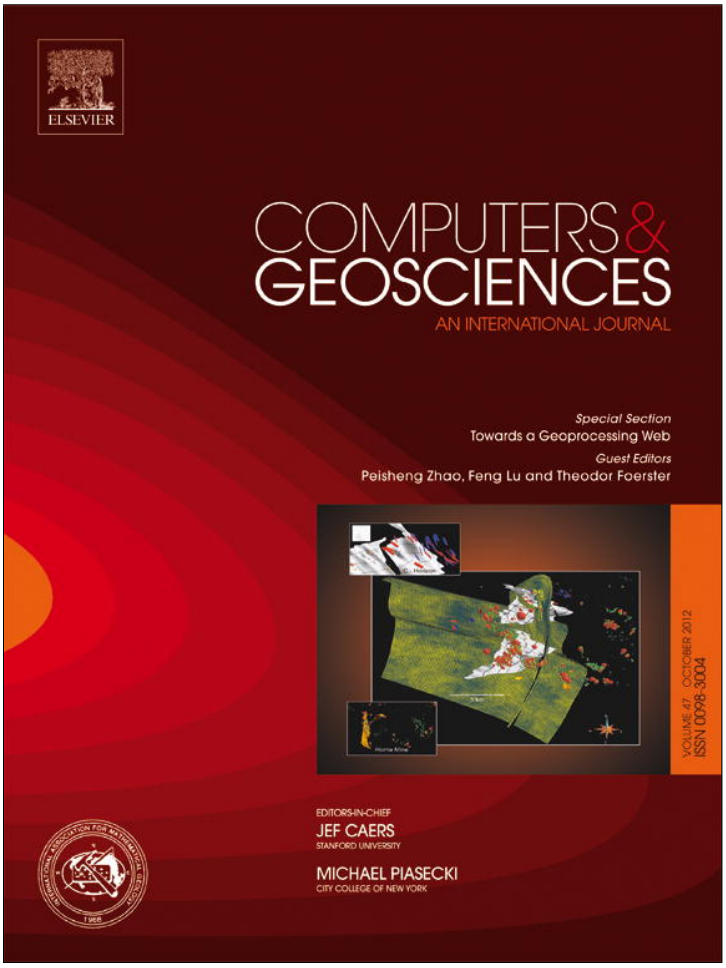
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The Geoprocessing Web

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ABSTRACT

As Web services technology has matured in recent years, an increasing amount of geospatial resources and processing functions are available in the form of online Web services. Consequently, effective and efficient data processing methods for geospatial information extraction and knowledge discovery over the Web are a major challenge for research and industry. The Geoprocessing Web, which consists of light-weight protocols, crowd-sourcing capability, and the capability to process real-time geospatial data sources provided by sensors, enables distributed, interoperable and collaborative processing of geospatial data for information and knowledge discovery. This paper provides a comprehensive overview about the state-of-the-art architecture and technologies, and the most recent developments in the Geoprocessing Web.

1. Introduction

With the advancement of Earth observing and sensing technologies, the volume of geoscientific data has increased tremendously in the past decade and is expected to keep growing continuously. This increasing is reflected by the anticipated operating satellite systems acquiring high-resolution remote-sensing data or by novel crowd-sourcing systems which make in-situ data available and support citizens as scientists. For example, the National Aeronautics and Space Administration (NASA)'s Earth Observing System (EOS) satellites alone collect 1000 terabytes annually (Clery and Voss, 2005). These collected data are diverse regarding their spatial and temporal properties as well their quality. As more information and knowledge is transformed from geospatial data, their value increases. While millions of people across the world are interacting with geospatial data via online tools such as virtual globes (Nature, 2006), geospatial exploration in existing applications is limited to data sharing and viewing. The integration of different data sources by the means of Web-based geoprocessing to acquire further information has not yet been explored thoroughly. Instead, users spend a lot of time on installing and learning a variety of software on local machines, searching for and collecting the geospatial data from a variety of sources, and preprocessing and analyzing the data on local machines. This "everything-locally-owned-and-operated" paradigm makes the analysis and application of geospatial data very expensive and time-consuming. Moreover, these resources are locked in silos and cannot be shared and integrated across organizations and communities. As a result, data analysis becomes a privilege owned by some well-educated domain-specific users, and much data may not been analyzed sufficiently. These traditional methods of analyzing data fall far short of today's increased demands for geospatial information and knowledge.

Interoperability and accessibility of geoprocessing resources improve the application of geospatial data in various domains and help to increase the geospatial knowledge available to society. This interoperability is achieved by common standards whereas accessibility to particular resources is enabled by the Web. Both aspects are supported by Web services technology, which has matured in recent years. Web-based distributed geospatial computing and large networks of collaborating applications is the next step in the evolution of geoprocessing (Kiehle et al., 2007). To address the demands of geoprocessing in distributed environments like the Web, the combination of conventional analysis functions and advanced computing technologies requires new technical infrastructure, domain-specific models and methodologies to support advanced data-mining tools and online community collaborations (Nature, 2008). The Geoprocessing Web provides architecture, standards and tools to meet these requirements. Some are Service-Oriented Architecture (SOA), light-weight protocols, crowd-sourcing capability and the capability to process and deliver real-time geospatial data provided by sensors. The Geoprocessing Web is changing the way in which

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geospatial applications and systems are designed, developed and deployed.

This article provides an overview of the current-state-of-the-art of the Geoprocessing Web. Section 2 documents the existing approaches and achievements of Web-based geoprocessing. Based on this analysis, the concept and framework of the Geoprocessing Web is described in Section 3. Section 4 discusses the issues and developments towards the establishment of the Geoprocessing Web. Section 5 introduces some operational Web-based geoprocessing systems and discusses the technology readiness of the Geoprocessing Web. Conclusions are given in Section 6.

