can obtain insights and views which would not be possible in the real world.

As mentioned above the 3D scene viewer is based on XNavigator. This software is implemented in Java and can be installed locally, initialised via JavaWebstart or embedded in a website as a Java Applet. The stone sutra web atlas makes use of the latter. The XNavigator Java Applet provides some scripting methods to the browser via an External Authoring Interface (EAI) in a

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[11] http://www.heidelberg-3d.de/

way that all the functions of layer management and navigation control can be done with the help of JavaScript and the graphical user-interfaces from ExtJS.

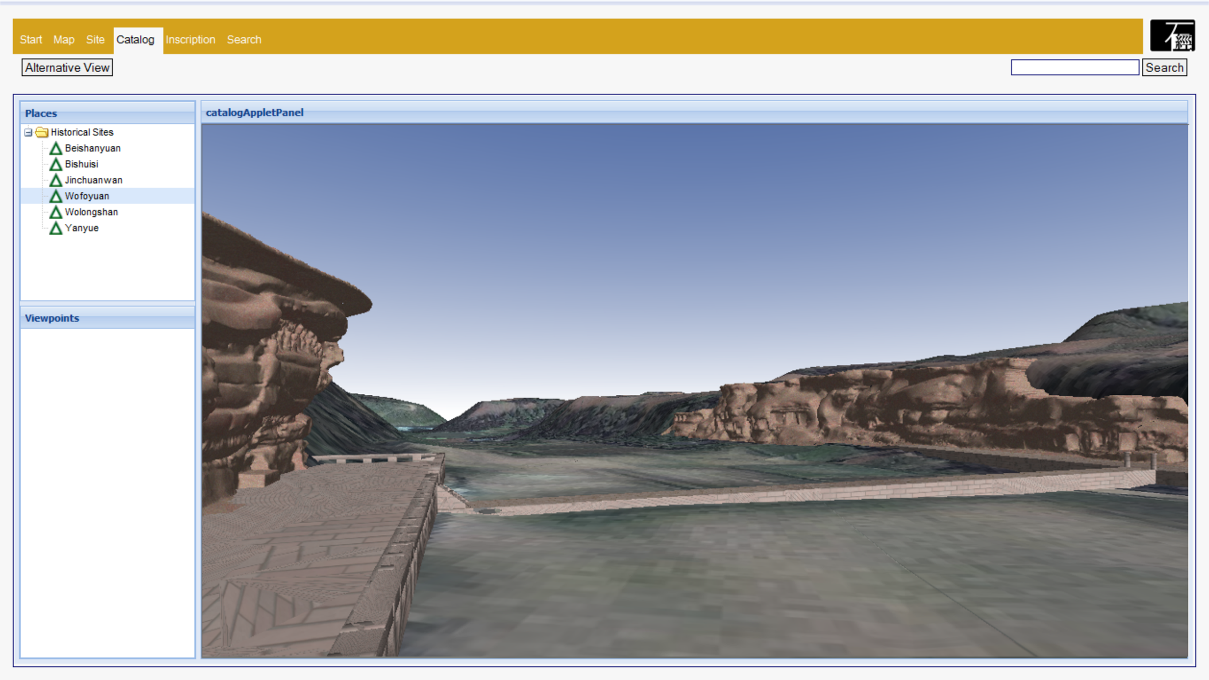

Figure II.1.4: 3D surface Model of stone walls with caves derived from terrestrial laser scanning in the Valley of Wofoyuan

To cope with the huge amount of data of the laser scanning models and the high-performance 3D visualisation, the data is prepared in several Level Of Details (LODs) and afterwards cut into several tiles with different sizes. This approach allows the presentation system to load and display just those parts of the 3D model which are in the field of view. Additionally, only the nearest parts of the model are shown in the highest quality. This procedure optimizes the size and transfer of the data, and therefore the time the user has to wait for the presentation.

II.1.3 A Sustainable Spatial Data Infrastructure

II.1.3.1 Standardised Web Services

An important issue in developing data infrastructures in general and SDIs in particular is to achieve sustainability. This means that in many cases of temporary limited research projects the collected data gets lost when the project is finished because of the absence of the persons who know where the data is, which formats are available etc. To avoid these kinds of problems the spatial data for this Web Atlas is stored in a standardised way and provided by different geo web services. With the use of the standards of the Open Geospatial Consortium (OGC) it is possible to gain interoperability, which means that the data can not only be used by our web application but it can also be accessed with any GIS system supporting OGC standards. This guarantees flexibility in further usage of the data beyond project duration. The web atlas is fed by four different OGC-Web-Services (OWS) which are: 1) WMS for the 2D map presentation, 2) WFS for vector data, 3) WPS for analysis processing and 4) W3DS for the 3D scenes, while the latter one is in the state of an OGC discussion paper on the way to become a new standard (Schilling and Kolbe 2010).

II.1.3.2 An Integtating Data Infrastructure Design

One of the challenges on the service infrastructure level was the integration of an existing XML document database and service used and maintained by the historians into the SDI design. This XML database stores the text-scientific results, transcriptions, catalogue meta-data of the inscriptions, context data about inscription sites and caves and other information. The XML documents about the inscriptions sites, caves and the metadata documents have been supplemented with a spatial component in form of geographic coordinates. This opens up the potential of spatial analysis and visualisation of the stored information. As the XML documents do not make use of geographic standard formats it cannot be distributed by OGC Services directly. To enable a standardised access to the data as well as to support the given structure of the XML database, an automated conversion step has been integrated which pulls new documents, whenever they are available, from the XML database and writes them as Simple Features into a spatially enabled PostgreSQL[12] database with PostGIS extension (Fig. II.1.5). From this source the information can be distributed easily by the different OGC services to the web client or any other GIS client. This approach allows archiving of new XML data by the text-scientists in a familiar way using a desktop XML Editor with database connection and ensures, through the automated update of the PostGIS database, that new features will be automatically shown on the map client and are available for GIS analysis through standardised geodata interfaces. In this case the OGC-WMS and OGC-WFS interface is provided by the opensource software Geoserver.

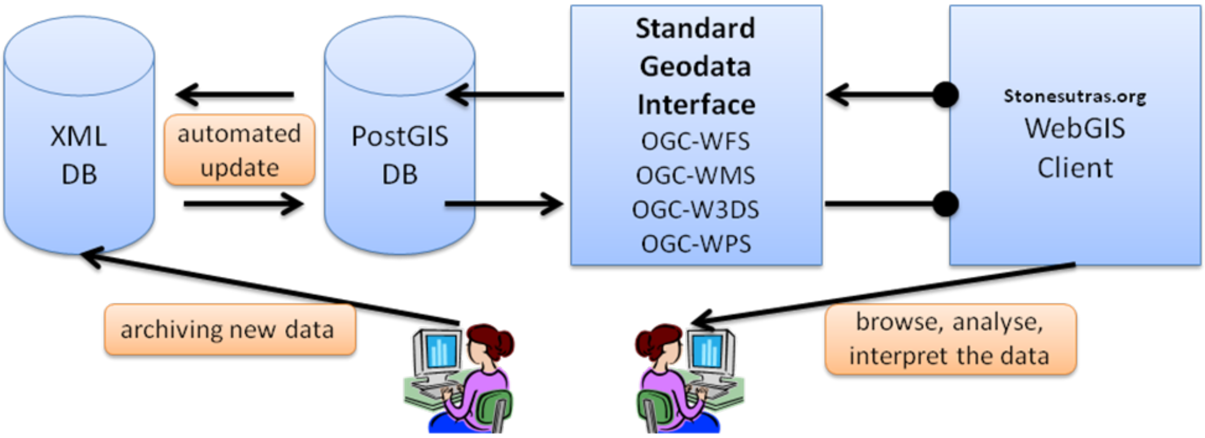

Figure II.1.5: Integration of an XML-Document Service into the spatial data infrastructure

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[12] http://www.postgresql.de/

The OGC-WPS has been realised with pyWPS using GRASS-GIS processes behind it while the W3DS is an implementation of the University of Heidelberg (Basanow et al. 2008).

II.1.4 Conclusion

The development of a web atlas for laser-scanned Buddhist stone scriptures in China was a challenging task. The interdisciplinary character of the project demanded a special integrating design of the data infrastructure to combine a non spatial XML database, which provides texts in standardised format for the humanities (TEI), with the spatial-aware SDI components standardised by the Open Geospatial Consortium (OGC). This could be realised using a PostgreSQL-script regularly checking for updates in the source database. This automated process and the consistent use of OGC-Standards makes the system interoperable with other systems and sustainable beyond the duration of the project. No GIS-experts are needed to add new data with geographic reference to the system. Furthermore, an online system could be launched which enriches a text/image information system with a GIS component combining classic 2D layers with interactive time-browsable layer series, linked multimedia features like 360° panoramas and a 3D visualisation component for a realistic impression of the historically important inscription sites. The OGC WPS specification has been used to provide several analysis functions for geographic data from different scale (China to Millimetre) to the web client. Altogether the Web Atlas with its GIS component gives the users the opportunity to develop new hypotheses by graphically revealing spatial distribution patterns and relationships between the inscriptions and the available related context data.

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II.2 Real-time Web GIS Analysis using WebGL

Abstract

Parallel processing methods in Geographic Information Systems (GIS) are traditionally used to accelerate the calculation of large data volumes with sophisticated spatial algorithms. Such kind of acceleration can also be applied to provide real-time GIS applications to improve the responsiveness of user interactions with the data. This paper presents a method to enable this approach for Web GIS applications. It uses the JavaScript 3D graphics API (WebGL) to perform client-side parallel real-time computations of 2D or 2.5D spatial raster algorithms on the graphics card. The potential of this approach is evaluated using an example implementation of a hillshade algorithm. Performance comparisons of parallel and sequential computations reveal acceleration factors between 25 and 100, mainly depending on mobile or desktop environments.

Keywords: Web GIS, WebGL, HTML5, Canvas, Hillshade, GPU Computation, Spatial Analysis

II.2.1 Introduction

The term real-time Web GIS can refer to different kinds of applications. It can be understood as a system visualizing in real-time measured sensor data, like GPS positions or in real-time generated data by human editors, e.g. in collaborative disaster management systems. In the scope of this paper it refers to an almost immediate visualization of GIS analysis results in order to provide a more interactive and responsive user experience, irrespective of the creation time of the input data. Reducing waiting times in web applications is a general aim. Besides that, a real-time linkage between user behavior and analysis results can also be used to enable visual data exploration in data mining processes. Two aspects of the presented approach contribute to the reduction of time between user request and presentation of the results. Spatial analysis execution in the web browser and doing this in an accelerated way using parallel computation on the graphics processing unit (GPU) instead of classic serial computation on the central processing unit (CPU).

In traditional web based GIS applications it is common to use a client-server architecture where the computational analysis part is done on the server side while the web client is just used as a user interface for requesting those computations and to display the processed results. The reason for this is the lack of graphic manipulation capabilities of current web standards. This restriction will change with future web standards and browser releases. Currently ongoing developments in web technology, like HTML5 (W3C 2012a; WHATWG 2012) and WebGL

(Khronos Group 2011b), offer great potential for the future development of more interactive, responsive, efficient and mobile Web GIS applications. This includes the usage of 2D, 3D and even temporal and animated content without the need of any third party plugins.

The HTML5 specification introduces a new element type called canvas. For the first time, since the invention of the first widely used graphical web browser "Mosaic" in 1993 (Peterson 2003), the canvas element enables web developers to not only present images, but manipulate images and also 3D scenes within the website using JavaScript. There are two different possibilities to manipulate graphics within a canvas element. One is the built in 2D drawing API for raster images and the other one is the WebGL API which can be used to create interactive 3D scenes with textured objects consisting of points, lines or triangles. Those two APIs are also referred to as "2d"- or "webgl"-contexts of the canvas element. The WebGL API has a close connection to the graphics card. Its hardware is designed to rapidly project and rasterize 3D vector objects to the canvas plane on the screen. It can do such transformations very fast because it uses hundreds of specialized microprocessors in parallel. The ability to compute self-defined functions in parallel and output a raster graphic on a webpage as a result is the key property of the WebGL 3D-Technology, which in this paper will be exploited to outline the possibilities for extremely performing client side 2.5D Web GIS analysis using the example of a hillshade computation. The application of this approach opens up new perspectives on user interaction and interface design for the experience of in real-time responsive analysis results. A demonstration of the method can be evaluated on http://webgl.uni-hd.de/realtime-WebGIS.

The following sections provide an overview on related work about parallel computation approaches of GIS analysis. A short introduction on the basics of 3D rendering and a detailed description how to use WebGL for the proposed method follows. Issues concerning the conversion of geospatial raster data to web compatible formats are addressed. An example hillshade algorithm is described and used to demonstrate and measure the performance of the approach. Furthermore some limitations of WebGL based spatial raster processing are discussed.

II.2.2 Related Work

Performing analysis as fast as possible is an intrinsic aim of any GIS application as the amount of available spatial data is growing fast and depending on the application domain sophisticated time-consuming algorithms are used. Therefore the approach to parallelize GIS processing has been applied in many different contexts (Healey 1996). Despite the potential of the approach, parallel GIS software has not yet become an everyday tool to GIS analysts and most commercial software doesn't support it as common parallel architectures depend on specific infrastructure like high performance computing clusters or Grid computing infrastructure (Lanig and Zipf 2009). A recent trend to speed up desktop GIS analysis has been enabled due to the development of frameworks for general-purpose computing on graphics processing units (GPGPU). A major drawback of these frameworks is that they are platform dependent. CUDA is the framework for Nvidia products (NVIDIA n.d.), whereas APP SDK is the one for AMD (n.d.). The non-profit industry consortium Khronos Group, which also released the specification for WebGL (Khronos

Group 2011b), has developed a platform independent standard called OpenCL (Khronos Group 2011a) to overcome these technology barriers. Several research projects have already illustrated the applicability to GIS with particular focus on raster operations. Huraj et al. (2010) are using GPGPU computation for an inverse-distance-weighting (IDW) interpolation to model snow coverage from meteorological data of 20 years. They could gain a speedup of 6.7 times compared to an implementation written in the C programming language. Xia et al. (2011) compare several implementation variants of IDW interpolation and viewshed calculation implementations. They could reach an acceleration of 13-33 times for IDW and 28-925 times for viewshed computation depending on different datasets. Beutel et al. (2010) use GPU computation for the construction of a large digital elevation model (DEM) from massive LiDAR point cloud data. All above examples use the CUDA framework. There are also examples of GPGPU GIS computations with OpenCL. Steinbach and Hemmerling (2012) discuss the possibility of batch processing of spatial raster analysis and implement a set of GRASS GIS modules used for neighborhood analysis. They observe an acceleration factor between 7.7 and 8.1 for their whole batch process, optimizing it by storing intermediate results on the graphic card instead of writing them to main memory or hard disk.

Besides research projects also commercial products start adapting the trend of GPU computing. The first one in this area was Manifold GIS (Manifold n.d.) providing parallelized surface tools in a desktop system. Others like Incogna GIS (Incogna n.d.) followed providing a broad range of different spatial analysis tools also as web services.

