[PD-04-029] Programming of Mobile GIS Applications

Abstract

Mobile technology has significantly changed how we communicate and interact with the outside world. With the increasing use of mobile devices and advancement of information communication information (ICT) technologies, mobile GIS emerged to provide real-time data collection and update, and made GIS easier and convenient to access. This entry introduces the concept, types, and general architecture of mobile GIS, key technologies used for mobile GIS development, and examples of mobile GIS applications.

Keywords: apps, development, mobile apps, mobile GIS, programming

Author & citation

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Explanation

1. Definitions

Mobile GIS: Mobile GIS refers to Geographic Information System (GIS) for use on mobile devices. Mobile GIS extends the traditional indoor GIS manipulation to outdoor work, enabling GIS accessibility at any location, and allowing field personnel to collect, store, edit, manipulate, analyze and display spatial data in an easy, inexpensive, and effective way.

Mobile Web GIS: If a mobile GIS is accessed with a browser app (e.g., Firefox, Google Chrome, Safari) installed on users' mobile devices, such a system is considered as mobile Web GIS application. It is developed based on web technologies, such as HTML5 and JavaScript (JS), hosted on remote server, and should provide mobile-optimized content access like normal websites (Malavolta, 2016). In other words, a mobile web GIS is essentially a web or online GIS accessible through mobile devices.

Native app: A native app consists of binary executable files that are directly downloaded to the user's device, stored and run locally (Malavolta, 2016). Such an app is distributed through app stores, such as the Google Play Store and the Apple app store.

Hybrid app: A hybrid app, also known as native web app, is created based on a hybrid development framework or a web-to-native middleware that can bridge service requests from the web-based JS code to the corresponding platform application programming interface (API) by providing a JS-based API to communicate with native device capabilities.

Wireless Application Protocol (WAP): As a global communication standard, WAP enables the interoperability of mobile applications communicated through different wireless networks.

Mobile client: The client side of a mobile GIS often includes both the hardware (i.e., a GPS-enabled mobile terminal), and software (i.e., a mobile GIS user interface) deployed on the mobile terminal to access the system functions. The mobile terminal could be a large variety of mobile devices, including smartphones, pocket PCs, PDAs, tablets, laptops, and smart eyeglasses.

User interface: For a mobile GIS, the user interface is a tool that can enable users to manipulate maps and their underlying geographic information through mobile devices.

Augmented reality: Augmented reality enables users to better interpret and interact with real-world objects, which are enhanced by computer-generated perceptual information across multiple sensory modalities, such as visual, auditory, haptic, somatosensory and olfactory.

2. Introduction

Mobile devices, such as smartphones, have become increasingly popular in society. In 2017, 77% of the U.S. population uses a smartphone and the number is consistently growing (pweinternet, 2018). Worldwide, the mobile population amounted to 4 billion unique users, and mobile devices contributed to 48 percent of web page views in 2019 (statista, 2019). These mobile devices, coupled with different sensors (e.g., GPS, compass, and magnetometer) and other technologies, such as LiDAR, virtual reality (VR) and augment reality (AR; Ma et al., 2018; Gazcón et al., 2018), computer vision, and cloud computing, created unique opportunities for data collection, process, analysis, visualization and interpretation. Mobile devices and applications have changed how we all live and communicate with others.

Mobile GIS is considered as an integrated software/hardware framework for accessing spatial data and services through mobile devices via wireline or wireless communications (e.g., WiFi, broadband and Bluetooth; Tsou, 2004). Simply put, it refers to GIS for use on mobile devices. Mobile GIS makes GIS available from desktop and cloud-based software and services to anywhere around the world. It extends the traditional indoor use of GIS to the outside world, enabling GIS accessibility at potentially any location. Today, field personnel can collect, store, edit, manipulate, analyze and display spatial data in an easy, inexpensive, and effective way using mobile GIS.