2. Existing approaches for geoprocessing

Geoprocessing is an operation used to manipulate spatial data. According to the International Organization for Standardization (ISO) 19119 specification (ISO, 2005), common geoprocessing includes spatial processing (e.g., network analysis and coordinate transformation), thematic processing (e.g., classification and geocoding), temporal processing (e.g., change detection and temporal subsetting), and metadata processing (e.g., geographic annotation and statistical calculation). The development of the geoprocessing paradigm is greatly influenced by the advances in information technology. Existing geoprocessing paradigms can be classified into four types (Orfali et al., 1999; Tsou and Buttenfield, 2002; Chang and Park, 2006; Zhao et al., 2006; Yue et al., 2010b), as shown in Fig. 1:

(1) Standalone environment
Traditional geoprocessing applications are performed in a standalone environment like a desktop computer. Data storage, visualization, and processing are tightly coupled in a software repository. Thus, geospatial users often access, transform, and visualize data using one software package.

(2) Client/server
Data storage and processing functions are performed at the remote servers, while data presentation functions are performed by local clients such as Web browsers (Abel et al., 1998). In terms of the assignment of functions to the client and the server, the client and server can be classified respectively as thin/thick clients and light/heavy servers (Chang and Park, 2006). For example, some data manipulation functions can be added on the thin client side to improve the performance of user interactions. Some simple geoprocessing functions can be executed at the thick client side, while complex data processing is performed at the server side.

(3) Distributed object
When the Component-Based Software Engineering principle is applied, geoprocessing functions can be provided by different software vendors by following the interoperable Application Programming Interface (API). These functional components can be assembled to accomplish a complex geoprocessing task, even though they may be provided by different software packages. There are three major distributed object-oriented middleware frameworks for developing enterprise-scale component-based applications, namely the Object Management Group (OMG)'s Common Object Request Broker Architecture (CORBA), Microsoft's Distributed Component Object Model (DCOM), and Sun's Enterprise JavaBeans (EJBs) (Tsou and Buttenfield, 2002; Preston et al., 2003). The geoprocessing functions implemented in these frameworks are technology-specific, and it is difficult to migrate from one framework to another.

(4) Web services
SOA provides an interoperable computing infrastructure for conducting advanced distributed geoprocessing tasks. These tasks use Web protocols and formats encoded in the eXtensible Markup Language (XML) (Yang and Raskin, 2009). In the context of SOA, geoprocessing functions are provided as loosely-coupled Web services, and coordinated to execute complex geoprocessing tasks collaboratively as workflows. The research and development on new geoprocessing infrastructures in the past several years have been occupied predominantly with the employment of technology for improving discovery, performance, and workflows (Zhao et al., 2006; Brauner et al., 2009; Yang et al., 2010). It is, therefore, necessary to set up a research agenda clarifying the promise of geoprocessing over the Web. This is the aim of the Geoprocesssing Web, as discussed in the next section.

3. The Geoprocessing Web

3.1. Definition

As SOA is emerging as the basis for distributed computing and an interoperable framework of collaborating applications, an increasing amount of geospatial processing functions and applications are built upon it. Users can collect, analyze and derive geospatial data, information, and knowledge over the Web. The Geoprocessing Web covers the conceptual, methodological, technical, and managerial issues that facilitate distributed and

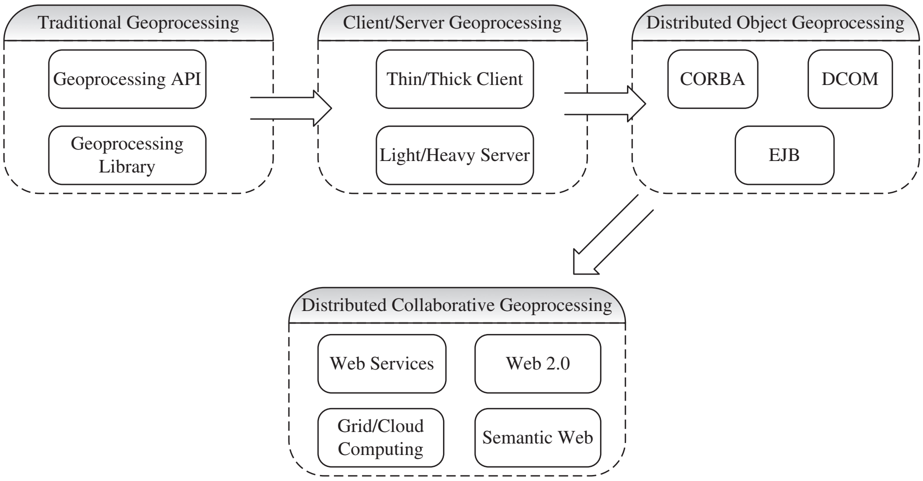

Fig. 1. The evolution of Geoprocessing Web.

collaborative geoprocessing over the Web. The Geoprocessing Web allows geospatial data to be processed in real time for creating value-added information. In particular, the Geoprocessing Web has the following distinguishing characteristics:

- Interoperability
  Geoprocessing services with syntactic and semantic descriptions are machine-to-machine as well as machine-to-human discoverable and executable through standard protocols. Clients can thus perform both single and sequences geoprocessing functions compiled as workflows. An example of interoperability is the Open Geospatial Consortium (OGC) Web Processing Service (WPS) interface (Foerster et al., 2011b).
- Light-weight protocols
  For scalability as well as for usability and acceptance in the developer community, light-weight protocols are required. Being light weight, the protocols are easy to be adopted in existing and new applications. Examples of such protocols are the REST-based (Foerster et al., 2011a) and lightweight exchange formats such as JSON.
- Collaboration
  Data, information and knowledge from different users or communities can be explored and integrated to promote geoprocessing functionalities in an open environment.
- Distribution of resources
  Using the SOA principles, service providers can distribute their resources in terms of hardware, operating systems, software environments and geographic location. Users can retrieve these sources through an interoperable access layer, which is based on common network protocols and data exchange formats.
- Real-time
  Users and providers of the Geoprocessing Web can process most current data in real-time. Real-time data stems mostly from sensors, which provide their data through services specified by Sensor Web Enablement (Bröring et al., 2011).
- Separation of concerns
  Through Web Service technology, different roles in service provision and user access can be identified. Besides the data providers, enterprises can start to host geoprocessing services to provide specific analysis functionality, which the users can access from existing applications. With the advent of cloud computing, this separation has become even more diverse, given the different levels of cloud provision: Infrastructure as a Service, Platform as a Service, and Software as a Service.

When combined with knowledge representation techniques, geoprocessing models can be established with the semantics of geoprocessing services and chains, thus minimizing or eliminating human intervention in the use of the Geoprocessing Web. The open access to knowledge and services allows wide participation of citizens in educational and scientific activities. The individuals can also share their algorithms as services, which could be deployed on a cloud computing platform. The extension of utilization and contribution of geoprocessing services and models in the educational sector or by citizens at large offers great potential to contribute, tag, rate, and comment on geoprocessing components and models, thus bringing social features to the Geoprocessing Web.

3.2. Framework

Fig. 2 illustrates a three-layer framework of the Geoprocessing Web. The first layer is the geoprocessing resource layer that provides sensors, geospatial data, and geoprocessing facilities. The second layer is the management platform aimed to provide basic utilities to manage geospatial data, services, and models. In particular, the basic utilities include some services for the retrieval, process, and visualization of geospatial data; the sensor services focuses on discovery of and accessing to sensor observations, as

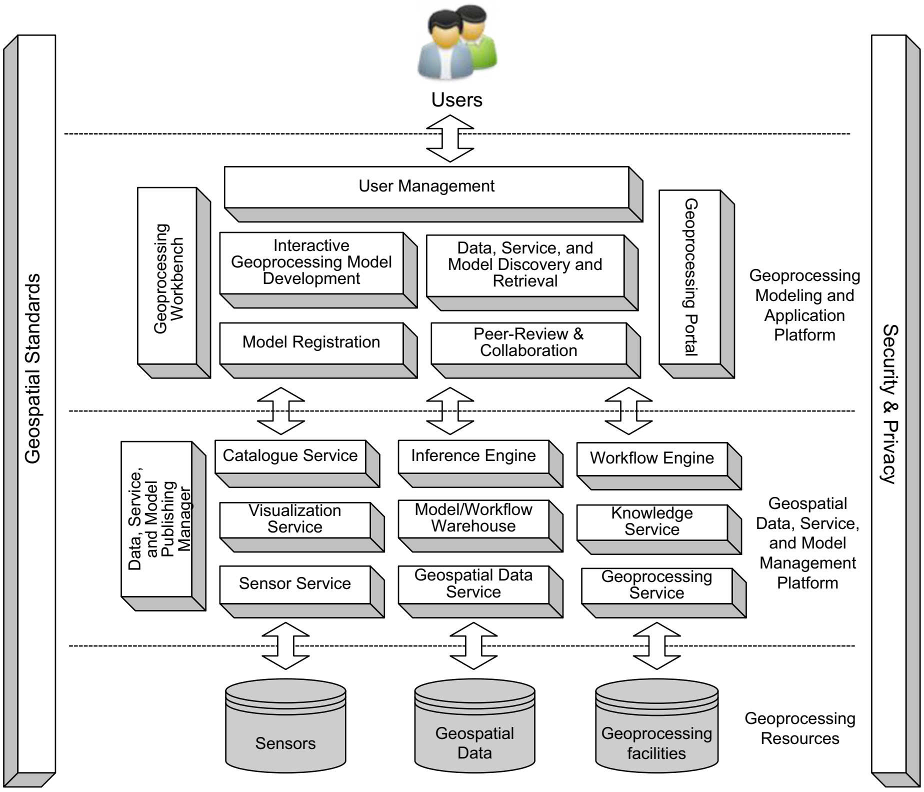

Fig. 2. Framework for the Geoprocessing Web (revised from Yue et al., 2010b).

well as receiving alerts and planning sensor tasks; the geoprocessing model and workflow management utilities are for process chaining; the catalogue service is used to locate geoprocessing services or models; the inference engines are required for a semantic match when needed; and the knowledge services provide geoprocessing knowledge, such as geospatial ontologies, rules, and geospatial process models, to support the public in learning and performing geoprocessing tasks. In the third layer, a workbench or portal facilitates users to discover and understand geospatial resources, and develop geoprocessing models and applications. Geoprocessing models, after going through a collaborative peer review, can be registered in the model warehouse as a type of knowledge. The Security and Privacy across three layers ensures the resource sharing rules and conditions for different types of users.

Service-oriented applications can increase individual and collective scientific productivity by making powerful information tools available to scientists, and allowing widespread automation of distributed data analysis and computation (Foster, 2005). The framework adopts the service-oriented view in which each component is developed as services following standardized interfaces and protocols. Standards enable the interoperability of service components, support the easy integration of distributed components, and ensure the components being accessible by the large public. The OGC standards on sensor services, data services, processing services, portrayal services, registry/catalogue services, and chaining services are being widely used. The development of interoperable and distributed service components enables the openness, growth, and evolution of the Geoprocessing Web.