The mentioned studies demonstrate the potential of total computation time acceleration through GPU based parallel GIS processing in various application areas. But as such, for an application in a Web GIS environment, these approaches could only be exploited as server-side processing services delivering final results to the web client. The reason is that CUDA, APP and OpenCL cannot be accessed from JavaScript. The Khronos Group is also working on this issue and is developing an API for web browsers to call OpenCL processes which will be called WebCL (Khronos Group 2012). Besides some prototypes showing the potential of WebCL, at the moment this API is not yet supported by standard browsers, in contrary to WebGL. Using OpenCL on the server side could increase analysis performance but there will always be a delay of visualization resulting from the transmission of the requests between client and service. By now the only way to enable a client side GPU based parallelization of spatial raster analysis is the access through the WebGL API. This approach of accelerating GIS analysis within web applications is presented in this paper. To the best knowledge of the author there is no related literature available on the topic of web based spatial analysis using WebGL. However similar approaches have been used for mathematical and physical simulations on the web (McMullen et al. 2012; *WebGL Demos* n.d.).

II.2.3 Methods: WebGL based Parallel Spatial Raster Analysis

II.2.3.1 The programmable WebGL 3D Rendering Pipeline

It is important to know about the 3D rendering pipeline and the possibilities to influence it using JavaScript and the OpenGL Shading Language GLSL (Khronos Group 2009) for a better understanding on how parallel 3D rendering within the WebGL context works. As WebGL is based on OpenGL for Embedded Systems (OpenGL ES 2.0), we have access from JavaScript to the so called programmable pipeline (Figure II.2.1). This consists of several fixed functions, like the assembly of primitives from their corresponding vertices, the rasterization of the 3D objects to the 2D plane of the canvas and the application of post processing steps like masking and blending etc. Most interesting for our case is the programmable part of the pipeline – the two shaders: 1) the vertex shader and 2) the fragment shader. These are two little programs written in GLSL. Here we can define the functions that the graphic card will compute in a parallelized way. The vertex shader will take JavaScript arrays of vertex attributes, like 3D positions and texture coordinates and will pass this information to the rasterizer. There all given attributes will be linearly interpolated according to each fragments position (pixel). Later in the pipeline the fragment shader will have access to these interpolated values as variables. These can be used in conjunction with other variables and texture values directly passed to it from JavaScript. The result of the pipeline is written to the framebuffer, which then can be drawn to the screen as visual result. Alternatively it can be read back into a JavaScript array for further use in the Web GIS application.

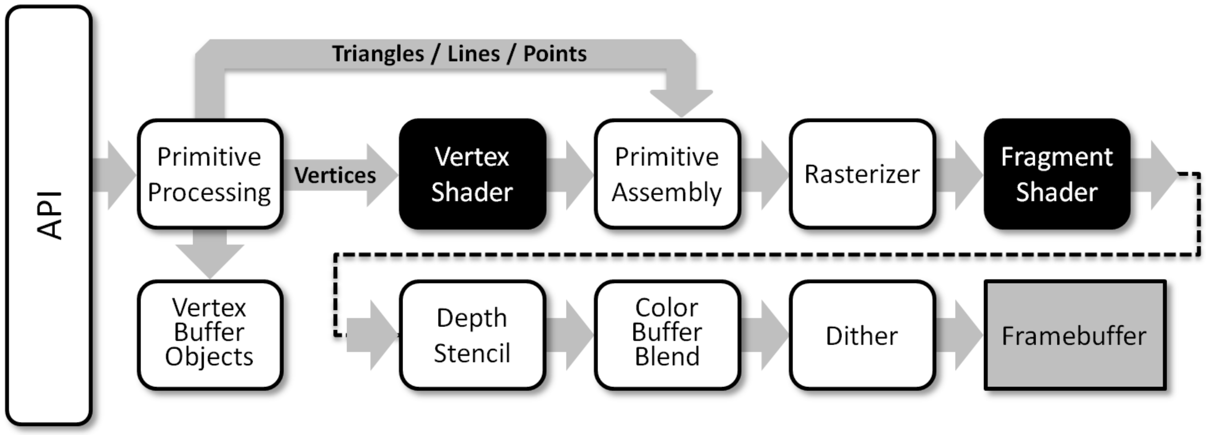

Figure II.2.1: OpenGL ES 2.0 Programmable Pipeline, modified according to Khronos Group (n.d.)

II.2.3.2 WebGL setup

The first step in the WebGL setup is to create a canvas element in the HTML5 document with an appropriate width and height. In our case a width and height of 1024 pixels has been chosen. This has two reasons: a) in most cases this is a screen filling size and most Web GIS applications do not visualize bigger images as this would require a frequent scrolling. It is more likely to reload adjacent data tiles if required. b) there is a restriction to texture size in WebGL. A texture must have a power-of-two size.

The second step is the creation of a 3D geometry which we want do display in the canvas. In our special case this is a plane rectangular surface which exactly fits in the viewport of the canvas. This can be done by defining two adjacent coplanar triangles in 3D space whose vertex positions match exactly the canvas surface (Figure II.2.2). An additional vertex attribute – the texture coordinate – is necessary to project the input raster values exactly to each corresponding canvas pixel during the simultaneous computation of the analysis algorithm in the two shaders.

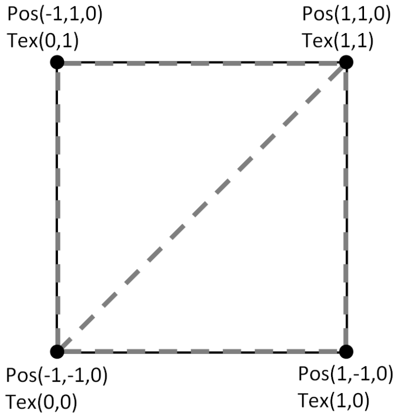

Figure II.2.2: Vertex attributes (position and texture coordinate) of the triangles used as projection surface for the computed results

The third step involves the creation of the texture from a DEM to be used as input data for the calculation. Having in mind that we are working in a web browser environment we are restricted to use a web graphic format (GIF, JPEG, PNG or BMP) as input for our texture object which is not optimal for the representation of geodata. Considerations on the image formats will follow later in the data section. For good reasons we encode our geodata in a PNG file and after passing this data to the WebGL API it will be internally treated as a 4-band raster with 8-bits for each of the Red, Green, Blue and Alpha channel.

After having prepared the data source the vertex shader and the fragment shader have to be prepared for the spatial computation task. The vertex shader will take the position and texture coordinate values from the vertices and will pass for each one a variable to the fragment shader with linearly interpolated values for each pixel of the triangle surface in between. With the interpolated texture coordinate it is possible to look up the corresponding texture value or rather the texture values of the surrounding pixels. In our example we perform a focal analysis with a 3x3 window of surrounding cells to compute the hillshade value for each pixel. Further details of the algorithm will be given later in the algorithm section. Other parameters, which will have the same value for the whole set of pixel computations, called uniform variables, can be passed to the fragment shader and included in the spatial processing. In our case this would be the azimuth and zenith angle of the light source which will shade our terrain and we obtain these values directly from the website using standard interaction events. Alternatively they can be read from HTML text input fields.

Figure II.2.3 provides a conceptual overview of the proposed method using the 3D WebGL Technology to accelerate client side spatial raster processing. After defining a triangle based plane which fits to the drawing canvas we use the parallel computing power of modern graphic cards with hundreds of microprocessors to simultaneously compute a spatial algorithm to each output pixel using textures and other variables as input parameters.

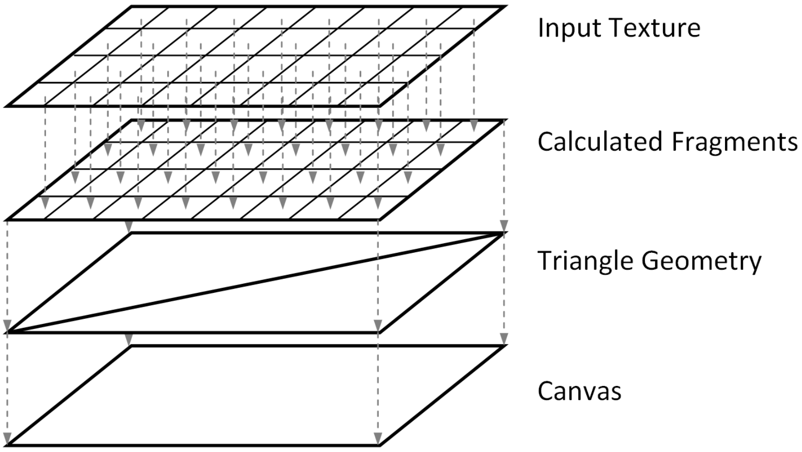

Figure II.2.3: Conceptual model of the WebGL based parallel spatial raster computation approach

II.2.3.3 Data Handling

This section presents two possible ways of data preparation. As we are dealing with a web application we cannot use typical spatial raster formats like GeoTiff for visualization. Typically modern web browsers natively support GIF, PNG, JPEG and the rarely used BMP format. As JPEG uses a lossy compression it is unsuitable to store geodata for calculation purposes. The other three formats provide lossless compression of different qualities. A high compression rate is important for short loading times in web applications and even if BMP supports bit depths up to 32 bits per pixel it uses a weak compression algorithm (run length encoding). The GIF format is working with just 8-bits per pixel and has like BMP no support of an additional alpha channel. Last but not least the PNG format is the most flexible web graphic format. It supports different variants with up to 16 bits per channel either using 1 grey channel, 3 color channels or 4 channels with an additional alpha channel. Theoretically this would provide the possibility of storing up to 64 bits per pixel. However, the current WebGL Specification only supports 8 bits per channel. Images with higher bit depths will automatically be downscaled to 8 bits per channel when used in a canvas context. Nevertheless the PNG format provides the highest possible bit depths in combination with a good compression algorithm (deflate)(Miano 1999). As a result of the above considerations the PNG format provides the best solution to store geodata for computational purposes in a WebGL application.

To demonstrate the capabilities of the proposed method in this paper a hillshade will be computed based on a rasterized DEM (Figure II.2.4). The test dataset used in this study is obtained from the "Large Geometric Models Archive" of the College of Computing at the Georgia Institute of Technology, Atlanta, USA. It represents height values from the area of the Puget

Sound in Washington State. It is stored as 16 bit PNG with one grayscale channel containing values from 0 to 43798 dm. The cellsize amounts to 160 m while the size is 1025x1025px. To exactly fit the data into a 1024x1024px WebGL texture the original data is geometrically scaled accordingly.

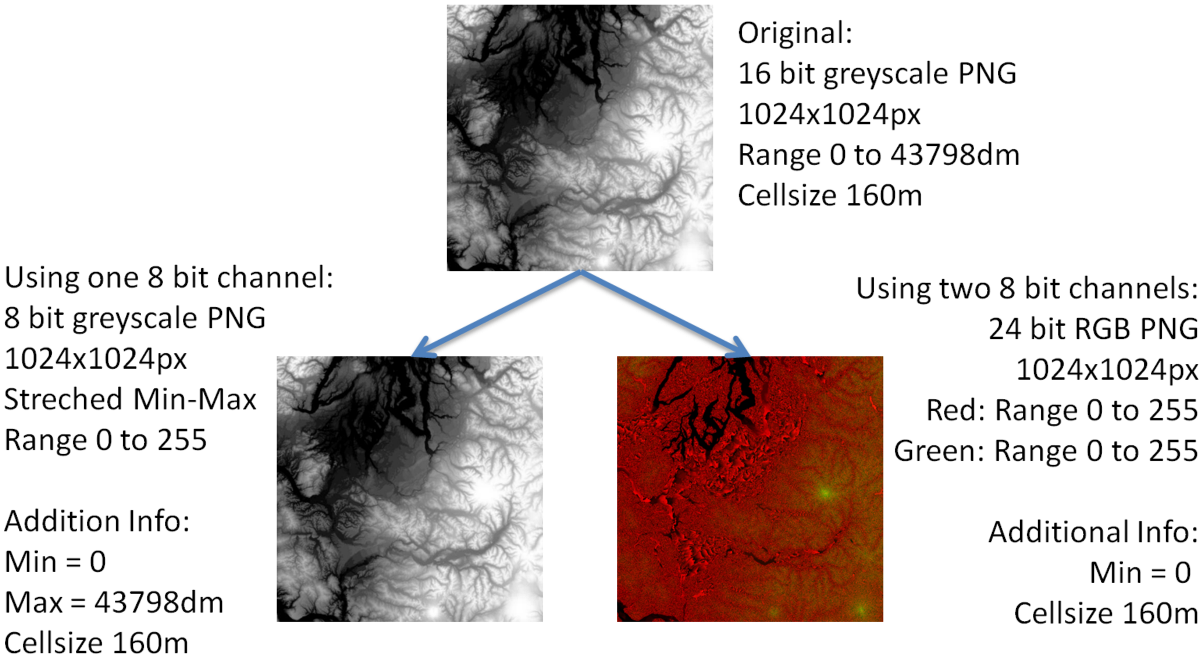

Figure II.2.4: Preparation of two DEM variants with different value encodings

To study the effects of different value representations within the PNG file and its influences on the result we compare two variants. 1) A simple variant, where values will be downscaled from higher bitrates to just 8 bits. In order to most efficiently use the available value range from 0 to 255 in the simple variant the original data will be stretched over the whole range from minimum to maximum of the original data. 2) An advanced variant which will use two 8 bit channels to encode the original 16 bit height values without loss by separating them to the red and green channel. In the latter performed algorithm the original height value can be recalculated from the two values in the respective 8 bit channels. Both versions require the storage of additional characteristic information on the dataset to be able to recompute the original height values which are needed for the hillshade algorithm as shown in the formulas below.

Recomputation of original height values from cell values:

One 8 bit channel: $height_{cell} = cellvalue_{grey}(height_{max} - height_{min})/255 + height_{min}$

Two 8 bit channels: $height_{cell} = cellvalue_{res} + cellvalue_{green} * 256 + height_{min}$

Depending on the range of values stored in the original data it is possible to encode the values with up to 4 channels (4 x 8 bits) providing the possibility of $256^4 \approx 4.3$ billion different values.

II.2.3.4 Algorithms

The hillshade algorithm used in the example scenario is based on Wiechel (1878 according to Horn 1981) who determined a formula to calculate the reflectance on an ideal diffusing surface, also called Lambertian surface. Shadings based on this assumption – how the surface would look like if it were made of a perfect material – do not result in a realistic visualization observable in nature. Nevertheless such shading methods have been widely accepted as providing a good perception of the surface shape. Horn (1981) gives a detailed overview on different approaches to generate shaded reliefs and also provides an estimation formula to compute the west-east and the south-north gradient using all eight outer cells in a 3x3 window. These gradients are necessary to compute the $slope$ and the $aspect$ values, which will be used as input parameters in the hillshade function. Burrough and McDonnell (1998) discuss alternative approaches of gradient computation and their use in $slope$ and $aspect$ calculation and give an overview on the quality of different methods. The following formulas have been used in the example workflow (Figure II.2.5) of this paper:

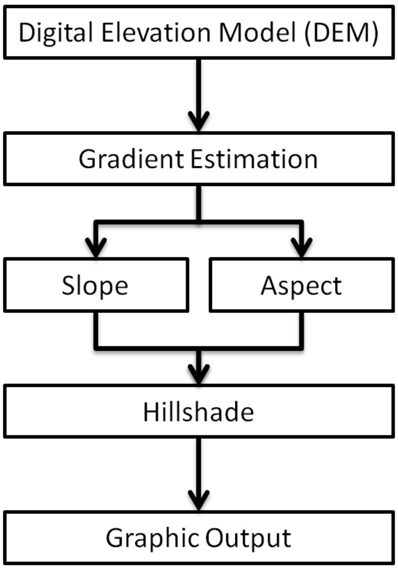

Figure II.2.5: Workflow of the hillshade computation

Horns's Gradient Estimation for raster cell e (letters according to Figure II.2.6):

West-east gradient p:
$p = [(c + 2f + i) - (a + 2d + g)]/8\delta x$

South-north gradient q:
$q = [(g + 2h + i) - (a + 2b + c)]/8\delta y$

$slope = atan\sqrt{p^2 + q^2}$

$$aspect = \begin{cases} atan(q/-p), & p \neq 0, q > 0 \\ 2\pi + atan(q/-p), & p \neq 0, q < 0 \\ 1/2\pi, & p = 0, q > 0 \\ 3/2\pi, & p = 0, q < 0 \\ 0, & p = 0, q = 0 \end{cases}$$

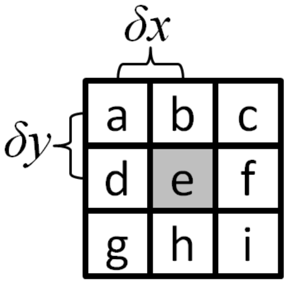

Figure II.2.6: 3x3 Window

$\boldsymbol{hillshade} = \cos(zenith) \times \cos(slope) + \sin(zenith) \times \sin(slope) \times \cos(azimuth - aspect)$

In this case the $aspect$ pointing to the west will result in a value of zero, growing clockwise to 2π. The clockwise calculation of $aspect$ values is chosen, as it will later be subtracted from the

$azimuth$ value. This comes from a user input in compass manner, which shares the clockwise orientation of values. Besides $azimuth$ also the $zenith$ angle will be taken from a user input.