Back in the 1990s, applications of mobile GIS were mostly used for in-vehicle navigation and field survey. In those systems, GIS data and software were preloaded and operated in a standalone mode without communicating to the Internet in the field. With the development of wireless and other communication technologies, such as fourth generation (4G), applications are able to access and transfer data over the Internet. These applications can integrate powerful GIS services distributed over the web, obtain updates of the latest GIS data, and regularly send the latest field information back to server side data collection and dissemination systems. As such, mobile GIS has evolved from being disconnected to wirelessly connected, and is increasingly considered a component of web GIS (Khasha et al, 2018; Tsou, 2004; Yamamoto & Zhou, 2018). Correspondingly, it overlaps the topics of web GIS (see Web GIS) and web mapping (see Web Mapping), and has been gradually offering more sophisticated online GIS functions and interaction accessible through mobile devices.

3. Mobile GIS Types

A mobile application, most commonly referred to as an app, is a type of application software designed to run on a mobile device, such as a smartphone. Mobile applications often provide users with similar services to those accessed on computers. Mobile GIS applications can be categorized in two ways, according to offered functions, and system access methods. According to a mobile GIS's primary functions accessible through the client side, it can be classified into one of the three categories (Figure 1): 1) real-time data collection and editing services in the field, 2) location based services (LBSs; see Location-Based Services), such as real-time tracking, navigation, monitoring and location identification using Global Positioning System (GPS), and 3) augmented reality (AR) services using camera, GPS, and GIS data. Similar to other GIS systems, these different types of mobile GIS would provide a set of common functions: 1) mobile mapping (visualization) for representing spatial information over a mobile interface; 2) spatial query and interaction that enables users to retrieve information about features displayed on map; and 3) map processing and spatial analysis, often limited due to the constraints of computing power and screen size for a given mobile device (Figure 1).