3.3. Relations to Web, and Geospatial Web

The Web is defined as a science on how decentralized information structures can serve scientific, representational, and communicational requirements (Berners-Lee et al., 2006a). The core components of the Web are “identification of resources, representation of resource state, and the protocols that support the interaction between agents and resources in the space” (Jacobs and Walsh, 2004). Web-related research has largely focused on information retrieval and routing (Berners-Lee et al., 2006b). Work on geospatial information retrieval over the Web inspires the research on the Geospatial Web (Scharl and Tochtermann, 2007). Moving focus from geospatial data to geoprocessing resources, the Geoprocessing Web allows service providers to move their geoprocessing functionality as a kind of resources into the Web. The conventional Web can be regarded as an information space in which information can be published, accessed, and retrieved, while the Geoprocessing Web emphasizes geoprocessing activities on changing information, and thus can be regarded as an action space.

3.4. Web-based geoprocessing in SDIs and cyberinfrastructure

Spatial Data Infrastructure (SDI) is a distributed infrastructure originally focusing on data acquisition, distribution, and usage (Maguire and Longley, 2005). The recent development of SDI is trying to adding geoprocessing capabilities (Friis-Christensen et al., 2007; Kiehle et al., 2007). Cyberinfrastructure aims to combine data resources, network protocols, computing platforms, and computational services to provide a virtual environment for science and engineering research and education (Yang, et al., 2010). The development of grid computing and recent advancement of cloud computing consolidate the development of the SDI and Cyberinfrastructure, and demonstrate the benefits of outsourcing of computing tasks on the Web, such as high availability.

The concept of the Geoprocesing Web advocates the importance of geocomputation in the network environment, and suggests the development of geoprocessing middleware and services on top of SDI or Cyberinfrastructure. Both SDI and Cyberinfrastructure can support the Geoprocessing Web by providing the underlying technical distributed infrastructures. The unique emphasis of the Geoprocesing Web is the share and access of geoprocessing utilities from the perspectives of communication, collaboration, and participation. It is essential for the Geoprocessing Web to meet the needs on information extraction and knowledge discovery in the geospatial information infrastructure.

3.5. Example scenario

Using the Geoprocessing Web, an example scenario for wildfire prediction can be described as follows. Assume a disaster manager, John, wants to know the probability of having (a) wildfire(s) the next day in an area of interest. He chooses a geoprocessing service that is rated 5 stars by the scientific community for its high quality. The service uses the input data of weather prediction and land cover/use types to predict (a) wildfire(s). To provide the input weather data for the next day, weather data from remote sensors, managed by the National Oceanic & Atmospheric Administration (NOAA), are observed and fed into the weather forecast service to predict the weather for the next day. The remote sensing data observed by NASA can be fed into the land classification service to find the land cover/use types. Using the weather predictions and land cover/use types, the wildfire prediction service can then predict the probability of having wildfire(s) in the area of interest. Thus, different organizations can collaborate on wildfire prediction using a coordinated service chain.

4. Developments of the Geoprocessing Web

Based on the characteristics of the Geoprocessing Web, the current developments of the Geoprocessing Web are grouped as data, geocomputing, geoprocessing services, service orchestration, and geospatial semantics.

4.1. Data

The privacy, security, and access of geospatial data are very important for data dissemination in the networking environment. To track and manage access and restriction of geospatial data, data rights management is the primary issue. Standards are required to enable data providers to use well-understood and common mechanisms to manage intellectual property rights cross organizations. The OGC Geospatial Digital Management (GeoDRM) working group has defined a reference model to provide a trusted framework and rights languages for the management of digital rights of in the area of geospatial data and services (Vowles, 2006). Based on the available digital licensing infrastructure, (Bishr et al., 2007) proposed the general components of the GeoDRM framework with a focus on the technical aspects. The Infrastructure for Spatial Information in Europe (INSPIRE) is using the GeoDRM framework to implement key functionality of the rights management layer (INSPIRE, 2008). OGC also defined a geo-specific extension to OASIS eXtensible Access Control Markup Language, GeoXACML. This extension includes spatial data types and spatial authorization decision functions to support the declaration and enforcement of access restrictions on geospatial data in a service-based infrastructure (Matheus and Herrmann, 2011). GeoXACML is being widely used to define and enforce expressive and fine grained geospatial authorization rules and access rights (Lin et al., 2009; Herrmann, 2010).

Provenance records the processing history of a data product. It is important for users to discover dependencies among data and services, repeat the process of derivation of data products, and make decisions about the quality of derived data products (Foster, 2005). In the ISO 19115 Geospatial information — Metadata standard, provenance is regarded as part of the metadata recording the events or source data used in constructing the data, and relevant data quality (ISO, 2003). In a service-oriented environment, geospatial data provenance records the data processing history, including source data, transformation functionalities, workflow, parameters, and date and time (Yue et al., 2011). For example, the OGC WPS specifies an element, "lineage", to get a complete copy of data inputs and output definitions. Kepler, a scientific workflow system, provides a generic provenance framework to trace workflow execution. It has been applied in the geological and biological domains (Altintas et al., 2006; Anand et al., 2010). To promote provenance information with semantics, provenance ontologies have been defined and used in the OGC Catalogue Service for Web (CS/W) for registration and query of semantic provenance (Wang et al., 2008; Yue et al., 2010a).