II.2.4 Results

For the evaluation of the proposed method a performance test has been conducted to show the differences between parallel computation on the GPU and sequential computation. Also the influence on performance of different browsers, mobile and desktop environments will be addressed in the following section. The influence of encoding the original data with different bit depths on the quality of the output will be presented in the second part of this section. Besides quality issues and the acceleration of client side spatial raster processing, there are also limitations of the approach, which will be discussed in the last part.

II.2.4.1 Performance

The proposed method has been implemented in two ways. 1) As a WebGL application using parallel computation on the GPU and 2) for comparison using the 2D context of the canvas element for a classical sequential computation. Both implementations have been tested in two different WebGL capable browsers on a desktop computer with an ATI Radeon HD 3600 graphic card, an Intel Core2 Quad CPU and 8GB RAM on a 64 bit Windows 7 operating system. To compare desktop and mobile performance both implementations have also been run on a Samsung Galaxy Nexus Smartphone with a Firefox for Android browser (Figure II.2.7). All following figures are mean values obtained from multiple measurements. For the 2D context 50 iterations have been averaged. For the WebGL context the number of screen repaintings per second have been measured using the Time-Control-for-Script-based-Animations API (W3C 2012b) which optimizes the invocation of drawing calls.

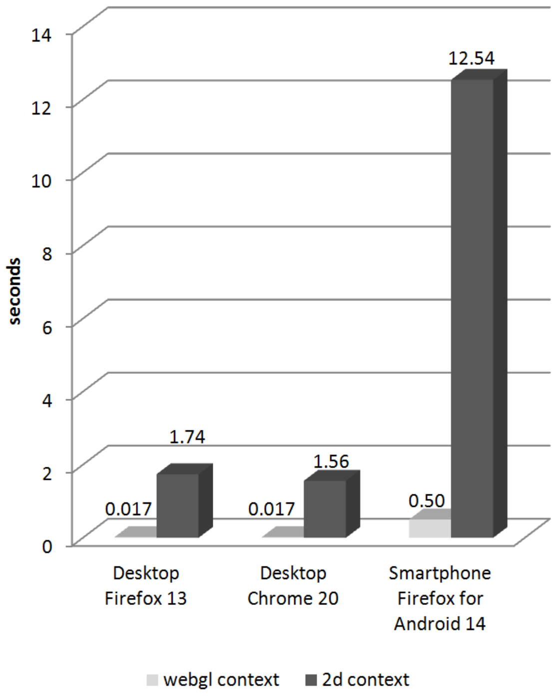

Figure II.2.7: Performance results comparing sequential (2d context) with parallel (webgl context) hillshade computation on different browsers and platforms

The desktop comparison revealed a high computation rate of the hillshade processing in the WebGL context. Both tested browsers could render the 1024x1024px hillshade in the fastest possible screen refreshing rate of 60 Hz which corresponds to 0.017 s for a single raster computation. This is about 90 to 100 times faster than the same computation using the sequential way with the 2D context, with Chrome being slightly faster than Firefox. It was predictable that the performance on a mobile platform would be lower. But nevertheless, the WebGL approach with 0.5 s was about 25 times faster than the sequential computation with 12.54 s. These figures demonstrate that the WebGL client side approach is a real option on desktop and mobile devices to speed up visual analysis results and reduce communication traffic at the same time.

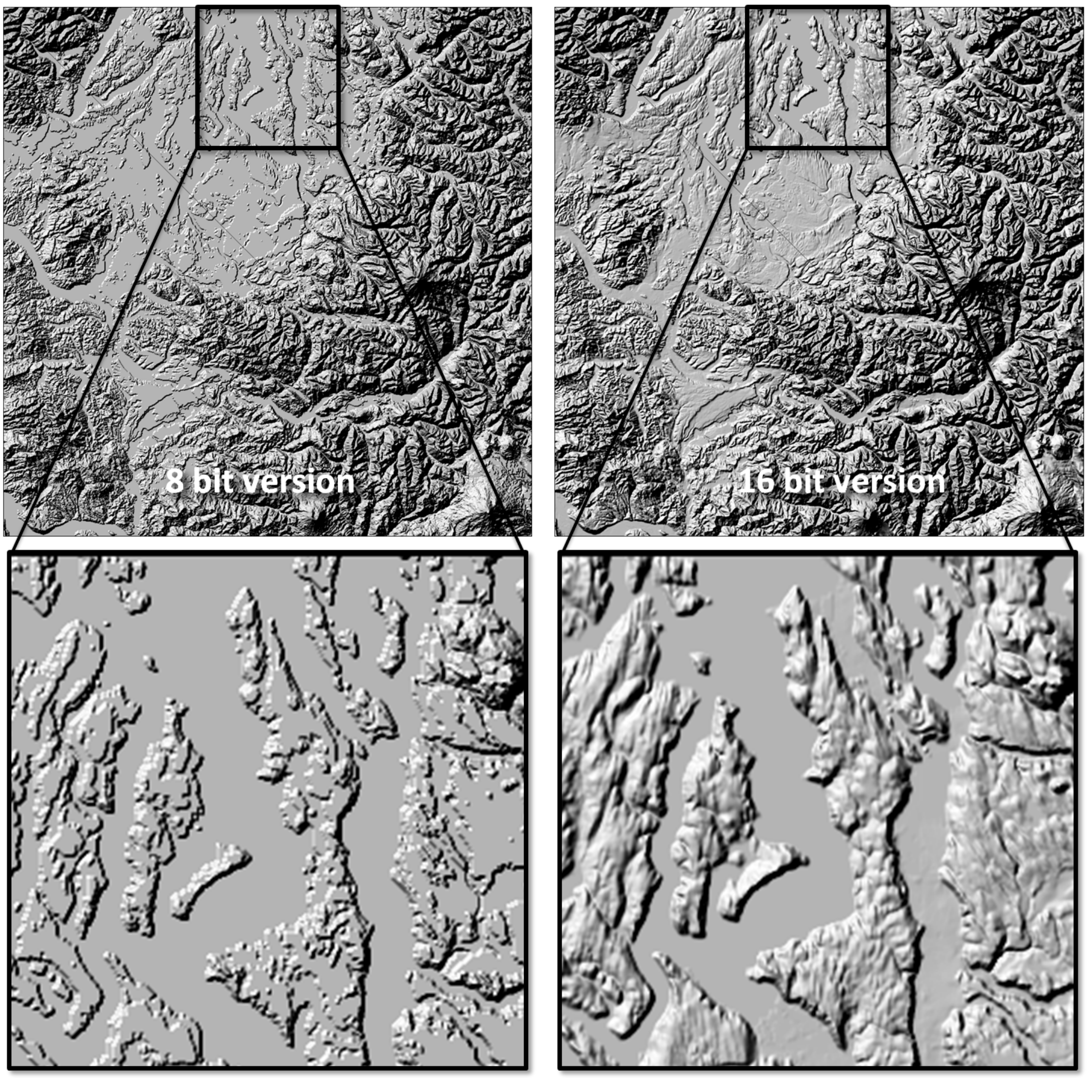

Figure II.2.8: Quality differences of 8 bit and 16 bit encoded height values on the hillshade output

II.2.4.2 Quality

In the section on data handling it has been already explained that PNG images will be automatically converted to an internal format of 4 channels (RGBA) with each having 8 bits at its disposal. A way to use two or more of the 8-bit channels to simulate higher bit depths per pixel has also been demonstrated. This section presents the influence on the results either using the standard 8 bit greychannel approach versus the encoding of height values in two 8 bit channels.

Figure II.2.8 shows the resulting hillshades of each version including a magnified area of a hilly landscape of the Puget Sound near Seattle, Washington, including water bodies and islands. A first glance on the whole pictures almost equally reveals a good overview on the landscape configuration. But having a closer look it can be clearly seen that the character of the surface shape is altered heavily in details. Depending on the purpose it can be suitable to downscale the quality. But for more demanding applications the original quality of the dataset can be preserved with the proposed method to deliver as good results as any other GIS Software.

II.2.4.3 Limitations

Up to now we have seen that it is possible to produce spatial analysis results with high quality at an enormous speed in WebGL enabled web browsers. However the proposed method has some limitations. As already discussed, WebGL textures, which will store the values from the input image, only support up to 8 bits per channel, but we can overcome this restriction by combining several channels for the storage of one value. In many cases geodata consists of decimal numbers. It is not possible to store them in a PNG file directly nor are they supported in WebGL textures by default. In case of a fixed number of digits in the fractional part, all values can easily be converted to integers by multiplying with the according power of ten. If it comes to floating point numbers, it would be possible to implement a conversion to 4 channels reaching a precision of 32 bits which corresponds to single precision according to the IEEE Standard for Floating-Point Arithmetic (IEEE 2008). This means using a conversion function we can also store different kinds of decimal numbers within a PNG. But as stated above also the WebGL textures do not support floating points by default. Nevertheless the WebGL API enables the application to request additional extensions which may be supplied by the hardware: on most desktop systems it is possible to enable the "GL_OES_texture_float" extension. This allows WebGL textures to directly store decimal numbers. Another restriction is the maximum allowed texture size. This size is device dependent and varies from 2048 px2 to 16384 px2. It limits the size of the data which can be processed within one step. For larger datasets a tiling mechanism or other appropriate reduction strategy has to be applied. A very important limitation is given by the OpenGL ES Shading Language Specification GLSL (Khronos Group 2009). It limits loop indices and control variables to be constant expressions. That means it is not possible to define a varying number of loop iterations based on global variables. The number of iterations shall be easily determinable at compile time. This has the effect that the parallel computations for each fragment or pixel will endure more or less the same amount of time. For the implementation of spatial algorithms which need to process varying amounts of values for each cell it is important to consider a division into parallelizable and non parallelizable parts. These different parts need to be restructured respectively, similar as Xia et al. (2011) proposed for a viewshed algorithm.

Last but not least there may be more limitations which have to be considered. This include for example the maximum number of different types of variables in the different shader programs, maximum number of texture units and many more which are device dependent. A very good overview of those parameters is given on the website http://webglstats.com by Florian Boesch.

II.2.5 Conclusion

The application of new technologies like HTML5 and WebGL in a geospatial context, not only for 3D Applications, can generate new user experiences due to the fastness of hardware accelerated parallel computations on the graphics processing unit (GPU). In this paper a new method has been introduced to use the processing power of GPUs for Web GIS applications and demonstrated its performance on an example implementation of a real-time hillshading. An acceleration factor of 100 could be reached using the WebGL approach in comparison to the sequential approach of the 2D canvas API on desktop platforms. Although there are several limitations to this approach, most of them can be overcome by certain strategies of data handling. Depending on the original data properties, taking care of adequate data preparation can lead to promising results. The possibilities offered by the proposed method extend the classic paradigm of Web GIS architecture from only server side analysis to a stronger focus on client side computation for the ease of browsing and analyzing of spatial data. The speed gained through the application of this method demands the development of new user interfaces which let the user perceive spatial information in a more responsive and interactive way. To make the proposed method usable for a large community of geo web designers there is still some future work to do. A JavaScript library of parallelized spatial algorithms would facilitate the use of this new technology without the need of being an expert in 3D graphics programming. The integration of such functionality into existing web mapping frameworks like OpenLayers and the likewise consideration of open geospatial standards to provide services for data preparation, e.g. an OGC Web Processing Service, seem to be a promising way.

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II.3 Web-based Visualization and Query of Semantically Segmented Multiresolution 3D Models in the Field of Cultural Heritage

Abstract

Many important Cultural Heritage sites have been studied over long periods of time by different means of technical equipment, methods and intentions by different researchers. This has led to huge amounts of heterogeneous "traditional" datasets and formats. The rising popularity of 3D models in the field of Cultural Heritage in recent years has brought additional data formats and makes it even more necessary to find solutions to manage, publish and study these data in an integrated way. The MayaArch3D project aims to realize such an integrative approach by establishing a web-based research platform bringing spatial and non-spatial databases together and providing visualization and analysis tools. Especially the 3D components of the platform use hierarchical segmentation concepts to structure the data and to perform queries on semantic entities. This paper presents a database schema to organize not only segmented models but also different Levels-of-Details and other representations of the same entity. It is further implemented in a spatial database which allows the storing of georeferenced 3D data. This enables organization and queries by semantic, geometric and spatial properties. As service for the delivery of the segmented models a standardization candidate of the OpenGeospatialConsortium (OGC), the Web3DService (W3DS) has been extended to cope with the new database schema and deliver a web friendly format for WebGL rendering. Finally a generic user interface is presented which uses the segments as navigation metaphor to browse and query the semantic segmentation levels and retrieve information from an external database of the German Archaeological Institute (DAI).

Keywords: Three-dimensional, Virtual Reality, Spatial Infrastructures, Visualization, Multiresolution, Segmentation

II.3.1 Introduction

In the realm of Cultural Heritage documentation, visualization and analysis important sites and monuments are studied over time by different means of technical equipment, methods and intentions by different researchers. This generally results in heterogeneous datasets spread around different research institutions, stored and archived in different media types and formats with heterogeneous data models and quality. These general characteristics also apply for the UNESCO World Heritage Site of Copán (Honduras), which already has been studied for over 100 years. It is an important historical place where rich written sources have been found along with impressive temple structures and stone carvings. This archaeological site provides unique insights into its history of construction which can be linked over several centuries to the local ruling dynasty of at least 16 rulers. Since the 19th century a lot of archaeological finds like sculptures, inscriptions and ceramics, but also scientific data have been found and recorded at different locations and archives all over the world.

In recent years the creation of 3D models in cultural heritage has become more and more popular. This is due to several reasons: a) increasing availability of capturing technology, specifically designed for objects of different scales, complexity in shape and surface and different materials b) increasing capabilities of hardware and software to process, store and visualize models, c) increasing demand for different use cases, e.g. conservation, restoration, education, 3D GIS analysis (Pavlidis et al. 2007; Manferdini and Remondino 2012).