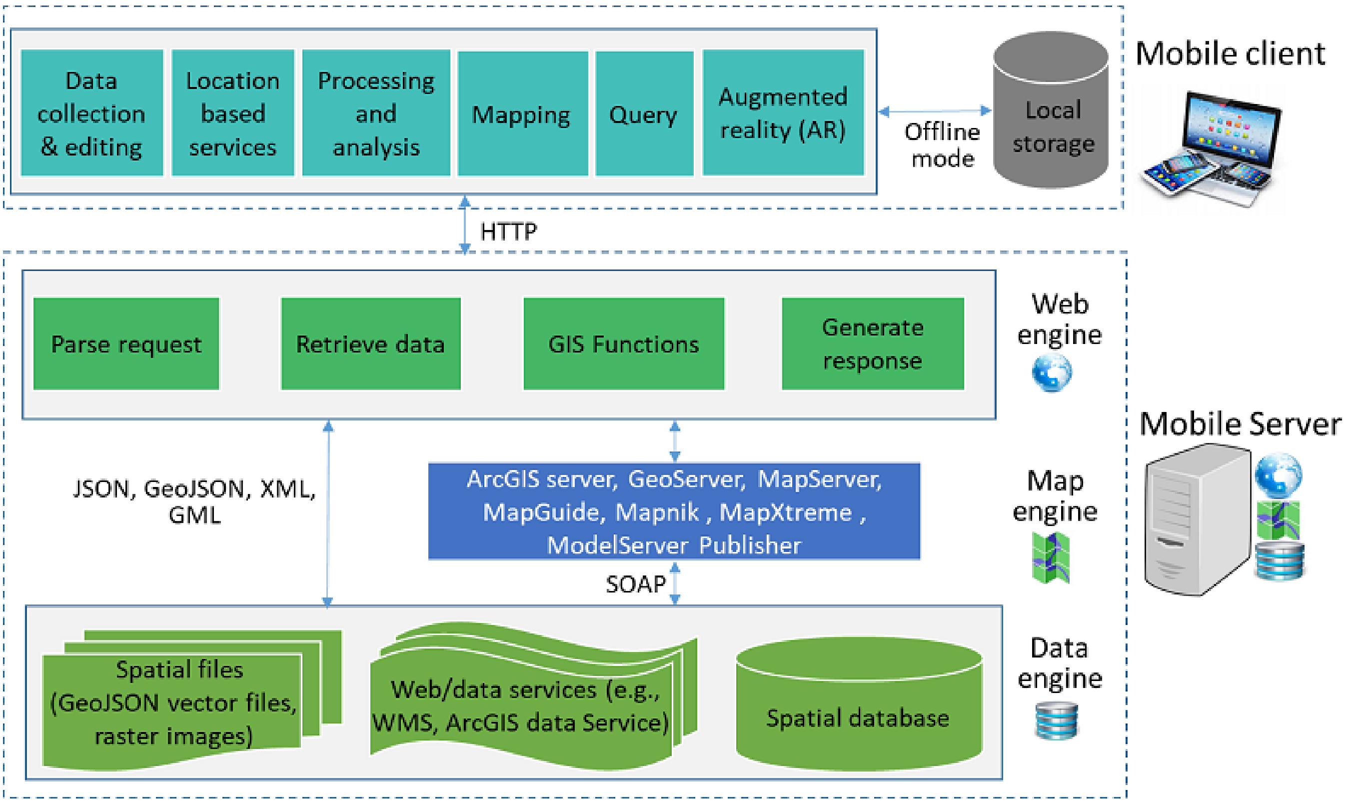

Figure 1. A generalized architecture of mobile GIS. Source: author.

The first two types, field-based (Giardino et al., 2010; Sun et al., 2008; Tsou, 2006; Yan et al., 2009; Ye et al., 2014; Zhong et al., 2010; Lafontaine et al. 2017; Teo, 2108; Fu et al. 2018; Roberts et al., 2019; Gharbi & Haddadi., 2019), and LBS-based (Chu et al., 2012; Bartie et al., 2018), are most common (Gao & Mai, 2018; Tsou, 2004). Field-based GIS helps field personnel to access, collect, store, modify, manipulate, analyze and display spatial data in the field. By enabling access to large digital datasets and spatial functions for practioners and researchers in the field, mobile GIS facilitates the data collection process and can contribute to the quality and the efficiency of fieldwork. LBSs primarily provide business-oriented location management functions, such as navigation, tourist guiding, finding a specific location, or tracking a vehicle. At present, most popular examples include Google Maps, Waze, Yelp, Facebook Places, and Foursquare.

Finally, AR systems are emerging as a new platform for visualization, allowing users to better interpret and interact with real-world objects (Ma et al., 2018). AR technology could be also incorporated in the fieldwork observation. As an example, Gazcón et al. (2018) developed an AR based system, named ARGeo, as a complementing tool for the geologist's fieldwork designed to be used in remote sites without the need of an internet connection for data acquisition. Similarly, AR technology offers a great potential to enhance LBSs, such as navigation (Cron et al., 2019) and tour services (Lo & Chang, 2019).

Similar to a general mobile app, an access method classification schema can be used to categorize a mobile GIS application into one of three types: a mobile web GIS, a native GIS app, or a hybrid GIS app. If a mobile GIS is accessed with a browser app (e.g., Firefox, Google Chrome, Safari) installed on users’ mobile devices, then this system is considered as mobile web GIS application. It is developed based on web technologies, such as HTML5, JavaScript (JS), Cascading Style Sheets (CSS), Document Object Model (DOM), and Asynchronous JavaScript and XML (Ajax), hosted on remote server, and provided mobile-optimized content access like normal websites (Malavolta, 2016). In other words, a mobile web GIS essentially is a web or online GIS accessible through mobile devices. A mobile web application has a variety of advantages, including rapid development options, simple maintenance, supporting across platforms (e.g., Android, and iOS devices), feature-rich and standards-compliant mobile web browsers, leveraging most of the current standard web technologies, such as offline data collection, use, and storage, network connectivity, and multimedia support (Charland & Leroux, 2011; de Abreu Freire & Painho, 2014; Kosmaczewski, 2012; Malavolta, 2016).