Access to geospatial data must overcome the heterogeneity of the data. Standardized open protocols and interfaces allow access to distributed and diverse data in a common way. OGC has issued a series of service specifications ranging from data service and portrayal service to catalogue service, making great progress on the use of Web services to publish and access geospatial data. For example, the OGC Web Coverage Service (WCS) provides common interfaces to access customized multi-dimensional and multi-temporal geospatial data as a "coverage" (Whiteside and Evans, 2008). The OGC Web Feature Service (WFS) supports the networked interchange of geographical vector data as a "feature" which is encoded in Geographic Markup Language (GML), an extensible markup language for support and storage of geographic vector data to meet the requirements of complex spatial analysis (Vretanos, 2010). The OGC Web Map Service (WMS) provides geospatial data in a common way as a "map", which is generally rendered dynamically from real geographical data in a spatially referenced pictorial image format such as PNG, GIF, or JPEG (Beaujardiere, 2006). The OGC Sensor Observation Service (SOS) provides standardized interfaces for managing deployed sensors and retrieving sensor observation data (Na and Priest, 2007).

4.2. Geocomputing

Geocomputing focuses on the utilization of the theory of computation and state-of-the-art High Performance Computing (HPC) technologies in spatial analysis. Geocomputing for spatial data must consider spatial and temporal properties and the relations between them. To address the computationally challenging demands of geospatial domain, new computational approaches and computing middleware must be developed to leverage the existing theories and technologies with spatial-temporal data (Yang et al., 2011).

In order to ensure that state-of-the-art HPC systems are optimally configured to support geoprocessing, better alignment between geoprocessing activities and HPC platforms, such as in the design of geoprocessing algorithms for different HPC environments, are needed. Theory about the nature of spatial computation, such as computability and computational complexity, is an important issue. The development and deployment of geoprocessing in the HPC platforms also requires a technological framework to provide functions such as task scheduling, fault tolerance, and data assimilation. There are different types of parallel computing such as cluster computing or grid computing in the available computing platforms (Chen et al., 2009). Approaches guiding parallel processing of computationally intensive geographical analyses are also required (Wang and Armstrong, 2009).

Cloud Computing is associated with a new paradigm for computing infrastructure (Vaquero et al., 2009). Several new aspects of the information infrastructure enabled by Cloud Computing are the illusion of infinite computing resources available on demand, the elimination of an up-front commitment by cloud users, and the ability to pay for use of computing resources on a short-term basis as needed (Armbrust et al., 2009). A cloud could be public or private, depending on the deployment approach. A public cloud is available to the public, while a private cloud is used inside an organization. Major categories of Cloud Computing include Infrastructure as a Service (IaaS), Platform as a Service (PaaS), and Software as a Service (SaaS) (NIST, 2009), depending on the capabilities provided. Providing geoprocessing functions in Cloud Computing platforms can bring scalable, on-demand, and cost-effective geoprocessing services to geospatial users (Gong et al., 2010). The development of both SDI and Cyberinfrastructure can benefit from the use of cloud computing technologies (Schaffer et al., 2010; Yang et al., 2010, 2011; Baranski et al., 2011).

4.3. Geoprocessing services

Establishing and performing a geoprocessing task over a network began in the 1980s, when clients were able to invoke computations performed on remote computers. Since the advent of the Web services, an increasing number of geoprocessing functionalities are available and accessible as Web services. The GeoBrain Processing Web Services, which have been developed using the functionality of the Geographic Resource Analysis Support System (GRASS)[1], provide geospatial data management, raster image processing, spatial modeling and analysis, graphic map generation, and data visualization over the Internet (Li et al., 2010). The Adam Web Services leverage the Algorithm Development and Mining Toolkit (Adam)[2] for mining remotely sensed and other scientific data dynamically over the network, such as pattern recognition, image processing and optimization, and association rule exploration.

For the increasing number of distributed and heterogeneous geoprocessing Web services, common service interfaces and standardized message encodings are required to support interoperable machine-to-machine interactions. OGC has formulated a WPS specification (Schut, 2007) that provides rules for standardizing inputs and outputs (requests and responses) for geospatial processing services. The OGC WPS defines a set of standardized interfaces to facilitate the publication and access of geospatial processes over a network. Since its official release as an implementation specification, several communities brought up their framework. This momentum has been solely created from and by the open source community mainly from 52°North, Deegree and PyWPS. An overview of the current development of OGC WPS is provided in Fig. 3. The 52°North Open Source Initiative[3] has developed open-source software that uses a pluggable architecture for processes and data encoding to enable the deployment of OGC WPS in a standardized way. Most GRASS GIS functionalities have been wrapped as OGC WPSs within the 52°North WPS framework, and are available online for public use (Brauner, 2008; Li et al., 2009).

The Quality of Service (QoS) that measures how well a service matches customer expectations determines the degree of service usage in an open networking environment. In the common model of QoS, the performance, reliability and availability are the major questions in the quality of geoprocessing services (Gao et al., 2009; Foerster et al., 2011b; Moses, 2011). By considering the diverse use requirements, the unique character of spatial data, and QoS related constraints on complex geoprocessing, (Onchaga, 2004) defines an

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[1] GRASS GIS, http://grass.osgeo.org/

[2] Data Mining and Image Processing Toolkits, http://datamining.itsc.uah.edu/adam

[3] 52°North WPS, http://52north.org/wps

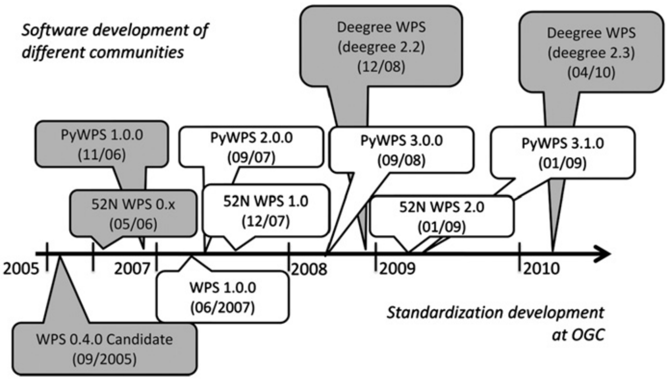

Fig. 3. Current development of OGC WPS.