In addition to the creation of reality-based 3D models of existing objects, there is often the need to create reconstructed versions of objects using CAD programs or other 3D modelling software to test archaeological or historical hypothesis and to present the results to the public. The diverse possibilities of 3D model creation in cultural heritage results in collections of very heterogeneous types of 3D data for a single cultural site with different resolutions, accuracy, surface properties, coordinate systems etc.

For the resource management, research and public-educational outreach of large heritage sites it is crucial to organize and facilitate the access to 3D models and the corresponding meta-, media- and attribute data. As the amount of data grows and the data are distributed at different archives and databases, the usual way is to tie all information sources together and grant access to them through web-based solutions. In this scenario 3D models can be used as an intuitive graphical interface to access the data behind. A segmentation of the 3D models, no matter being reality-based or reconstructed, into semantic entities and subentities according to different aims is an important step in preparing and organizing the data to connect geometry with semantic information using virtual reality as an intuitive communication vehicle.

The following introductive sections describe the frames determining the conditions in which our approach applies semantically segmented models, the greater thematic research frame and the technical circumstances that have to be considered.

Section II.3.2 will describe in detail the process of visualization and query and all the preconditions for storing, transmitting, interacting and querying such kind of data.

The paper ends with a short conclusion and outlook of the upcoming fields of research.

II.3.1.1 MayaArch3D research platform

The MayaArch3D project – a collaboration between the German Archaeological Institute (DAI), the Chair of GIScience Heidelberg University and the 3D Optical Metrology Research Group of the Bruno Kessler Foundation (FBK) Trento, funded by the German Ministry of Education and Research (BMBF) – is currently working on a web-based research platform for the Maya archaeology of Copán (Billen et al. 2013). It will combine 2D and 3D georeferenced datasets together with ungeoreferenced datasets and tie these to further textual and graphical data stored in the non-spatial *iDAI.Field* database of the DAI, which contains mainly archaeological records and associated media like images and drawings based on FileMakerPro. It will further combine airborne and terrestrial laser scanner data with photogrammetrically derived and CADreconstructed 3D models of different resolutions. All 2D and 3D geometric information will be stored in a spatial database (based on PostgreSQL/PostGIS), while all semantic information will be kept inside the yet existing archaeological database *iDAI.Field*. The platform will connect both databases, spatial and non-spatial, to a group of mostly standardized web services to form a spatial data infrastructure (SDI) for archaeological research. These services include 2D/3D portrayal services (OGC WMS, W3DS), 2D/3D feature services (OGC WFS, 3DPostGIS- Geometry-Service, FileMakerPro-Attribute-Service), a raster service (OGC WCS), a Time-Service to convert Gregorian Calendar dates to Maya Long Count dates and vice versa and an Lightweight Directory Access Protocol Service (LDAP) as security service to provide different levels of access to the data.

Having all these web services at hand, a web-based Geographic Information System (GIS) is built to access, visualize and analyze the collected data in a spatio-temporal way over the World Wide Web. The client application therefore builds on top of the open-source geomajas[1] 2D web GIS framework and is complemented by a spatially enabled 3D framework GIScene developed by GIScience Heidelberg University using WebGL technology (Khronos Group 2013) and the open-source Three.js[2] JavaScript library.

For the 3D part of the application two components will be integrated. First a georeferenced 3D scene is provided to explore landscape, settlement, building and other structural features. Because of the georeferenced coordinate system in this scene, it becomes possible to combine it with other GIS related data e.g. overlays from raster files or map services or user defined vector data, thus providing individual analysis possibilities for researchers from different domains with different research questions and approaches.

Besides the scene viewer for georeferenced 3D data, a single object viewer is provided to study objects in higher resolutions, providing different modes for georeferenced and nongeoreferenced models.

Both 3D components support the user's interaction with models segmented into a hierarchy of semantic entities and provide the necessary user interface to access attribute information from databases on all semantic segmentation levels and groupings. Segmented models can be used to differentiate parts of objects with different meanings and as interface to either access models of higher resolutions or other information related to that specific semantic entity (Manferdini and Remondino 2012).

With this infrastructure, the extent of data that can be visualized and analyzed reaches from the Mesoamerican distribution of archaeological Maya sites to small 3-dimensional laser-scanned stone objects of a couple of centimetres found during excavations of temples and other structures.

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[1] http://www.geomajas.org/

[2] Three.js is an open-source JavaScript API for 3D visualization using WebGL, http://threejs.org/

II.3.1.2 Constraints and potential of web-based 3D visualization using WebGL

Using WebGL for the visualization of 3D models has several implications. One the one hand, it offers the integration of 3D content into web applications without any dependencies of third parties. No plugins or Java applets have to be installed by the end-user and all major browsers[3] have implemented at least a partial support. Further in the scope of 3D GIS analysis the usage of a WebGL based technology has the advantage over plugin-based solutions, in that there is a direct access to the rendering pipeline of the graphics card, the so called programmable pipeline of OpenGL ES 2.0 (Khronos Group 2010). Instead of simply using predefined rendering shaders, e.g. Gouraud or Phong shading, developers can define their own functions to be executed very fast in parallel on the graphics processing unit (GPU) (Auer 2012). This offers a great potential for new web-based 3D GIS analysis. First results have been achieved in the project visualizing orientation or alignment of surfaces towards compass directions or point locations.

On the other hand, a WebGL application completely relies on the JavaScript engine the browsers uses to interpret the application code. In contrast to desktop applications, browser applications written in JavaScript have no direct control over the memory management. Dealing with large 3D models of heritage sites implies that a careful selected strategy to load and unload 3D model data has to be applied. This can only be reached when the model data can be loaded incrementally as parts and in different resolutions depending on the visible field, observer distance and viewing angle. The goal here is to visualize only those parts in high resolutions that are near and visible to the user and to reduce the amount of data for the rest of the scene. With the multi-resolution and segmentation approach presented in this paper such a strategy can be realized. A test about memory consumption using Three.js revealed that it is suitable to show models or scenes with up to 1.000.000 triangles at a consumption rate of about 1 GB of RAM, whereas point cloud representations are far less memory intensive (Fig. II.3.1).

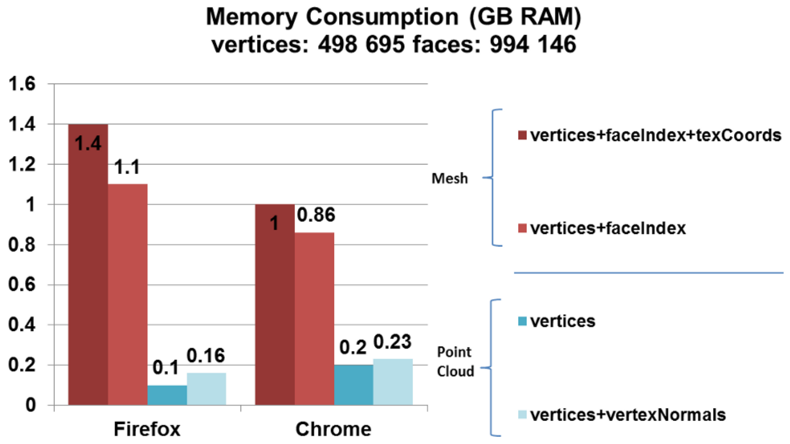

Figure II.3.1: Memory consumption visualizing large 3D models using Three.js

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[3] InternetExplorer11, Firefox4, Chrome8, Opera12, Safari5.1 (see http://caniuse.com/webgl for up to date information)

II.3.2 Related Work

In terms of a 3D platform to query semantic information with the help of segmented models, a previous project developed a tool named QueryArch3D (Agugiaro et al. 2011b; Agugiaro et al. 2011a; Schwerin et al. 2013). In contrast to the current project, the predecessor was based on a plugin solution from unity3d[4] and exclusively dealt with 3D data.

Combining 2D and 3D georeferenced data in a single web GIS application has also been realized by a project called 3D Sutras but without using segmented 3D models as user interface for data queries. On the other hand, that project used the W3DS as well and other OGC standardized web services to deliver 2D and 3D data and similar to this project integrated a non-spatial database already existing with the newly created spatial database (Auer et al. 2011; Lanig et al. 2011).

Apollonio et al. (2012) use semantically structured 3D models in a 3D web-based repository of reality-based data. They use this type of data not only as representations of real world objects but also as metaphors to navigate in other types of data. WebGL-based GIS analyses have been described for 2D and 2.5D data in Auer (2012).

Hierarchical concepts to store and exchange geometric-semantic relationships are used in standards for different domains than cultural heritage, like Building Information Models (BIM) for planning and management of facilities (ISO 2013) or CityGML, an OGC standard for modelling 3D city models (Gröger et al. 2012). The approach presented in this paper is reflecting those principles, but specifically adopt the necessary object entities to the concepts of Maya architecture and arts.

Manferdini and Remondino (2012) give an overview of segmentation methods, purposes of semantic segmentation and existing hierarchical modelling concepts from other domains which relate geometry parts to semantic information.

Unfortunately, the existing concepts are not always suitable for an application in cultural heritage because of the variety of structures found in ancient cultures like in the Maya architecture and art, which often is mixed with textual information in form of relief glyphs.

II.3.3 Visualization and Query of Semantically Segmented 3D Models

The following sections describe our approach to store, transmit and interactively query semantically segmented 3D models in a web application. In the case of the MayaArch3D project the segmentation process is done manually by Maya researchers. The entities to which the different kinds of objects are segmented have been defined beforehand by agreeing on a hierarchical system of semantic object classes and several levels of subclasses. These well-defined ontologies ensure that the segmentation process is transparent, replicable and reusable for future acquisitions and incorporation of Maya structures into the research platform presented in this paper.

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[4] https://unity3d.com/unity

II.3.3.1 Storing semantically segmented models

For the MayaArch3D project an approach to store and integrate both the geometric and the thematic information has been studied and implemented, given the several constraints and requirements to be taken into account during the development of the database structure. The goal was to overcome interoperability and performance issues between PostgreSQL and FileMakerPro (the latter already containing all attributes of the Copan features). As a consequence, following design decisions were taken:

1. PostgreSQL (together with its spatial extension PostGIS 2.0) stores only geometries, textures and the very minimum amount of data to allow the connection to the corresponding FileMakerPro records (essentially: foreign IDs). This split design corresponds to an initial requirement to keep the FileMakerPro in use as source of the attribute data. Each object stored in PostgreSQL is linked to the corresponding FileMakerPro record containing the attributes and metadata.

   The spatial extension PostGIS 2.0 has been chosen as, besides the well-proven capabilities in 2D geometry, new 3D object types with corresponding 3D operations have been added. They can directly be used during the SQL queries.

   For a better reading, in the following the PostgreSQL/PostGIS-based database will be called *3dmaya-db*, while the FileMakerPro-based database will be referred to *iDAI.Field*. The former is hosted at the Heidelberg University, the latter by the German Archaeological Institute (DAI) in Cologne.

   iDAI.Field applies a thoroughly developed database schema, which was tested and enhanced in several archaeological projects.

2. Particular attention was paid to create an ontology for the objects to be stored in *3dmaya-db* (temples, palaces, etc.), as well as the accompanying hierarchies for all "part-of"-relations. The goal was to ensure a spatiosemantic coherency which allows to define what exactly an object is and how it relates to the other objects (e.g. a wall to a room).

3. As a consequence, it is possible to store models both as a whole, or their segments. Moreover, for the same object, multiple representations are possible. For example, one can store a model as a 2D feature, its extruded 3D model, or other fully 3D models obtained by means of laser scanning or photogrammetry (either as mesh or point cloud).

4. Despite this initial "split" configuration, particular care has been put into the design of the database structure to obey to the rule of simplicity, avoiding unnecessary data redundancy, and allowing for enough flexibility to be extended in future in case of special or new needs. The separate storing of geometry and attributes make it easy to adopt the system to use other attribute databases in case of changes due to technology advancements or new project requirements. For example, should one day *iDAI.Field* be dropped completely, it will not be hard to integrate the existing attributes into the existing *3dmaya-db* structures or connect to another database.

In order to cope with the complexity of multiple geometric models, which are required to reflect independent data collection processes, multiple levels of details (LoDs) were defined. LoDs facilitate efficient visualization and data analysis. In analogy to the CityGML approach (Kolbe 2009), and drawing from previous experiences with Copán data (Agugiaro et al. 2011a), five levels of detail were defined for the structures of Copán: the higher the LoD rank is, the more detailed and accurate the model is.

- LoD0 contains simplified 2D polygon (or multipolygon) entities. This LoD is thought to allow for a classical 2D GIS-based representation. Original data were provided as a shapefile (Richards-Risetto 2010). These data are not used in the 3D visualization tools.
- LoD1 contains simplified 3D prismatic entities with flat roofs. More specifically, all LoD1 models were obtained starting from the LoD0 data by means of extrusion and triangulation of the features.
- LoD2 contains 3D structures at a higher level of detail, however only the exteriors of the structures. The substructures (e.g. walls, roofs or external stairs) can be identified. For the LoD2, hypothetical reconstructions models obtained for example in 3D Studio Max can be imported and stored. The upper limit in terms of triangles is set to be 150.000 in an area of 1024 m^2.
- LoD3 adds the interior elements (rooms, corridors, etc.) to the structures. Some simplified, reality-based model parts can be optionally added, both to the interior and to the exterior of the structures. The reality-based models can be obtained from the more detailed ones used in LoD4 by applying mesh simplification algorithms. For each feature, the upper limit in terms of triangles is set to be 100.000.
- LoD4 contains structures (or parts of them) as highresolution (e.g. laser-scanner-acquired) models. These models can be further segmented into subparts. For each feature, the upper limit in terms of triangles is set to be 300.000.

The limits of triangles chosen in the above LoD concept reflect several constraints, such as the amount of data to guarantee a high rendering performance, the memory management in JavaScript (see Section II.3.1.2) but also the application design. The application design allows users to open several windows with 3D content, so the limits for each LoD is not what theoretically could be displayed but rather a practical estimation to keep the web application stable in different usage scenarios.

The adoption of a LoD-dependent hierarchical schema required the contextual definition of a geometric and semantic hierarchical schema. This was achieved by an accurate identification and description of the so-called "part-of"- relations, in order to guarantee a spatio-semantic coherence (Stadtler and Kolbe 2007).

Such a database structure that reflects all the considerations mentioned above, allows at the same time the development of a user interface which enables jumping forth and back between different LoDs and other representation types, and also traversing up and down through the

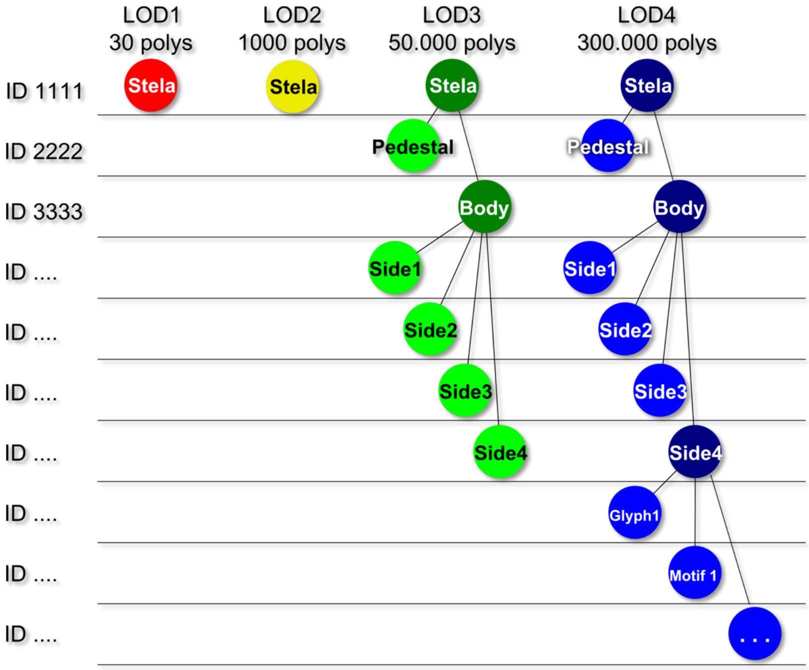

Figure II.3.2: Database structure to store semantically segmented models in the MayaArch3D project

semantic segmentation levels using the same database structure for temples, houses, stelas, altars and other object types.