Native mobile apps consist of binary executable files that are directly downloaded to the user’s device, stored and run locally (Malavolta, 2016). These apps are distributed through app stores, such as the Google Play Store and the Apple app store (Malavolta, 2016). Programming languages and software development kits (SDKs) are platform-specific, designed only for one specific operating system. Android based apps are primarily developed using Java within the SDK environments such as Eclipse. C/C# or Swift are often adopted for app development on iOS devices, whereas C/C# for windows apps. Native mobile apps ensure the best interaction with the device hardware, such as accelerometer, bluetooth, gesture recognition, GPS, camera, microphone, and file system. Native apps can also support rich user experience, and achieve relatively high performance (Charland &

Leroux, 2011; Malavolta, 2016). However, native code written for one mobile platform (e.g., the Java code of an Android app) cannot be used on another (e.g., the C code of an Apple iOS app), posing a grand technical challenge to the mobile development community in developing and maintaining native apps for multiple platforms (Malavolta et al., 2015).

As a result, hybrid mobile app development emerges as a new solution to make mobile apps compatible across different platforms using both web and mobile technologies. A hybrid app, also referred to as a native web app, integrates useful features from both native apps and web apps. While considered a web app, it is hosted inside a native-to-the device app container. A hybrid app is developed based on an hybrid development framework or a web-to-native middleware (e.g., Apache Cordova) that can bridge service requests from the web-based code (i.e., JS code) to the corresponding platform application programming interface (API; e.g., Android API) by providing a JS-based API to communicate with native device capabilities (Malavolta et al., 2015). As such, it is installed, launched and used like any native app, and can access a variety of device APIs to interact with device hardware, but developed based on standard web technologies (Charland & Leroux, 2011).

4. Mobile GIS Architecture

Similar to web GIS (see Web GIS and Web GIS Programming), most mobile GISs are developed based on a client-server architecture. The client side includes a GPS-enabled mobile device, and a mobile GIS software with a user interface (UI; see User Interface and User Experience (UI/UX) Design), a tool that can enable users to manipulate maps and their underlying geographic information through the mobile device. A general mobile sever may contain three components (see Figure 1, above):

- Web engine: provides the GIS and mapping functionality of the mobile GIS application, e.g., responding to the requests sent through the mobile UI.
- Map engine (also known as GIS Engine): responsible for the transport of data from its source format to the web services (see Web GIS), or maps. Examples include ArcGIS server, GeoServer, MapServer or other open source map servers.
- Data engine: organizes and manages both spatial and non-spatial data through a spatial database or traditional file systems.

A wireless communication network ensures communication between the client and the server for data uploads and downloads, or information request and response. Requests and responses are processed through different server-side engines. Depending on the functions, and the number of clients (i.e., users) that may use the mobile GIS simultaneously, the web, map and data engines can be deployed on one, or multiple servers to implement a scalable and flexible system.

4.1 Mobile Client

The client side often includes both the hardware (i.e., a GPS-enabled mobile terminal), and software (i.e., a mobile GIS UI) deployed on the mobile terminal to access the system functions. The mobile terminal could be a variety of mobile devices, e.g., smartphones, pocket PCs, PDAs, tablets, laptops, and smart eyeglasses. While these devices are commonly equipped with display, memory and central processing units, they may be developed based on different operating systems, such as Android, Bada (Samsung Electronics), iOS, and Windows Mobile. Except for Android, iOS is the most popular operating system.

The mobile GIS UI (or portal) is the gateway for users to access the system functions through the graphically and usually touch-sensitive display on the mobile device. The interface could be opened in a browser, native, or hybrid app (Section 3). Similar to web GIS, mobile GIS client scripting or programming heavily relies on web technologies. React Native, Vue.js, Express, Angular, Ionic2, jQuery Mobile, Sencha Touch, Apache Cordova are JS libraries and frameworks with a set of components and features for building UIs for mobile applications (Table 1). Herein, React Native allows developers to build native apps in JS that can run on both iOS and Android, whereas Cordova serves as a container for connecting our web app with native mobile functionalities.