extensible QoS model that covers performance, cost, reliability, availability, security, reputation, interactive support, location, and health of services for QoS-aware discovery and composition of geospatial services. Technically, the geoprocessing services are implementation and algorithm specific. Their qualities also depend heavily on the complexity of the input data and the processing functions involved. The quality of service outputs is generally measured by their completeness, logical consistency, positional accuracy, temporal accuracy, and thematic accuracy (ISO, 2002). (Donaubauer et al., 2008) proposed to use Geographic Markup Language (GML) and ISO 19139 to dynamically generate quality information for the service outputs based on the quality of the service input data and spatial analysis methods. In addition to common processing quality factors and output quality factors, (Gui et al., 2009) integrated dynamic features of services, such as data size and network bandwidth into a preliminary QoS assessment model for geoprocessing services.

Enabling the commercial use of geoprocessing services in an on-demand and ad-hoc fashion depends strongly on the efficiency of service security, and manageability. (Schaffer and Gartmann, 2011) have presented OGC's generic security extension that goes beyond classical role-based access control models to support ad-hoc license agreements directly in process, without any prior offline negotiated agreements being necessary between the service provider and service user for on-demand access.

4.4. Geoprocessing orchestration

By dynamically collaborating distributed individual Web services into long-lived, transactional and multi-step service chains, the service orchestration allows design and execution of a complex processing workflow across domains and applications (Peltz, 2003). The ISO19119/Service Architecture standard defines a service chain as "a sequence of services where, for each adjacent pair of services, occurrence of the first action is necessary for the occurrence of the second action" (ISO, 2005). Three architectural patterns for geospatial service chains are identified (Alameh, 2003; ISO, 2005):

- Transparent chaining
  In transparent chaining, the knowledgeable user plays a central role in finding all the required geospatial services and data and defining a service chain with different components and specific interactions. Furthermore, the user is responsible for invoking the services and passing around process results. Since all service details are visible to the user, this pattern is called transparent chaining.
- Translucent chaining
  Translucent chaining pattern allows a user to execute a service chain that is abstractly predefined and managed by a workflow engine. The user is aware of all components of the service chain, but does not have to deal with the execution order or mediate processing results. But since the user knows all participating services, he/she is able to view and adjust the current status of each participating service.
- Opaque chaining
  Opaque chaining pattern exposes a service chain as a single service and hides all details from the user. The user sets all the required parameters, submits the request, and gets back the results without knowing that the single service hides a chain, and what types of services are being used. Essentially, the single service is responsible for all service coordination.

Typical activities of a service chain include *Sequenc*e, *Split*, *Split*+*Join*, *Choice*, *Any-Order*, *Condition*, *If-Then-Else*, *Iterate*, *Repeat-While*, and *Repeat-Until*. Several orchestration languages are available. The XML Process Definition Language (XPDL) as a Workflow Management Coalition (WfMC) workflow language (WfMC, 2008), the Yet Another Workflow Language (YAWL) as a popular open source language (Aalst and Hofstede, 2004) and the Web Services Business Process Execution Language (WS-BPEL) as a popular business workflow language (OASIS, 2007) are the most relevant and popular. Since WS-BPEL provides rich vocabulary and control structure, and is widely supported by commercial vendors and open-source communities, it is becoming the de-facto standard for describing the control logic required to coordinate those Web services participating in a processing workflow (Akram et al., 2006). In particular, the WS-BPEL script describes the roles involved in the message exchange, supported port types, and orchestration information of a process to enable the composition of workflows based on loosely coupled services. Therefore, WS-BPEL is being widely used in geoprocessing orchestration (Fleuren and Muller, 2008; Meng et al., 2009; Schaeffer, 2009; Zhao et al., 2011).

The orchestration of geoprocessing services is one of the major research areas promising for enabling complex geospatial applications and knowledge discovery over the Web (Brauner et al., 2009). One of the earliest studies on chaining geographic information Web services was by (Alameh, 2003). She proposed a Web service model that allowed users to freely combine Web services to create customized geospatial information applications with minimal programming, integration, and maintenance efforts. To enable scientists to harvest online geospatial resources and create models for designing and executing experiments, (Jager et al., 2005) presented a workflow framework for discovering, registering, composing, and executing Web services. (Di et al., 2005) and (Granell et al., 2005) proposed the abstract process and relevant elementary workflow patterns for the conceptual foundation of reusing existing domain models and services in service orchestration. (Friis-Christensen et al., 2009) introduced the term Distributed Geographic Information Processing (DGIP) and presented different architectural patterns for chaining of geoprocessing services. (Dasgupta and Ghosh, 2010) developed a framework which could incorporate business logic for chaining of data and processing services to generate user specific geospatial information at any location for mobile device users.