The key point of the database structure here is, on the one hand, the use of consistent IDs for all LoDs and further representations of the same object and, at the same time, to store parent relationships for all objects to reflect the position of each object inside the semantic hierarchy tree, as shown in Figure II.3.2.

II.3.3.2 Transmission of semantically segmented models

For the transmission of the segmented models and their semantic content several web services have been deployed. The Web3DService (W3DS) is currently in the process of standardization and its specification is available as a discussion paper at the Open Geospatial Consortium (OGC)[5] (Schilling and Kolbe 2010). Though very useful for building 3D web GIS because of its capability to retrieve a collection of georeferenced 3D models by specifying a spatial bounding box and a LoD, in its current version it lacks the possibility of requesting single objects by their ID. Therefore a second web service – the Geometry Service – has been implemented to specifically demand models or model segments in a given LoD by specifying its ID (Fig. II.3.3). It traverses the graph structure in the *3dmaya-db* and allows to either request for a specific node or all children of a certain node. If a "children" request is received, all child-nodes of the given node-ID will be returned. If a specific "node" is requested, the service returns this node and its

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[5] `http://portal.opengeospatial.org/files/?artifact_id=36390`

```
<server>/<servicename>/<output format>/<SRID>/
  <id>/
  {node,children}/
  lod/<x>/
  [
    bbox3d/<x1>/<y1>/<z1>/<x2>/<y2>/<z2>/
  XOR
    bbox2d/<x1>/<y1>/<x2>/<y2>/
  ]
  [
    offset3d/<x>/<y>/<z>/
  XOR
    offset2d/<x>/<y>/
  ]
```

Figure II.3.3: RESTful URL schema of the Geometry Service

geometry, if available. The service is implemented as RESTful interface as shown below (Fig. II.3.3).

Both services, the W3DS and the Geometry Service, are able to retrieve data from the *3dmaya-db* and convert them to a suitable format for delivery. Generally, for the exchange of hierarchically segmented models all formats that are capable to represent a scenegraph could be used. In this specific case, the native scene format of Three.js is used. It is a JSON[6] based text format, which specifies the parent-children relationships of the scene, its materials and it can either contain inline geometry definitions or references to other sources also stored in different formats. This approach grants a great flexibility for the future in case other formats for single objects in the scenegraph would prove more successful.

A third service can be used to gather attribute information on the geometries fetched earlier from one of the two 3D services. This Attribute Service is defining a RESTful interface to retrieve data by IDs which are coherently attached to the geometries.

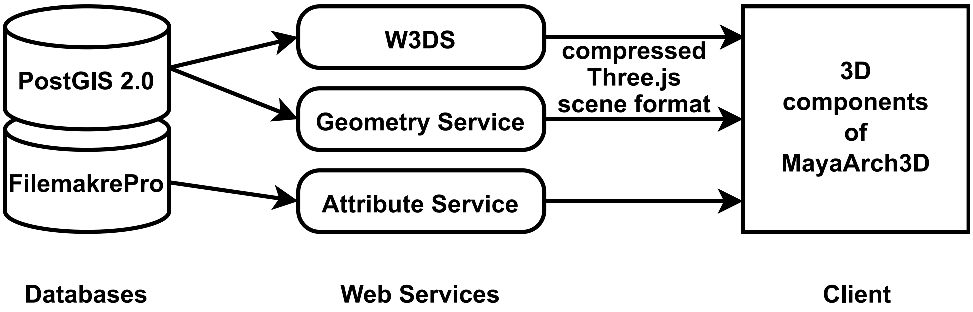

Figure II.3.4: Compressed transmission of segmented models from PostGIS 2.0 database via web service to the 3D components of MayaArch3D

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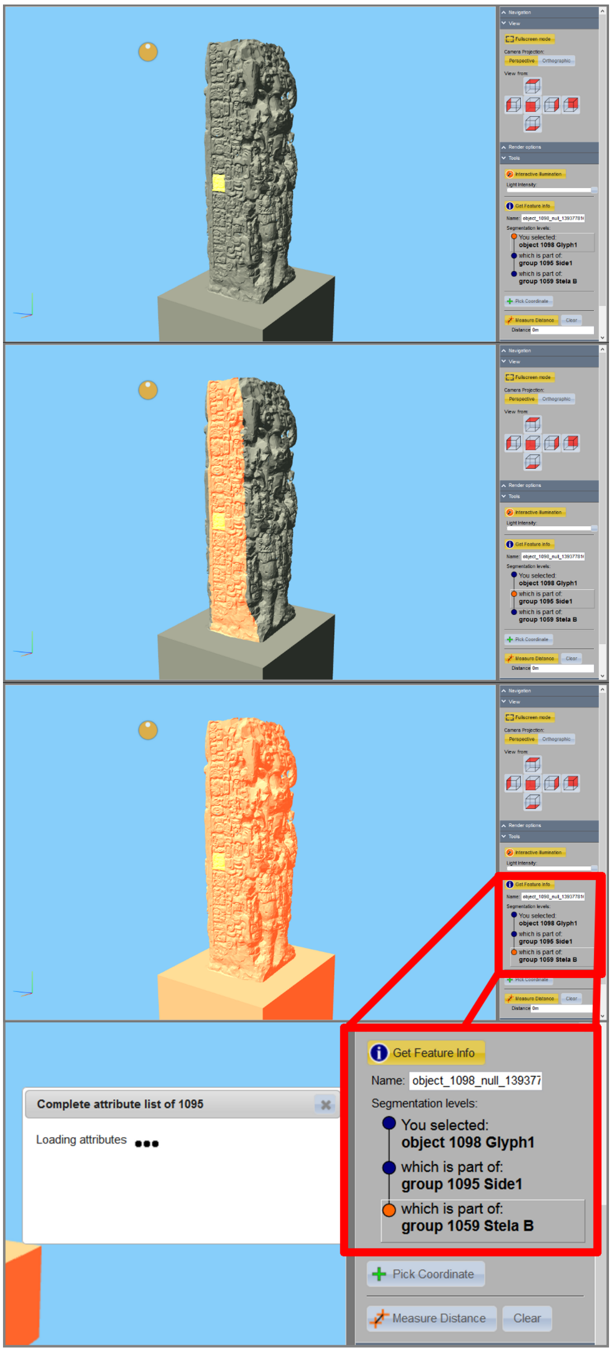
[6] JSON: JavaScript Object Notation

To achieve short download and response times in the web application it is of great importance to reduce the amount of data to be transferred. A compression of data to be transferred over the web always is a trade-off between the time needed for the compression and the time for the transfer without compression. Large polygonal 3D models with 300.000 triangles have a size of about 30MB as JSON text. Depending on the network speed, it can take up to several minutes to load. A very fast and on-the-fly applicable compression algorithm is the deflate-algorithm (Network Working Group 1996). In several tests with different models in the initial project phase it achieved a compression rate of about 25%. One big advantage of this compression method is the capability of all major browsers to automatically decompress files that are indicated as compressed by their http headers. This means no further processing in JavaScript is necessary to receive the original uncompressed content.

II.3.3.3 Interaction and query user interface for semantically segmented models

After the automatic decompression of the incoming scene file from the services by the web browser, the resulting JSON text can directly be converted into JavaScript objects. Nevertheless it is necessary to process this information to:



Complete attribute list of 1095

Loading attributes •••

Name: object_1098_null_139377

Segmentation levels:

You selected:
object 1098 Glyph1

which is part of:
group 1095 Side1

which is part of:
group 1059 Stela B

Figure II.3.5: Interactive query of segmentation levels of a manually segmented Stela

1. Generate an internal JavaScript representation of the delivered scenegraph

2. Generate all the necessary data structures (geometry, textures, texture coordinates, colors, normals etc.) and send them via the WebGL API to the graphics card for visualization

3. When dealing with georeferenced 3D models whose coordinates contain big numbers apply a shifting transformation to obtain short coordinates. This is necessary to avoid jitter effects in the display because of limited precision of number representations on the GPU

4. Retrieve all leaf nodes of the scenegraph (nodes which contain geometry) to make them selectable for interactive information retrieval

Once the data structures inside JavaScript and the GPU have been created, it is necessary to provide a user interface that allows the user to easily explore the data and query the respective attributes from the database via the Attribute Service.

The user interface consists of two components: 1) the canvas which depicts the 3D scene 2) an additional dialog on the sidebar to choose the segmentation level.

In a first step the user selects a model segment in the 3D canvas which will be highlighted, e.g. a glyph. Directly after this selection, the second dialog will be generated. Therefore it is necessary to determine all parent nodes of the selected segment and their IDs. A process traverses up the internal scenegraph representation of the segmented model from the clicked segment up to the root node and collects a list of parent entities. This list can then be used to generically create the dialog. Hovering over the resulting list with the segmentation branch the user can select the semantic segmentation level he is interested in, e.g. the stela side, to perform a database query via the Attribute Service and the given ID.

Figure II.3.5 illustrates the process of clicking one of the objects of the highest segmentation level and the interactive highlighting of all possible parent groupings which then can be selected to retrieve further information. For an effective browsing of the data only a few characteristic attributes are shown directly inside the sidebar dialog. Several of such short attribute lists can be retrieved and compared. Then in a second step the user can decide to display a complete list of attributes for a segment in an additional floating window. This way an effective and rapid browsing of the data can be achieved to facilitate the creation of new hypothesis about relations in the data or getting quick access to the data of a specific semantic piece.

II.3.4 Conclusion and Outlook

The work presented in this article is an approach for the visualization and query of semantically segmented models of multiple resolutions. It outlines the thematic and technological frames in which this approach is successfully applied. It describes in detail the conceptual considerations and technical challenges that led to the presented solutions of storage, transmission, interaction and query of the specific data structures of semantically segmented models in the field cultural heritage.

The proposed infrastructure is highly flexible and compatible with other cultural heritage sites as it separates between the two- and three-dimensional geometry data and attribute data connected to the 3D models.

Two 3D components have been developed:

a. a georeferenced 3D scene allowing the exploration of landscape, settlement, building and additional structural features and

b. a single object viewer allowing the study of georeferenced or non-georeferenced objects in high resolutions.

These tools give researchers of various domains in the field of cultural heritage the possibility to visualize and interact with semantically segmented 3D models and provide the necessary user interface to access attribute information from databases on all parts of a semantically segmented model.

The use of WebGL technology proves to be a feasible approach. Despite its constraints in memory management, it offers a great new field of possibilities to develop 3D GIS visualization and analysis components for the World Wide Web while improving the accessibility to the growing amount of detailed and complex cultural heritage data.

Future work will concentrate on the study and development of 3D GIS analysis functionality in the area of 3D visibility and accessibility of ancient settlement structures in the scope of Maya archaeology. Further interest exists in the comparison of semantic segments of different objects located at different places to study patterns of similarity, e.g. of stone carved glyphs and motifs.

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II.4 3D WebGIS: From Visualization to Analysis. An Efficient Browser-Based 3D Line-of-Sight Analysis

Abstract

3D WebGIS systems have been mentioned in the literature almost since the beginning of the graphical web era in the late 1990s. The potential use of 3D WebGIS is linked to a wide range of scientific and application domains, such as planning, controlling, tracking or simulation in crisis management, military mission planning, urban information systems, energy facilities or cultural heritage management, just to name a few. Nevertheless, many applications or research prototypes entitled as 3D WebGIS or similar are mainly about 3D visualization of GIS data or the visualization of analysis results, rather than about performing the 3D analysis itself online. This research paper aims to step forward into the direction of web-based 3D geospatial analysis. It describes how to overcome speed and memory restrictions in web-based data management by adapting optimization strategies, developed earlier for web-based 3D visualization. These are applied in a holistic way in the context of a fully 3D line-of-sight computation over several layers with split (tiled) and unsplit (static) data sources. Different optimization approaches are combined and evaluated to enable an efficient client side analysis and a real 3D WebGIS functionality using new web technologies such as HTML5 and WebGL.

Keywords: 3D, WebGIS, performance, analysis, line-of-sight, visibility

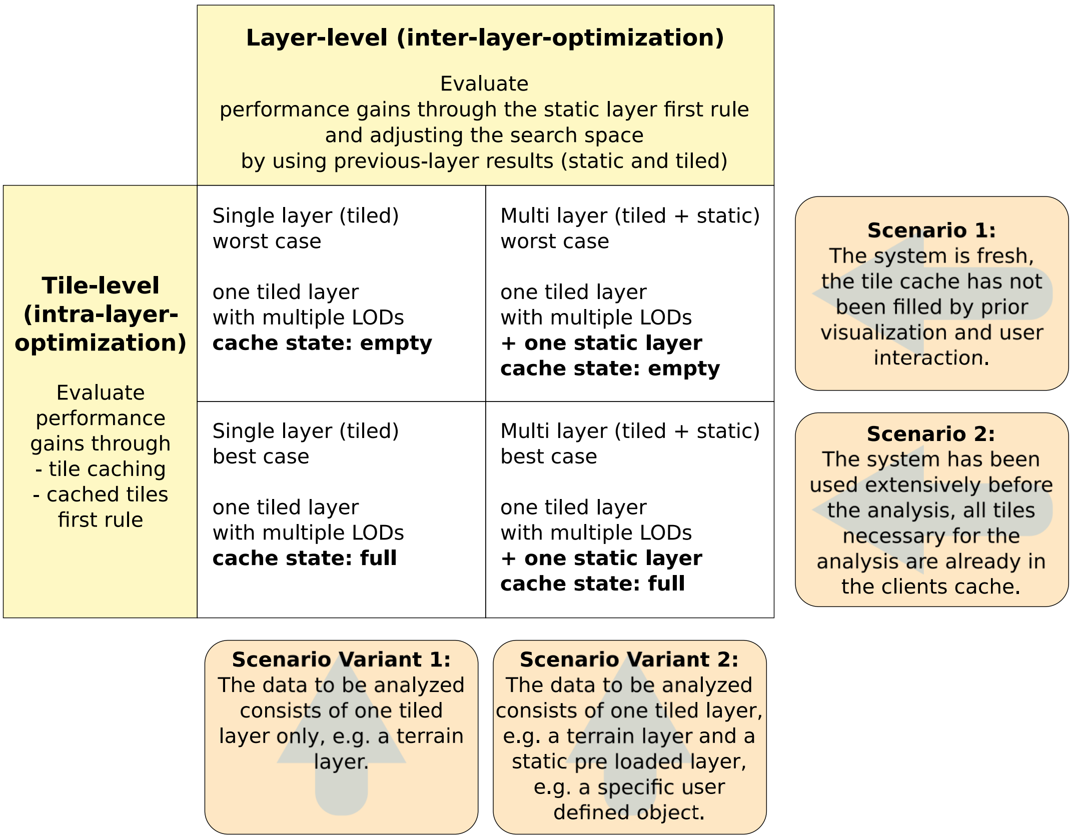
II.4.1 Introduction

This paper aims to promote the usage of WebGIS beyond visualization as an analytical tool. We describe the implementation and evaluation of a browser based 3D line-of-sight analysis. Besides computing if the line between two points in 3D space is obstructed or not, the analysis returns the point of obstruction, which is determined by finding the closest intersection of the sight line with any triangle in the scene. To tackle performance and scalability issues, it uses strategies such as compression, tiling, streaming and caching known to work for visualization and adapts them to carry out data intensive analyses over the web. It takes a holistic view on the problem scope by presuming a realistic use case where an analysis has a prior phase of visualization, and that the data to be analyzed are composed of several layers with different characteristics and potentially integrated from distributed sources. The described method for a

3D line-of-sight analysis takes advantage of that holistic view, which opens more possibilities for process optimization than considering only the visibility computation.