Compared to a general mobile app, mobile GIS UI should provide spatial data layers, as well as simple mapping and spatial functions, which are typically enabled through various client-side spatial APIs and SDKs, such as Google Maps APIs (Table 1; Section 5.2). The data layer typically includes one digital basemap layer displaying the geographic background of current location of a mobile device, and thematic layers depicting physical or socioeconomic properties, such as population, traffic, and facilities (Gao & Mai, 2018).

Table 1. Common Client and Server Side Programming Solutions for Mobile GIS

<table>
<tr><th colspan="2">Programming</th><th>Language</th><th>API / Framework</th></tr>
<tr><td rowspan="2">Client Side</td><td>General</td><td rowspan="2">HTML, CSS, JavaScript</td><td>React Native, Vue.js, Express, Angular, Ionic2, jQuery Mobile, Sencha Touch, and Apache Cordova</td></tr>
<tr><td>Spatial</td><td>ArcGIS Runtime SDKs, Google Maps SDK for Android, HERE Android & IOS SDKs, TomTom Maps SDKs, Carto Mobile SDKs, NextGIS Mobile SDKs, and Mapbox Maps SDK</td></tr>
<tr><td rowspan="2">Server Side</td><td>General</td><td rowspan="2">ASP.Net, C#, C++, Objective-C, Java, PHP, Python, Ruby, Swift, Kotlin</td><td>• ASP.Net, C#, Objective-C, and C++: .NET framework;
• PHP: Zend Framework, and Laravel
• Python: Django, Flask and Drupal
• Java: Java Server Pages (JSP), Java Server Faces, Struts, Spring, and Hibernate
• Ruby: Ruby on Rails
• Others: Swift, and Kotlin</td></tr>
<tr><td>Spatial</td><td>• ASP.Net: Feature Data Objects (FDO) API
• Java: Java Topology Suite (JTS), and GeoTools</td></tr>
</table>

At present, the data synchronization and communication between the client side and server side of a mobile GIS heavily relies on wireless communications technologies, such as WiFi, broadband and Bluetooth. Global system for mobile (GSM), general packet radio service (GPRS), and code-division multiple access (CDMA) are the most widely used wireless network that mobile GIS will run on in the future (G. Chen et al., 2010). The last two decades have witnessed the evolution of the mobile communication technology from the first generation to fifth generation (5G), including simulation mobile phone, digital mobile commination, multi-media mobile communication providing internet service (G. Chen et al., 2010).

Wireless Application Protocol (WAP) is a global communication standard for enabling the interoperability of mobile applications communicated through different wireless networks (e.g., GSM, CDMA (Erlandson & Ocklind, 2000). Similar to HTTP protocol, WAP specifies the standards for data access and exchange between a web server and a mobile client (G. Chen et al., 2010). To transfer data between a web server and a mobile client, extensible markup language (XML) and javascript object notation (JSON) data formats are typically used. However, it is recommended to use a smaller data size format, such as JSON, compared with an equivalent XML dataset, depending on how the XML is formatted (Charland & Leroux, 2011). As a language for describing two-dimensional graphics in XML, scalable vector graphics (SVG) is a text-based graph data format for network features transferring (Zuo & Li, 2005).

A mobile app with offline mode enables the users to perform critical tasks when not connected to the Internet by accessing the local stored datasets in the hard disk of mobile device. For example, Cordova APIs enables mobile app developers to build applications that cache REST resources for offline use and then synchronize all offline changes with the server when the device goes online again. By supporting an offline mode, a mobile app is resilient to different network scenarios (e.g., slow Internet), and can be used at any place where mobile data is expensive, or users can't get online. For example, by saving an area from Google Maps to our phone or tablet, we can use the Google Maps app in offline mode. Users can still get driving directions, use navigation and search for locations without retrieving transit, bicycling, or walking directions, as well as traffic information, alternate routes, or lane guidance that requires online data synchronization with the Google server side.