On the standardization level, the OGC, the ISO TC211 and WfMC have been collaborating for many years, and producing a significant body of knowledge and experience in geospatial service specifications, workflow architecture, workflow metadata and language, workflow security and licensing, and workflow interface and implementation. These standardization efforts have made great progress on the use of Web services to build geospatial processing workflows (Keens, 2007; Werling, 2008; Schaeffer, 2009). (Deng et al., 2004) implemented a prototype system by which users can build a workflow with OGC services to do image processing for remote sensing data. (Kiehle et al., 2006) used standardized OGC Web services and workflow management facilities to implement highly complex service chains with geoprocessing capabilities. (Weiser and Zipf, 2007) and (Stollberg and Zipf, 2007) discussed how OGC Web services, in particular Emergency Route Service (ERS) and OpenLS Route Service, could be used within a service chain through BPEL scripts for disaster management. (Schaeffer, 2008) introduced a BPEL deployment profile to expose geospatial processing workflows as simple OGC WPS-based geoprocesse models. Thus, geoprocessing workflows can be triggered using OGC-compliant messaging. For e-Science applications in a sensor web environment, (Zyl and Vahed, 2009), (Yu et al., 2010), and (Chen et al., 2011) proposed to use OGC Sensor Model Language (SensorML) and WS-BPEL to integrate logical and physical processes into a composite geoprocessing chain for sensor observations.

Besides the current research, still some challenges remain open. Performance is an important issue in geoprocessing orchestration. To transfer large volumes of geospatial data among distributed services efficiently, suitable workflow patterns and data encodings have to be found. Use of reference data might be one solution for centralized workflow approaches (Yu et al., 2008; Foerster et al., 2011b). (Friis-Christensen et al., 2009) studied several patterns of geoprocessing workflows, which are promising to be elaborated for efficient encoding of data in the future. Asynchronous mechanisms, by which clients can resume their processing without waiting for a lone response, are very useful for the performance of complicated geoprocessing workflows. (Zhao et al., 2011) discussed the different asynchronous patterns and examined different ways to implement asynchronous geoprocessing workflows, but in which the notification mechanisms still need to be enhanced. Security and licensing of specific geoprocessing workflows might is another issue, as foreseen by INSPIRE (2008), for the sustainability and the commercial potential of Geoprocessing Web. Challenges regarding the delegation of rights between secured service providers, workflow engines and service users are arising. One solution to solve this issue in an interoperable way, which uses open standards and generic security extensions, has been presented by (Schaffer and Gartmann, 2011) for opaque workflows, but has to be extended to other workflow patterns.

4.5. *Geospatial semantics*

Semantic Web (Berners-Lee et al., 2001) technologies, which give machine-processable meanings to the documents, enable the semantics of geospatial data and geoprocessing services machine-understandable and thus can be processed by machines (reasoning) for more effective discovery, reuse, automation, and integration of geospatial information and knowledge. The importance of semantics on accessing and integrating geospatial information has long been recognized (Bishr, 1998; Sheth, 1999; Kuhn, 2005). The semantic interoperability assures that the contents of data and geoprocessing services are correctly understood when data/services are connected (Yue et al., 2007).

Since 2005, OGC has issued the Geospatial Semantic Web Interoperability Experiment (GSW IE) aiming to develop a method of discovering, querying and collecting geospatial content on the basis of formal semantic specifications (Kolas et al., 2005; Kammersell and Dean, 2006; Lutz and Kolas, 2007). In this experiment, five types of ontologies, including base geospatial ontology, feature data source ontology, geospatial service ontology, geospatial filter ontology and domain ontology, are identified. With the help of these ontologies, a user's query can be translated to semantic queries for data source via semantic rules, and then transformed to OGC WFS queries for real data through Extensible Stylesheet Language Transformations (XSLT). To facilitate semantic reasoning, the query is represented using SPARQL Protocol and RDF Query Language (SPARQL), and the semantic rules are represented using Semantic Web Rule Language (SWRL). More recently, the GeoSPARQL standard, a geographic query language for RDF data, is proposed by OGC to define the spatial extensions to the W3C's SPARQL.

In the Geoprocessing Web environment, large volumes of geospatial data and diverse geoprocessing functions are often accessible as services. An intelligent mechanism is required to facilitate discovery and integration of geospatial data and services. (Lutz, 2007) presented a methodology for ontology-based discovery of geoprocessing services using ontologies of geospatial operations and function subtyping. In the EU-funded Semantic Web Services Interoperability for Geospatial Decision Making (SWING) project, Web Service Modeling Ontology (WSMO) is used to facilitate the discovery and invocation of semantically described geoprocessing services (Roman et al., 2006; Zaharia et al., 2009). A semantic layer including Web Ontology Service and Web Reasoning Service is further proposed for semantic discovery, dynamic orchestration of sensors and Web services, and semantic interoperability (Janowicz et al., 2010). To support the effective reasoning during the service discovery, (Fitzner et al., 2011) proposed to annotate geoprocessing services as conjunctive queries in a logic programming language. The linked data approach also shows promise to connect distributed resources including geospatial data and geoprocessing services. Some work has been conducted on applying linked data principles to OGC service standards (Schade et al., 2010).

To enable semi-automated or automated geospatial knowledge discovery, (Yue et al., 2007) proposed a semantics-enabled architecture for automatic geoprocessing service chaining. Further, a three-phase intelligent chaining method was addressed to cover process modeling, model instantiation, and workflow execution (Yue et al., 2009). In order for the chaining results to be consumable, semantics-enabled geospatial metadata needs to be generated, validated, and propagated through the service chains. The generated metadata not only provides a context in which end-users can interpret data products before intensive execution of service chains, but also assures semantic consistency of the service chains. The geospatial catalogue service that imports geospatial metadata with semantics can be used to support semantics-enhanced discovery of geoprocessing resources (Yue et al., 2010b).

5. Implementation of the Geoprocessing Web

5.1. *Geoprocessing Web systems*

The different aspects of Geoprocessing Web have been addressed in a variety of existing successful Web systems.

The Global Earth Observation System of Systems (GEOSS) provides Web portals for searching and exploring the geospatial data, information, imagery, services, and applications across organizations (GEOSS, 2012). The European Commission Ground European Network for Earth Science Interoperations-Digital Earth Communities (GENESI-DEC) project uses semantic technologies to facilitate the annotation, search, discovery and access of heterogeneous Earth science data with metadata catalogues (GENESI-DEC, 2012).