The example of a 3D line-of-sight computation demonstrates well the challenges that have to be solved in the context of the browser based spatial analyses. Its efficient computation is relevant for the development of further 3D WebGIS functionalities, as the line-of-sight can be used as an atomic process of more complex visibility analysis such as viewsheds.

To demonstrate the qualities of the proposed concept, it was evaluated in different scenarios (Figure II.4.1) to reveal the potential performance gains and its scalability as well as its limitations in different usage constellations.



Layer-level (inter-layer-optimization)

Evaluate
performance gains through the static layer first rule
and adjusting the search space
by using previous-layer results (static and tiled)

Tile-level (intra-layer-optimization) Evaluate performance gains through - tile caching - cached tiles first rule		
	Single layer (tiled) worst case one tiled layer with multiple LODs **cache state: empty**	Multi layer (tiled + static) worst case one tiled layer with multiple LODs **+ one static layer** **cache state: empty**
	Single layer (tiled) best case one tiled layer with multiple LODs **cache state: full**	Multi layer (tiled + static) best case one tiled layer with multiple LODs **+ one static layer** **cache state: full**

Scenario 1:
The system is fresh, the tile cache has not been filled by prior visualization and user interaction.

Scenario 2:
The system has been used extensively before the analysis, all tiles necessary for the analysis are already in the clients cache.

Scenario Variant 1:
The data to be analyzed consists of one tiled layer only, e.g. a terrain layer.

Scenario Variant 2:
The data to be analyzed consists of one tiled layer, e.g. a terrain layer and a static pre loaded layer, e.g. a specific user defined object.

Figure II.4.1: Scenario and evaluation matrix.

Before discussing the related work of 3D WebGIS, 3D line-of-sight computation and WebGIS performance research in Section II.4.2, the following two subsections provide an overview of the context in which this work makes its contribution, beginning with general remarks on the relevance of WebGIS in the next subsection and closing the Introduction with a short summary of research challenges in the realm of WebGIS.

II.4.1.1 Why Do We Need WebGIS?

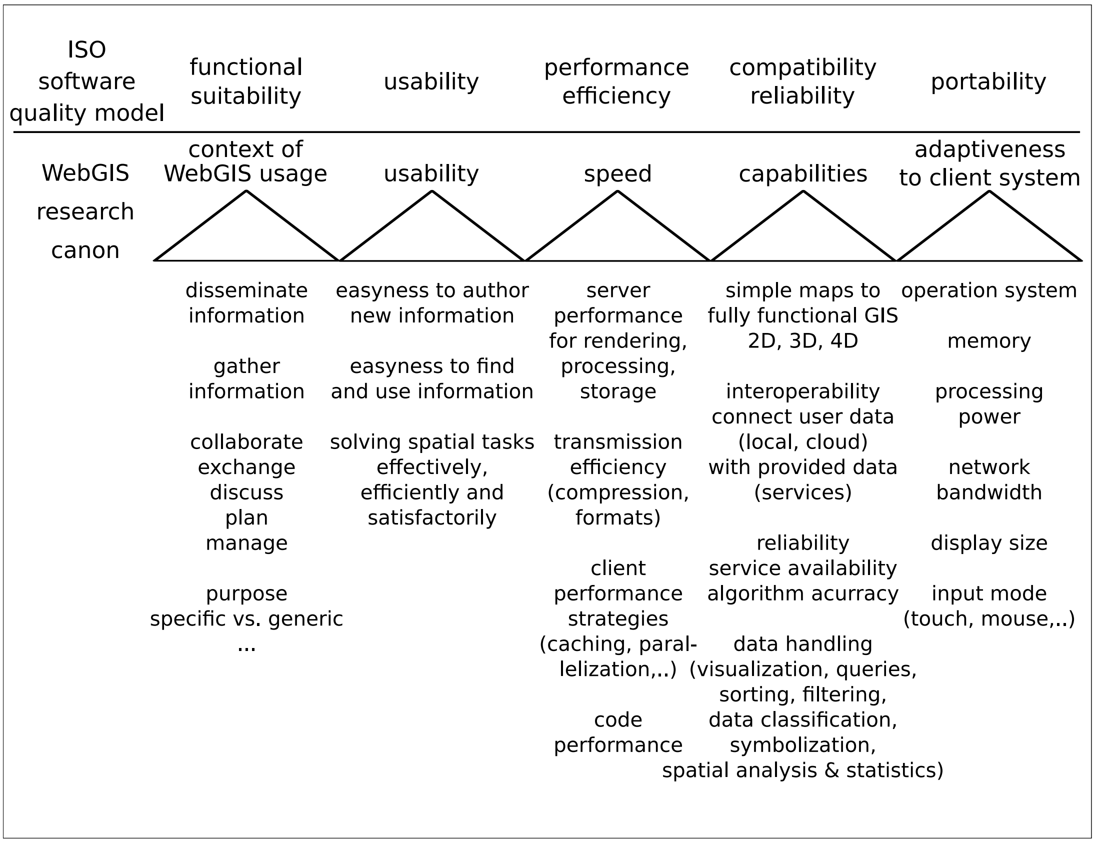
At the end of 2017, there were about 4 billion (~51.8%) people using the Internet worldwide (De Argaez 2018). In developed countries, more than 80% of individuals use the Internet (ITU 2015).

These numbers show the simple fact that our societies have incorporated the Internet as one of the most important technologies for information and communication. The Internet, and especially the World Wide Web, facilitate access to spatial information and services that can provide fast and easy solutions to spatial questions from private individuals, over public administration to business applications. However, why do we need WebGIS? We are using the web extensively to solve our daily tasks and we have a big demand for spatial information in a wide spectrum of use cases and application domains, e.g., public participation in planning (e.g., (Dragićević and Balram 2004)), natural resource management, market research or logistics, just to name a few. The widespread use of GIS applications distributed over the web has changed the early role of desktop GIS as specialized analysis tools to being a media type for communicating geographic information to a broad audience (Sui and Goodchild 2001). Many WebGIS applications have a strong focus on communication by means of web mapping, nevertheless it is important to enable WebGIS applications to cover other important aspects of GIS software, such as data capture, data management and especially data analysis. The effort made in the approach of this paper is a step in the direction of enabling WebGIS applications to perform analysis even on large datasets efficiently over the web. Hereby, the approach follows the paradigm of client-side computation in favor of more flexibility on how the user can combine private local data with provided published data from a spatial data infrastructure (SDI) without the need to upload any of his data to a remote server.

Before giving the details of the proposed method for a browser-based client-side line-of-sight analysis, some remarks on the general research scope of WebGIS are given below.

II.4.1.2 The Research Challenges of WebGIS

The challenges that have to be addressed in research to make WebGIS a useful means of understanding spatial phenomena and communicating geographic information are manifold. The main topics in Figure II.4.2 are related to the ISO/IEC 25010 standard for Systems and Software engineering (ISO/IEC 2011), which defines a software product quality model. This model is composed of eight characteristics. Having these general characteristics of software quality in mind and relating them to the context of WebGIS reveals a subjective selection of topics and issues for a research canon of WebGIS. However, it might provide a useful starting point of discussion to sort and develop the field of WebGIS research. Some of the issues are more general and also apply to other kinds of web applications, e.g., adaptiveness, while others are more specific to WebGIS applications and need specific solutions, such as map usability, compression techniques or data retrieval strategies and high-performance analysis computations. In the overall concept of WebGIS, various different scientific fields are involved in the research scope, e.g., cartography, psychology of perception, human–computer interaction, communication science, ergonomics, art and design, computer science, geoinformatics, and domain experts from the thematic field of usage where the WebGIS is applied. To solve all the challenges in the realm of web-based GIS research, a broad interdisciplinary effort would be necessary. This paper mainly focuses on two aspects of browser-based client-side GIS analyses, speed and capabilities (compare in Figure II.4.2). The strategies to reach these goals are exemplified by examining and evaluating an implementation of a browser-based 3D line-of-sight analysis.



ISO software quality model	functional suitability	usability	performance efficiency	compatibility reliability	portability
WebGIS research canon	context of WebGIS usage	usability	speed	capabilities	adaptiveness to client system
	disseminate information gather information collaborate exchange discuss plan manage purpose specific vs. generic ...	easyness to author new information easyness to find and use information solving spatial tasks effectively, efficiently and satisfactorily	server performance for rendering, processing, storage transmission efficiency (compression, formats) client performance strategies (caching, parallelization,..) code performance	simple maps to fully functional GIS 2D, 3D, 4D interoperability connect user data (local, cloud) with provided data (services) reliability service availability algorithm acurracy data handling (visualization, queries, sorting, filtering, data classification, symbolization, spatial analysis & statistics)	operation system memory processing power network bandwidth display size input mode (touch, mouse,..)

Figure II.4.2: Challenges in WebGIS research.

II.4.2 Related Work

II.4.2.1 History and Current State of 3D WebGIS

The development of 3D WebGIS can be subdivided into a history of formats, hardware, bandwidth and software. While the first format for 3D web content was developed already in the early days of the World Wide Web in 1994—namely VRML (Ragget 1994)—the other components needed almost 30 years to be usable in a broad market. Hardware in the sense of powerful graphics cards became continuously better over time. The access to high bandwidth rates are still very dependent on the place where someone lives. Until today, developing countries, as well as rural areas in industrial countries, often lack access to fast Internet (ITU 2015). In the case of software, it took until December 2010 for the first web browser to natively support 3D content, when Google Chrome version 8 started to partially support the new WebGL Standard (Khronos Group 2011), which was officially released three months later in 2011. Today, WebGL is at least partially supported by all major desktop and mobile web browsers (Deveria n.d.). Before, mostly plugins (e.g., Cortona3D (`http://www.cortona3d.com/de/cortona3dviewer`), FreeWRL (`http://freewrl.sourceforge.net/`), etc.) or Java applets (e.g., XNavigator (`http://xnavigator.sourceforge.net/doku.php`)) have been used for direct browser integration or standalone desktop applications. Both were able to communicate with web resources (e.g., WorldWind (`https://worldwind.arc.nasa.gov/`), Google Earth (`https://www.google.com/intl/de/earth/desktop/`), etc.) but had to be downloaded and installed. Current examples of WebGL based 3D WebGIS frameworks are: OpenWebGlobe (`http://www.openwebglobe.org/`), Cesium (`https://cesiumjs.org/`), NASA Web World Wind (`https://worldwind.arc.nasa.gov/`), TerraExplorer for Web (`http://skylineglobe.com/sg/TerraExplorerWeb/TerraExplorer.html`), ESRI 3D Scene Viewer (`http://www.esri.com/software/scene-viewer`), or GIScene.js (`http://giscience.github.io/GIScene.js/`).

Another important part of facilitating 3D WebGIS is the efforts of standardization. In 2010, two standardization proposals were published as OGC Discussion Papers: (1) the Web View Service (WVS) (Hagedorn 2010) using server side rendering; and (2) the Web 3D Service (W3DS) (Schilling and Kolbe 2010) delivering 3D data for client side rendering. Both strategies have been included in the recently approved OGC 3D Portrayal Service Standard 1.0 (3DPS) (Hagedorn et al. 2017) which enables interoperable service based presentation of 3D content.

A good overview on 3D representation, geometric and topological datamodels, database models, formats and applications is given in Coors and Zipf (2005) and Abdul-Rahman and Pilouk (2008).

II.4.2.2 3D Line-of-Sight Computation

Lines-of-sight play a role in different research areas. In computer graphics, visibility computations are used to determine visible surfaces for rendering, improving this rendering through visibility culling, computing shadows as a result of being not visible from a light source and more (Bittner and Wonka 2003). In GIS, lines-of-sight are used, e.g., in urban planning, telecommunication planning (De Floriani et al. 1994), military simulations (Liu et al. 2012) or archaeological analyses (Paliou et al. 2011).

In computer graphics, ray shooting is involved in many algorithms used to solve visibility problems. A special case of ray shooting can be used to compute point-to-point visibility in 2D and 3D (Bittner and Wonka 2003). Many visibility analyses in GIS are available for 2.5D data based on raster (Osterman et al. 2014; Tabik et al. 2015; Ferreira et al. 2013; Bartie and Mackaness 2017) or TIN structure (De Floriani and Magillo 2003; Hillen and Höfle 2013; Alderson and Samavati 2015). In these cases, for the line-of-sight computation, several restrictions can be observed: (1) observer and target must be on or above the surface; and (2) all participating data layers must be preprocessed into a single digital surface model. In the case of 3D ray shooting, these limitations can be overcome. A ray is a half-line, which is represented by a start point and a direction. Such a ray can then be tested on intersection with the surface triangles of objects in the scene. Thus, it does not matter if the objects in the scene originate from one or several sources or layers. All intersection points of triangles that have been detected to intersect the ray can be sorted by their distance to the rays starting point. The closest intersection identifies the object that causes the visual obstruction. Several ray-triangle intersection algorithms are available (Badouel 1990; Bogart and Arenberg 1988; Moller and Trumbore 1997; Eberly 2016).

II.4.2.3 WebGIS Performance Research

There is a lot of literature about WebGIS in general and even more about applications, but searching explicitly for scientific work on “WebGIS performance” reveals sparse results. Some early work exists describing techniques to reduce the amount of data transmission through a tiling and indexing approach (e.g., (Wei et al. 1999)). The general idea of this approach is also used in this paper, although in a different shaping. Further WebGIS performance improving techniques have been described by Yang et al. (2005) and Yang et al. (2011). For the server-side, they proposed multi-threaded request handling and distributed processing using computer clusters. For the reduction of data transmission, they proposed a pyramid approach for raster images and evaluated the effect of compression on vector data. Further, client side data caching is proposed to reduce server and network loads. Zhang et al. Zhang et al. (2011) optimized the performance of a JavaApplet based WebGIS Application. The largest gain of performance could be reached through a serve-side cache for map tiles to avoid on-the-fly map rendering. Recent work on WebGIS performance focuses more on distributed data storage and processing in cloud environments (e.g., (Liu et al. 2009; Zhong et al. 2012)). Current implementations for geospatial and even spatiotemporal storage and processing of Big Spatial Data are, e.g., Spatial Hadoop (`http://spatialhadoop.cs.umn.edu/`), Geomesa (`http://www.geomesa.org/`), GeoWave (`http://locationtech.github.io/geowave/`) or especially for large rasterdata repositories the rasdaman database (`http://www.rasdaman.com/`).