4.2 Mobile Server

The server side typically consists of a web engine, a map engine, and a data engine. These engines are all optional depending on the design and functions offered by a mobile GIS. For example, if a mobile GIS only displays static information, fully working without the query and access of data from the server side interactively, then it may not need a data engine. The web engine parses the data and service requests from the client side, retrieves the data (e.g. a subset of an image or a vector layer) from the data engine, performs the spatial operation (e.g. a geo-spatial analysis or summary of the records retrieved from a spatial database), and generates and returns the results to the client. To transfer data and communicate with the mobile client, a web engine uses HTTP protocol which specifies the format of request and response message.

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To interact with the client requests, many server-side technologies are available (Table 1; also see Web GIS Programming), including Java-based, C#, ASP.NET, PHP (Hypertext Preprocessor), Python and many others for mobile apps of different operating systems. C#, C++, and Python could be used to build mobile apps running on different OSs, including Android and iOS. Objective-C and Swift are two main programming languages used to build iOS apps. In early 2018, Swift replaced Objective-C in popularity and became top programming language for iOS (Chand, M., 2019). Java and Kotlin are mostly used for Android based app development. Kotlin is a cross-platform, statically typed, general-purpose programming language.

Java servlet is the foundation of the Java-based server-side technology to handle clients' requests and return a customized or dynamic response for each request. The dynamic response could be based on user's input (e.g., spatial querying, and online mapping) with data retrieved from databases or other applications (e.g., web services). Java Server Pages (JSP), Java Server Faces, Struts, Spring, and Hibernate, to name a few, are extensions of the servlet technology. However, JAVA servlet and JSP pages are server-side technologies that have dominated the server-side Java technology market, and became the standard way to develop interactive online applications.

A map engine, also widely defined as map server in the literature, is the component for publishing, sharing and rendering spatial data stored in the data sever. A map server can read and transfer spatial raw data of varying formats, such as shapefiles, GeoTIFFs, GIFs, and JPEGs, and making it accessible in commonly used formats, such as Web Map Server (WMS), Web Feature Server (WFS), and Web Coverage Server (WCS), via standard web service requests (Kropla, 2006). Web services enable large-scale data sets available and sharable to the public through a web service Uniform Resource Identifier (URI), and reduce the need for storing data locally and continual data storage upgrades. While the map server was originally designed to build interactive online web applications, and part of a web GIS architecture, it is now widely leveraged for mobile applications.

Finally, the data engine manages the spatial data, which could be stored in spatial databases or directly organized as spatial files. Since mobile devices only have limited storage space, data are mostly stored in the server side (Gao & Mai, 2018). However, a mobile app may leverage both client side storage and server side storage, and the app will manage the flow of data between server and client. The local side database is especially useful for performing tasks when offline.

Besides, it can provide data preprocessing functions, such as indexing, and generating metadata, to facilitate the access of the raw data. However, some spatial data, such as weather and natural disaster locations, are constantly being updated (streaming). Rather than frequently downloading and updating such data, a cost-efficient approach is to integrate live data feeds to maps that access web services in real time or near-real time. In fact, one of the great advantages of web and mobile GIS applications is that you can mash up remote web services (e.g., as different data layers or functions) with local content to assemble unique and focused GIS applications. Various web services can be accessed and assembled as part of your web or mobile GIS application, such as a basemap service, operational map services, geoprocessing services, geodata services, and image services.

5. Mobile GIS Apps and Development

This section first introduces several poplar mobile GIS apps from both industry and open-source communities, and then describes common SDKs to implement such an app.