The NASA **G**ES-DISC (Goddard Earth Sciences Data and Information Services Center) **I**nteractive **O**nline **V**isualization **AN**d a**N**alysis **I**nfrastructure (Giovanni) provides a series of Web portals for online visualization, access, and analysis of Earth science remote sensing data (Berrick et al., 2009). It has an intuitive and responsive interface running in a Web browser. Web services and workflows are used in analyzing the data. The provenance on data processing is also provided to users. Giovanni has been used in many Earth scientific research efforts and applications (Prados et al., 2010).

GeoBrain is a geospatial service, modeling and knowledge building framework (Di, 2004). The GeoBrain Online Analysis System (GeOnAS) takes advantage of open and standardized Web services and architecture to provide interoperable online analysis of geospatial data (Han et al., 2008). It provides an open data platform by which users are able to discover and access distributed geospatial information using the NASA EOS Metadata Clearinghouse (ECHO), NOAA Comprehensive Large Array-data Stewardship System (CLASS), and U.S. Geological Survey (USGS) Landsat Archive Catalogs. Within the context of SOA, GeOnAS provides an interoperable application platform to enable users to create customized data analysis systems with a collection of loosely coupled Web services. Moreover, GeOnAS provides a collaboration platform that allows different users to contribute geospatial processes and data products for sharing, exchange, and reuse (Zhao et al., in press).

The European Space Agency (ESA) Grid Processing on Demand (G-POD) is an operational system for Earth science applications. It provides a Web portal to support users to create geoprocessing tasks, manage tasks, select data, and monitor jobs using high-performance and sizeable computing resources managed by grid technologies (ESA, 2012).

The U.S. National Science Foundation (NSF) funded GEON project aims to develop a cyberinfrastructure for integration of 3 and 4 dimension Earth science data (GEON, 2012). It uses a set of software services to build Web-based geoinformatic systems for different Earth science applications. For example, the Open Earth Framework provides a geological and geophysical data integration, analysis and visualization environment.

5.2. *Technology readiness*

In order to develop, deploy and invoke distributed geoprocessing services in an efficient way, performance and interoperability issues need to be more investigated (Kiehle et al., 2007). For example, some geoprocessing tasks can work more effectively on users' desktop computers or a centralized server than on distributed services, considering factors on the time of transferring massive datasets across networks or multiple interactions between clients and services. There are some design decisions, including transactional mode, service granularity, communication manners, and transmission formats, for improving the service performance (Tu et al., 2004; Scholten et al., 2006; Michaelis and Ames, 2009). The transactional mode includes synchronous and asynchronous modes. Solutions on asynchronous geospatial processing workflows with Web services have been available (Zhao et al., 2012). The granularity of individual services is an important factor that affects the flexibility, applicability, and reusability of service modules in different geospatial models. If a module's functionality is too small, many modules are needed to construct a complex geospatial model, hence reducing the system performance. If too many functions are aggregated into a service module, the module is not easily plugged into other geospatial models. Thus, service flexibility, applicability, and reusability will decrease. The fundamental geoprocessing functions in GIS software systems, which are tailored to users' preferences, can provide a valuable reference for determining the granularity of geoprocessing services (Yue et al., 2010b). The communication manner and transmission format involve service message and data transfer. The XML based communication and stream based delivery have been commonly used in improving service interoperability and performance.

The syntactic interoperability issue has been addressed intensively by geospatial communities such as OGC and ISO/TC211. Standards on different types of geospatial services have been available and widely used in geospatial Web applications. Some existing standards may need to be extended to work in the Geoprocessing Web. For example, the ISO 19115 metadata standard defines lineage information classes and subclasses. But, it misses some key information needed for documenting the provenance or geoprocessing, such as the running environment, the algorithms, and software executables. Therefore, the lineage model in ISO 19115 alone cannot meet the need for capturing the provenance in the Geoprocessing Web. One potential solution is to combine lineage models in ISO 19115 and ISO 19115-2 to provide a comprehensive provenance information model (Di, 2011).

The Semantic Web technologies have been investigated intensively in recent years, and have been proved to be useful in improving semantic interoperability and facilitate knowledge exchange and services. For example, Web Ontology Service and Web Reasoning Service can be used to provide the knowledge services (Janowicz et al., 2010). Although there are still some open issues on automatic semantic annotation and consensus based Web geospatial ontologies and alignment, the use of semantics in limited-domain applications has shown great promise in operational systems such as GeoBrain, GENESI-DEC, and GEON.

6. Conclusions

From the Web science (Berners-Lee et al., 2006a) perspective, the Geoprocessing Web is about engineering a geoprocessing infrastructure, utilizing openness to reuse geoprocessing facilities, making distributed and interoperable geoprocessing tools, and enhancing geoscientific collaboration with the ready-to-use geoprocessing tools. This paper discusses the current state-of-the-art of the Geoprocessing Web. The key issues and related technologies include the concept and framework for building cutting-edge distributed and interoperable geospatial applications, the basic knowledge and recent progress of standards for interoperable geospatial data and services, the techniques for design, development, deployment, and operation of geospatial services, the theories and applications of the geospatial Semantic Web, the models, methods, languages, and tools of geospatial service orchestration, and some operational Web-based geoprocessing systems and related technological readiness.

Our study reveals the Geoprocessing Web is changing the way in which geospatial applications and systems are designed, developed and deployed. While there are still some important challenges in this field, we believe the Geoprocessing Web provides a promising framework to facilitate distributed geospatial computation and large networks of collaboration.

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