II.4.3 Methods

II.4.3.1 Creating a LiDAR-Inspired Artificial Test Dataset

For the evaluation of the proposed optimizations for the data handling during the analysis phase, it is very useful to have full control over the data structure, data size, and obstacle locations. Full control can only be achieved by designing and creating an artificial dataset. To achieve a realistic behavior of the WebGIS and the analysis process, the test data represent the characteristics of an airborne LiDAR derived triangulated digital elevation model (DEM) with a horizontal resolution of 1 m (point spacing) and a total area of $\sim$16 km^2 (4096 m × 4096 m). As a single regular triangulated DEM, this would result in a dataset with 16,785,409 vertices and 33,554,432 triangles. With current technologies, it is not feasible to load such a dataset into a browser-based WebGIS at once for visualization or analysis purposes. It has to be prepared making use of different strategies that enable the web-based usage of such a dataset. Typically, for visualization purposes, the data would be further processed into a series of datasets with each having a lower resolution to reduce the data size. The resulting set of datasets, known as Levels-of-Detail (LoD) (e.g., (Heckbert and Garland 1994; Clark 1976)), can be cut afterwards into smaller units, e.g., tiles. To be able to display several parts of different LoDs simultaneously in one scene, e.g., depending on the distance to the camera, the parts of one LoD have to be interchangeable with parts from the adjacent LoDs. In the case of partition into tiles, each one can be represented in the next higher LoD by four tiles, such that a quadtree-like data structure evolves (Figure II.4.3). The tiled structure of the dataset is not only useful for the visualization of large datasets, but enables also the reduction of the data size necessary to be loaded for a specific line-of-sight analysis. We can use this data structure to reduce the potential data to be downloaded for the analysis to just those tiles whose 2D bounding boxes are intersected by the 2D line segment, projected on a horizontal plane, representing the line-of-sight. By tiling a triangulated dataset, it becomes bigger so that finally the artificial test dataset with the original resolution gets 17,989,632 vertices, an increase of ∼7%, while in our case the numbers of triangles stays constant.

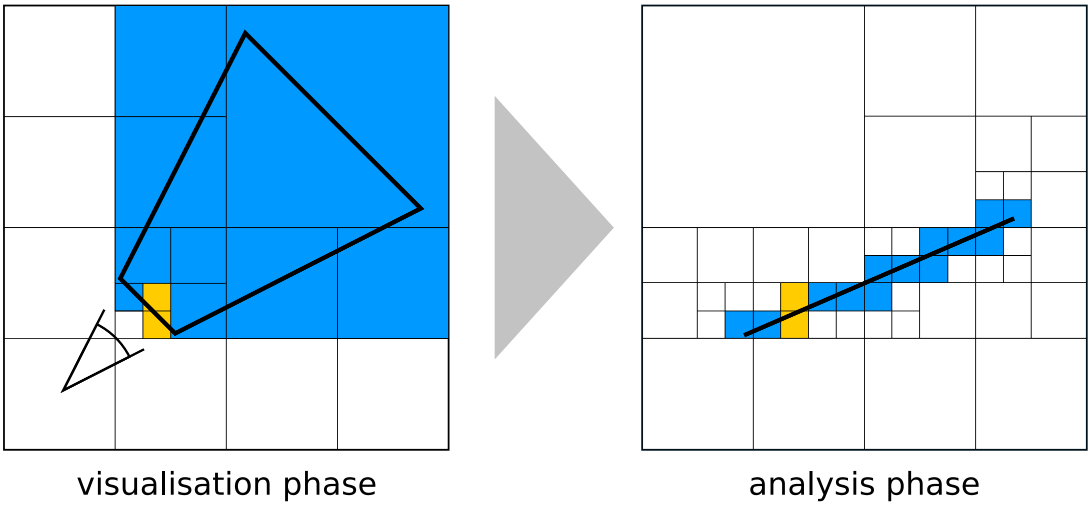


Figure II.4.3: The LoD Schema during the visualization phase (**left**) shows the tiles of different levels which have to be loaded to display a certain field of view, based on the distance to the camera. After switching to the analysis phase (**right**), some tiles can be reused from the cache (orange). For the analysis only the highest available level of detail must be loaded that intersect the line-of-sight.

The dataset is designed such that its surface is completely flat except for systematically distributed obstacles in some of the tiles (Figures II.4.4 and II.4.5). This way, we can run several test analyses with varying oberserver–obstacle distances to measure the effect of the different optimizations.

The test data were created using a script that automatically creates tiles in different LoDs with different resolutions and tile sizes and stores them in a database such that each LoD is represented in one table. The geometry is stored as polyhedralsurface, a PostGIS data type that stores 3D surfaces as a collection of polygons, but also as JSON representation in the THREE.js-JSON scene-format 3.2 (`https://github.com/mrdoob/three.js/wiki/JSON-Model-format-3`), which is natively supported by the THREE.js JavaScript visualization library. Additionally, a centroid is stored in a separate database column for fast spatial indexing of the tiles. The LoD tables are all indexed using the gist-index provided by PostGIS as the standard spatial index to speed up search times for spatial queries such as bounding box queries. The simultaneous storing of two geometry representations has the advantage that one type, the polyhedralsurface, can be used in spatial queries with PostGIS functions while the other type, the JSON representation, can directly be given out to be delivered to the web client without ad hoc conversion from one format to the other.

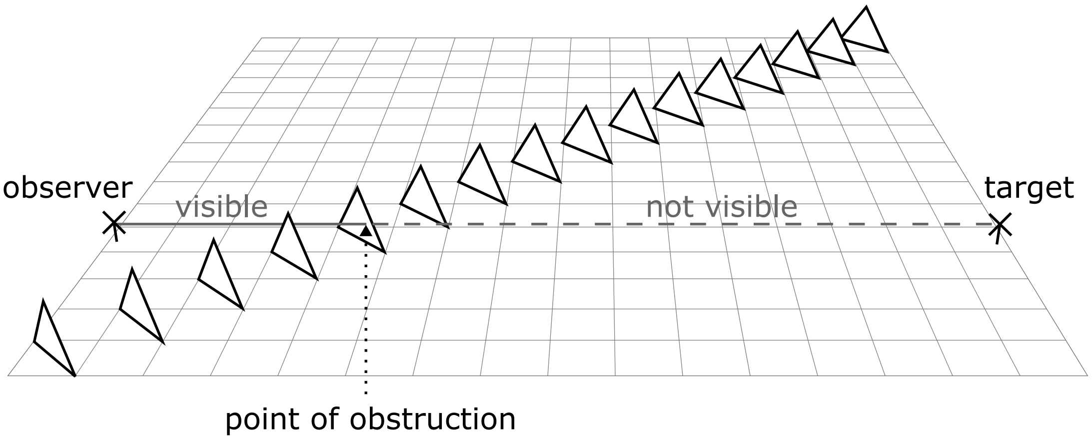


Figure II.4.4: Distribution of obstacles in the test dataset with example of a line-of-sight indicating the visible and non visible part, which are divided by the point of obstruction.

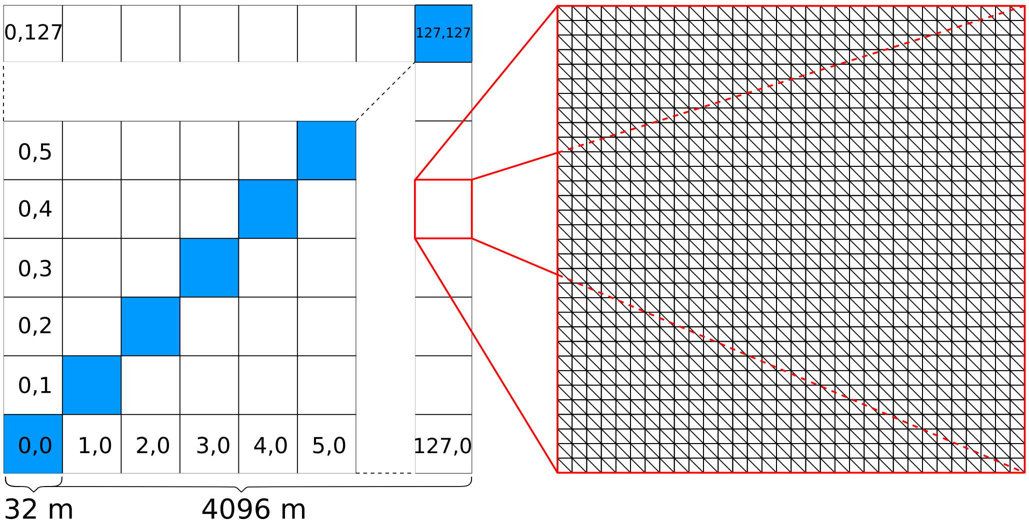


Figure II.4.5: Tile-grid setup: Each tile is composed of 2048 triangles (**right**). The whole artificial DEM is made of 128 × 128 of such tiles (**left**). Some of those tiles (blue shaded tiles) contain a large vertical triangle, spanned diagonally across the whole tile, which serves as obstacle.

II.4.3.2 Test Environment

To deliver the test data to the client, a test environment was created (Figure II.4.6). This environment contains a spatial database (PostgreSQL/PostGIS) and a web service that delivers the data based on Node.js (`https://nodejs.org`—Node.js is a JavaScript runtime for server-side scripting and development of web services). The service API implements the interface of the Web 3D Service (W3DS) specification (Schilling and Kolbe 2010), which is currently an OGC Discussion Paper for standardization. The client in this case is a browser application using the

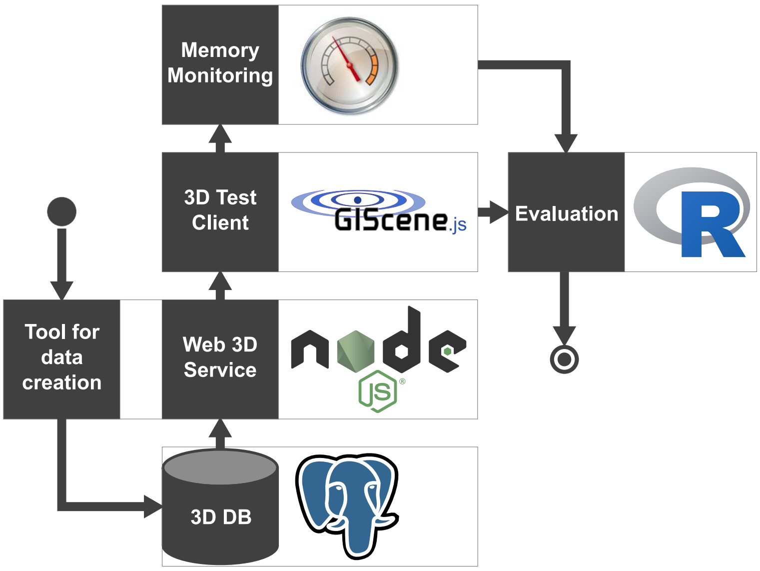


Figure II.4.6: Test environment.

JavaScript library GIScene.js (`http://giscience.github.io/GIScene.js/`) which itself depends on Three.js (`https://threejs.org`—THREE.js is a popular library for web-based 3D Visualizations using the browsers native API for WebGL) and WebGL (Khronos Group 2014). While Three.js is an abstraction library for WebGL, GIScene.js adds geographic concepts to the 3D library such as spatial reference systems, data organization as layers, implementation of OpenGIS Web Service (OWS) standards and geospatial analysis functionality.

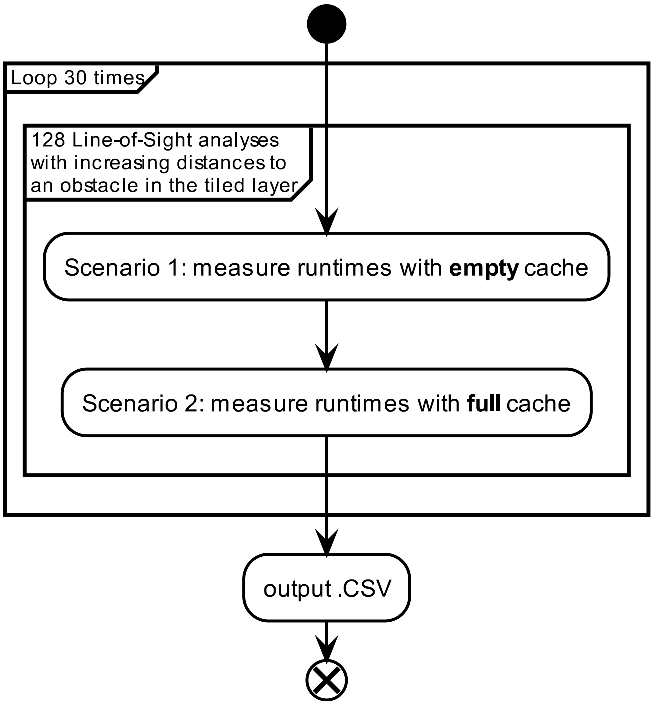


Figure II.4.7: Pattern of the test functions.

To measure the performance behavior in the different scenarios (Figure II.4.1), two test functions were implemented for the test client: one for the “single layer” scenario variant and one for the “multi layer” scenario variant. Both test functions follow the same pattern (Figure II.4.7).

According to the tile layout (Figures II.4.4 and II.4.5) of the artificial dataset, the lines-of-sight to be tested were constructed as follows. At the center position of each of the 128 grid rows, one line-of-sight was constructed from the western border to the eastern border of the dataset. Each line represents a test case of the analysis with equal distances between observer and target points but with varying distances to the point of obstruction, which has to be found. This layout gives the possibility to test each line-of-sight twice, one after another, to measure the influence of the caching strategy (empty cache vs. full cache) and the influence of topographic variance in the 3D scene (varying distances to obstruction points). The cache filling automatically takes place during the first run of each line-of-sight analysis. All first runs with an empty cache deliver the worst case measurements (Figure II.4.8a,c), while all second runs deliver the best case values (Figure II.4.8b,d). The comparison of both results shows the potential performance gains by utilizing a tile cache for the analysis process and secondly it illustrates the extremes between which a real case could perform. These variations indicate the advantage of the method, that is, through using tiles in a split-up analysis, we can skip a part of the analysis, once we have determined the closest obstacle from the observer. This means that those analyses, finding a close obstacle, will finish much faster than analysis with far obstacles, independently of the total length of the line-of-sight. These 128 double measured analysis are further repeated 30 times to create a median value of the performance behviour to eliminate other influences on the measurements such as varying network speed or other activities performed by the operating system during the measurement phase. Finally, all measurements are given out as a comma separated value list for further usage.

To measure the duration with sufficient precision, especially for the best case scenarios, where an analysis runs only a few milliseconds, it was necessary to use the “W3C High Res Time API” (Mann 2012), which in contrast to the common JavaScript Date-object, is independent of the system clock and therefore can deliver monotonic time values. Its resolution is up to five microseconds (=0.000005 s).

To measure and evaluate the memory consumption during the analyses, the built-in MS-Windows tool “Performance Monitor” was used to log the amount of Private Bytes of the browser process together with a timestamp into a CSV file. Using the timestamp, this information can then be combined with the log running inside the browser during the analysis which measures the durations of the line-of-sight computations. For the memory measurement, the used browser was an instance of Google Chrome Version 52.0.2743.82. To minimize external influences in the measurement, the browser was started with a disabled disk-cache, which normally caches a certain amount of server responses on the local hard drive to avoid network traffic and download times. Further, the in-memory-cache implemented in GIScene.js for tiled data was also disabled, such that the measurements reflect only what is used for holding the code, the input and results data, and what is needed for the computation.