5.1 Mobile GIS Apps

As one of the leading companies in the GIS field, ESRI offers mobile GIS solutions in its palette of mobile apps, including ArcPad, ArcGIS for Windows Mobile and Tablets, and ArcGIS for Smart Phones and Tablets. Many of these applications can be scripted or extended to add new capabilities. In addition to the configurable apps, ArcGIS also has one mobile app builder solution-AppStudio which allows users to publish mobile applications based on templates, and also provides options for deeper customization (ESRI, 2018).

- ArcGIS for Windows Mobile and Tablets helps organizations deliver GIS capabilities and data from servers to a range of mobile devices running on a Windows device. ArcGIS for Windows Mobile comes with a ready-to-run mobile application, and a configurable SDK. The mobile application enables field personnel without any GIS experience to perform mapping, spatial queries, sketching, GPS integration, and GIS editing, whereas the SDK allows the developers to create stand-alone mobile applications, embed GIS functionality into existing applications and build custom tasks and extensions.
- ArcGIS App for Smart Phones and Tablets is a part of the ArcGIS system, and extends GIS functions from the office to the field on a variety of devices. Using this app, users can navigate maps, collect and report data, and perform GIS analysis. The app also includes an SDK to further custom and enhance the mobile applications. As such, the ArcGIS App is a great way to 1) collect, edit and update features and attributes, 2) extend your GIS to wider audience, and 3) develop a custom app to meet specific application needs.
- AppStudio for ArcGIS is a tool in the GIS app revolution. It allows users to convert the maps into consumer-friendly mobile apps for different OSs and publish them to all the popular app stores without any coding. AppStudio allows app development either using a browser or on the desktop depending on how much configuration or customization users want to perform.

Other industry vendors, such as Mapbox, MapInfo, Hexagon Geospatial and General Electric (GE), also develop apps or provide solutions for designing and customizing apps. For example, Mapbox offers Mapbox Studio for developing mobile maps by uploading, editing and managing spatial data, utilizing Mapbox-provided tilesets, adding custom fonts and icons, or refining the built-in template map styles (Mapbox Studio, 2019). MapX Mobile is a development tool provided by MapInfo for creating mobile applications running on the Pocket PC Windows operating system (CDR GROUP, 2020). It provides a variety of sample applications, and offers a streamlined object model, extensive methods and events, and many wizards to facilitate the development of applications, which can be further customized through standard development languages such as Embedded C++ and Microsoft .NET. Hexagon Smart M.App is a cloud-based geospatial platform that can be used to design, build and host Hexagon Smart M.Apps, which are interactive mobile-based map application (Hexagon Geospatial, 2020). Mobile Enterprise Suite owned by GE, is a mobile platform that extends critical back office functions to the field, enabling office and field personnel to visualize and share network data and work tasks (Mobile Enterprise Suite, 2020). It provides rapid application deployment, uniform data access and field automation across the enterprise.

Besides the products offered by the industry vendors such as Esri, open-source communities have also contributed to a variety of mobile GIS apps described as below.