II.4.3.3 A Browser-Based 3D Line-of-Sight Analysis

Definition

In the context of this paper, the aim was to optimize the computation of a browser-based 3D line-of-sight Analysis. The computation took place on the client-side in a web-browser. The 3D line-of-sight Analysis uses a 3D line-of-sight, which is a line from an observer point to distant target point in three-dimensional euclidean space, to compute whether an obstacle is intersecting that line and additionally determine the closest point of intersection with an obstacle (point of obstruction) seen from the observer point .

Aims and Strategies

The intention of the proposed method is to fulfill the following aims: performance, scalability, practicability and robustness. To develop a practicable and robust analysis method, it is important to account for the fact that real world 3D datasets often contain topological errors, and may not be manifold, especially when surfaces are automatically reconstructed from point clouds. Scenes may be composed of many different and disconnected objects which have been created from different data sources and by different processing methods. To avoid time consuming data preparation, the proposed method uses a visibility algorithm (Eberly 2016) that does not rely on a specific data structure, except that the objects are composed of triangles. No manifoldness or special topology is needed. This allows spontaneously including multiple and different types of layered data possibly stemming from different remote or local sources, which is an important feature for the practical usage of a WebGIS. To reach scalability, in this context, means to design the analysis process in such a way, that the consumption of memory becomes independent of the size of the underlying data to be analyzed and also independent of the length of the line-of-sight which has to be tested. The strategy followed here is to process data chunks such as tiles if available (e.g., for terrain data) or object groups retrieved by bounding boxes (e.g., buildings). For web applications, the timely performance is a crucial factor to gain user acceptance. Generally, the time (T) of a browser based analysis can be formulated as:

$$T = T_{send} + T_{server\ side\ processing} + T_{receive} + T_{client\ side\ processing} \tag{II.4.1}$$

While T_{send} and $T_{receive}$ are dependent of the data size and available bandwidth, the processing parts depend on hardware, software and the size of input data. As the available bandwidth and hardware cannot be influenced by the application, the performance optimizations should concentrate on reducing the data size to be transmitted and processed and the algorithms for processing that data. In this case, the dominating time component is $T_{receive}$ so that the applied strategy is to reduce downloads and processing by analyzing already loaded layers or cached tiles first to determine a possibly smaller amount of necessary data that has to be analyzed and thus downloaded. This aim can be targeted at two different points in the processing pipeline, before starting new data downloads.

Two Levels of Optimization

In this paper, a two-level approach is applied to improve the WebGIS performance in a holistic way rather than just to focus on a single algorithm optimization. The approach introduced here is based on the assumption that, before the actual analysis phase begins, a prior visualization phase has already taken place. This leads to the advantage that some of the required analysis data may already have been loaded in the web clients memory and can be accessed very quickly and thus can be used for performance optimization. For the computation of the line-of-sight, optimizations can be performed on two different levels—the layer-level (inter-layer-optimization) and the tile-level (intra-layer-optimization). Both optimization levels can be combined into a 2 × 2 scenario matrix (Figure II.4.1). This matrix is used to evaluate and demonstrate the contribution to the performance gain under different usage conditions.

1. The layer-level

   The inter-layer-optimization makes use of two principles. First, the algorithm examines static layers before tiled layers. Static layers are not tiled or requested by grid-based bounding boxes but instead consist of objects that are loaded at once and afterwards are constantly kept in the client memory for visualization. Static layers are useful to add specific objects to a scene that are not too big in data size but are required for individual visualizations or analyses, e.g., a model of a planned building in a cityscape. Second, the search space that has to be examined in subsequent tiled layers will be reduced by the results of the previously examined static and other tiled layers. Between the examination of two layers, the target point parameter of the next layers analysis is adjusted to the closest obstacle intersection found in the previous layer. This reduces the search distance and thus the number of tiles that have to be downloaded and analyzed during the next layer check.

2. The tile-level

   On the tile-level (intra-layer-optimization), three strategies can be applied to optimize performance. First, the chunked (i.e., tiled) nature of the data allows loading just a necessary subset of the whole dataset, and thus enables data streaming. Data partitioning is a crucial strategy to be able to handle very large datasets and to process it piecewise. Second, some tiles that have to be analyzed may already be found in the client cache (because they were loaded earlier either for visualization or for another earlier analysis) and can be accessed and analyzed fast. Such cached tiles can be accessed and analyzed very fast and should be prioritized when determining the sequence of tiles to be analyzed. A sorting of the tiles by being cached or uncached and starting the analysis with the cached ones, which can reveal a new closest intersection, that can, similar to in the layer level, be used to reduce to search space and reduce the number of uncached tiles that have to be loaded, separates the analysis in a faster and a slower part. If during the fast part an intersection with the line-of-sight can be found, all slow parts (uncached tiles) that lie behind that intersection can be skipped and thus improve the overall performance. Third, the remaining uncached tiles can now be requested asynchronously, which means that, depending on current browser implementations, 6–13 parallel connections can be established from the browser to resources of the same Internet domain (Souders n.d.) (host server addresses of the data services) to download the pending data. Thus, some of the server and network load can be handled in parallel to speed up the process.

II.4.4 Discussion of the Results

II.4.4.1 Performance

For the evaluation of the performance, four different scenarios were measured (Figure II.4.8). The two scenarios with a single tiled layer (Figure II.4.8a,b) demonstrate that the process duration is linearly dependent on the number of tiles to be analyzed between observer point and nearest obstacle. In other words this means that using this method the analysis performance is independent of the total size of the underlying tiled layer dataset and it is only dependent of the total distance between observer and target point if no obstacle can be found in the line-of-sight. The earlier an obstacle in the line-of-sight is found, the better is the performance.

Further, comparing the worst case (Figure II.4.8a,c) and best (Figure II.4.8b,d) case scenarios, one can see a very big difference in the analysis duration—in the test case, approximately by factor 90. This can vary if applied under different network conditions, but underlines the importance of applying strategies to avoid downloading unnecessary data to reach a good performance.

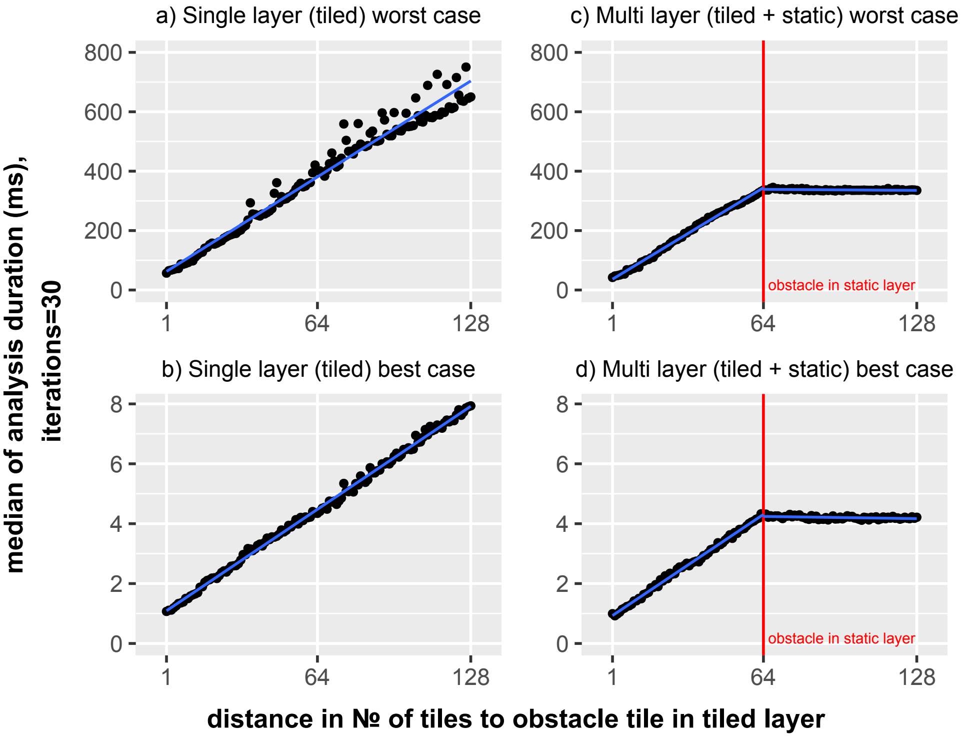


Figure II.4.8: Performance of the line-of-sight computation in different scenarios.

This can be achieved by applying a local memory cache to avoid multiple downloads of data that have already been used for visualization or prior analyses.

Figure II.4.8c,d represents the equivalent to Figure II.4.8a,b but with a second layer included in the analysis. In our test setup, this second layer obstructs the line-of-sight exactly at the midpoint between observer and target point. The diagram shows the advantage of the approach by including multiple layers to reduce the amount of data that have to be fetched from the remote server. In practice, this means that the inclusion of data from all static layers into to computation can help avoid time consuming downloads of dynamic tiled layer data and thus improve the overall performance.

II.4.4.2 Scalability

Figure II.4.9 shows the memory consumption of the browser during a test run of 128 different line-of-sight analyses with increasing distances to their nearest obstacle. It shows a constant consumption of RAM, independently of the amount of data that have to be processed for the different analyses. This demonstrates the scalability of the approach. In practical use, this means that there is no limitation of the length of a line-of-sight or resolution of the underlying obstacle layers as long as they can be retrieved in a partitioned way, e.g., tiled or by bounding box, to

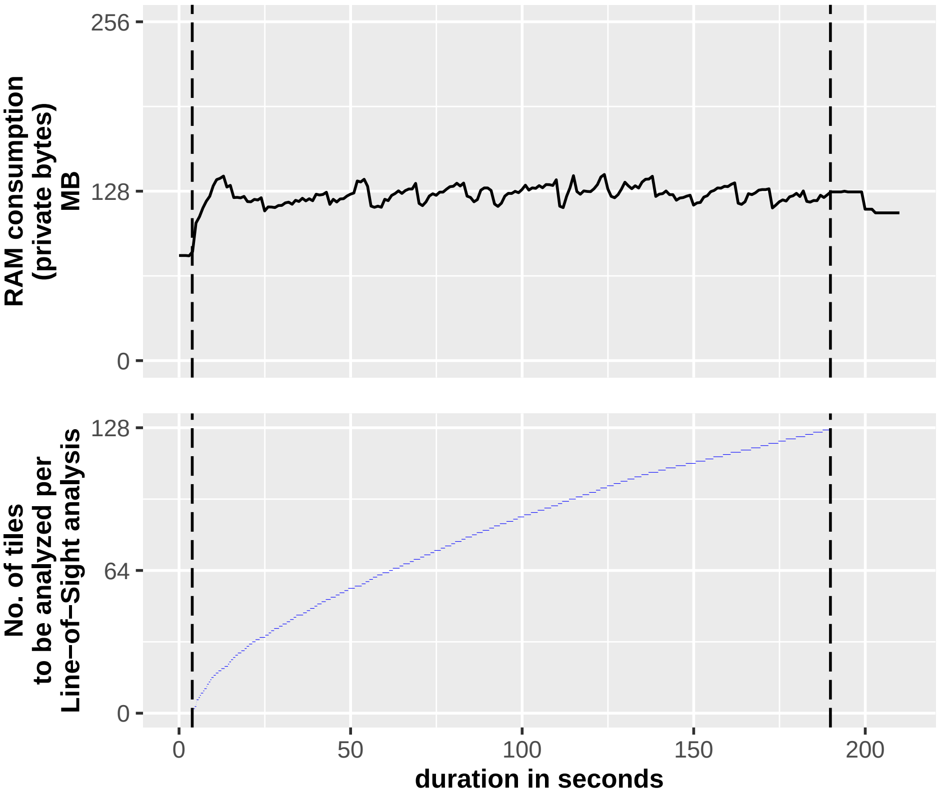


Figure II.4.9: Memory consumption (**top**) during 128 different line-of-sight analyses (blue line segments) (**bottom**) with increasing distances to their nearest obstacle.

support streaming. To control the amount of necessary memory, the only parameter to adjust would be the tile size or bounding box size depending on the resolution of the underlying data.

II.4.5 Conclusions

This paper discusses the potential of browser based WebGIS applications beyond its typical usage as geodata viewer. It exemplifies its extended usage as real web-based analysis interface by evaluating an implementation of a browser-based 3D line-of-sight computation under different scenarios to prove acceptable performance and scalability by applying the suggested methods from above. To ensure comparable test conditions, an artificial dataset has been created, simulating a LiDAR derived Digital Terrain Model. Further, an evaluation framework was set up to measure performance and memory consumption during four different test scenarios. The results show that the applied approach with its holistic view on WebGIS usage and its two levels of optimization (layer-level and tile-level) lead to greatly improved performance, while the streaming and partitioned way of processing of the data leads to an independence between memory consumption and the length of the line-of-sight as well as the resolution of input data, thus showing that the approach is scalable, which is important, especially in web-based environments.

Author Contributions

Conceptualization, M.A. and A.Z.; Data curation, M.A.; Formal analysis, M.A.; Funding acquisition, A.Z.; Investigation, M.A.; Methodology, M.A.; Project administration, A.Z.; Resources, A.Z.; Software, M.A.; Supervision, A.Z.; Validation, A.Z.; Visualization, M.A.; Writing—original draft, M.A.; and Writing—review and editing, M.A. and A.Z.

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Conflicts of Interest

The authors declare no conflict of interest. The founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

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Part III

Declarations

Eidesstattliche Versicherung gemäß § 8 der Promotionsordnung der Naturwissenschaftlich-Mathematischen Gesamtfakultät der Universität Heidelberg

1. Bei der eingereichten Dissertation zu dem Thema „*Advancing 3D WebGIS - browser-based Methods for Visualization and Analysis and their Integration in Virtual Research Environments in the Context of Cultural Heritage*“ handelt es sich um meine eigenständig erbrachte Leistung.
2. Ich habe nur die angegebenen Quellen und Hilfsmittel benutzt und mich keiner unzulässigen Hilfe Dritter bedient. Insbesondere habe ich wörtlich oder sinngemäß aus anderen Werken übernommene Inhalte als solche kenntlich gemacht.
3. Die Arbeit oder Teile davon habe ich bislang nicht an einer Hochschule des In- oder Auslands als Bestandteil einer Prüfungs- oder Qualifikationsleistung vorgelegt.
4. Die Richtigkeit der vorstehenden Erklärungen bestätige ich.
5. Die Bedeutung der eidesstattlichen Versicherung und die strafrechtlichen Folgen einer unrichtigen oder unvollständigen eidesstattlichen Versicherung sind mir bekannt.

Ich versichere an Eides statt, dass ich nach bestem Wissen die reine Wahrheit erklärt und nichts verschwiegen habe.

Ort und Datum	Michael Auer

II.1 3D-Sutras: A web based atlas of laser scanned Buddhist stone inscriptions in China

Authors	Michael Auer, Bernhard Höfle, Sandra Lanig, Arne Schilling, Alexander Zipf
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II.2 Real-time Web GIS Analysis using WebGL

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Outlet	*International Journal of 3-D Information Modeling*
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Date

II.3 Web-based Visualization and Query of Semantically Segmented Multiresolution 3D Models in the Field of Cultural Heritage

Authors	Michael Auer, Giorgio Agugiaro, Nicolas Billen, Lukas Loos, Alexander Zipf
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II.4 3D WebGIS: From Visualization to Analysis. An Efficient Browser-Based 3D Line-of-Sight Analysis

Authors	Michael Auer, Alexander Zipf
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Reference	Auer, M & A Zipf (2018). ’3D WebGIS: From Visualization to Analysis. An Efficient Browser-Based 3D Line-of-Sight Analysis’. *ISPRS International Journal of Geo-Information*, 7 (7), 279. DOI: 10.3390/ijgi7070279.

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