- gvSIG Mobile is a free and open source GIS, as well as a Spatial Data Infrastructures (SDI) client for mobile devices for GIS professionals (Mobile, 2018). It is a version of gvSIG Desktop, an OSGeo project under incubation, adapted for mobile devices, with support for spatial data of the most common formats, such as shapefiles, gvSIG Mobile has a user-friendly interface, being able to access a wide range of GIS and GPS tools. Specifically, it provides tools for project management, display of local and remote information (e.g., WMS), layers management (e.g., symbols), querying information of the elements, editing data using customized forms, creating GPS trajectories etc. Besides, it also has different tools that facilitate its integration with the rest of the gvSIG Suite. For example, it has a data importer and exporter from/to gvSIG Online (Mario, 2017).
- Enebro allows view and editing spatial vector data, visualizing images, and navigation using GPS systems. It is a useful tool for conducting field work related with field inventories, territorial inspection, field work data revision, etc. (Montesinos 2010).
- tangoGPS is a lightweight mobile navigation application for use with or without GPS. It runs on any Linux platform from the desktop computer down to phones. By default tangoGPS uses map data from the Openstreetmap project. Additionally, a variety of other repositories can be easily added. If connected to a GPS, your current position and track can be displayed on the map and positional data can be logged for further processing, i.e. for geocoding photos or uploading streets to Openstreetmap (TangoGPS, 2018).
- FoxtrotGPS is easy to use, open-source GPS/GIS application that works well on small screens and is especially suited to touch input (FoxtrotGPS, 2010). It spun off of tangoGPS in 2010 with a focus on cooperation and fostering community innovation. FoxtrotGPS is freely available to the public for use, redistribution, and modification under the terms of the GNU General Public License (GPL). This lightweight GPS-enabled navigation application can pull maps from different sources.
- SW Maps is a free GIS and mobile mapping app for collecting, presenting and sharing geographic information. Specifically, SW Maps can assist in various GIS and mapping tasks, such as conducting a field survey with high precision instruments, collecting location-based data using smart devices, or simply viewing a few shapefiles with labels over a background map. Finally, users can share the collected data with other users as keyhole markup language (KMZ) or shapefiles, or export them to external storage (Maps, 2018).

5.2 Mobile GIS Programming

Mobile application programming requires the use of specialized development environments, and mobile SDKs. Along with these general JS libraries for UI programming (Table 1), a number of commonly used client-side spatial SDKs are available to develop a native mobile GIS app on mobile devices from scratch (Table 2). Most mobile SDKs, such as Google Maps SDKs (Google, 2018), support app development on Android and iOS platforms, and a very few such as Carto Mobile SDKs (Carto, 2018), are available for the Windows platform. These mobile SDKs all include basic APIs to handle access to its web mapping service, download of map tiles, and display of tiles on the device screen. Various interaction controls can be included, such as pan and zoom, to respond to map gestures (e.g., zoom) by moving the map and zooming in or out. With these APIs, a mobile GIS application can also allow the addition of markers, polylines, polygons, and overlays to a basic map, the change of the user's view of a particular map area, and user interaction with the map. Search APIs provide search functionality for addresses, Points of Interest (POIs) or a combination of both with auto-completion and correction.

In addition, some mobile SDKs offer advanced and unique features to enhance mobile GIS apps with additional functions. For example, as one of leading companies producing traffic and navigation products, TomTom's mobile SDKs allow visualizing traffic incidents and/or traffic flow on top of a map, and offer routing features for mobile GIS apps that enable the users to pick the best route to get from one location to another.

Table 2. Comparison of Different Spatial Mobile SDKs for Client-side Programming

SDK	Platform			Mapping	Interacting	Editing	Searching	Routing	Traffic
	Android	IOS	Windows	Download/display map tiles	Pan and Zoom	Add/edit markers, polylines, polygons, and overlays	Search for an address, POI, place, etc.	Calculate routes with different parameters such as traffic avoidance, etc.	Display traffic flow or traffic incident
ArcGIS Runtime SDKs (Esri, 2018)	☒	☒		☒	☒	☒			
Google Maps SDK for Android (Google, 2018)	☒	☒		☒	☒	☒			☒
HERE Android & IOS SDKs (HERE, 2018)	☒	☒		☒	☒	☒	☒	☒	
TomTom Maps SDKs (TomTom, 2018)	☒	☒		☒	☒	☒		☒	☒
Carto Mobile SDKs (Carto, 2018)	☒	☒	☒	☒	☒	☒			

NextGIS Mobile SDKs	×	×	×	×	×	×		×	
Mapbox Maps SDK	×	×		×	×	×			

5.3 Mobile GIS Development

Mobile GISs have been widely developed to enable various operations and applications (see Section 6) by aiding in fieldworks, and offering spatial data access, mapping and visualization functions. These systems ranges from simply enabling the report and access of information, such as crime (e.g., Manazir & Rubina, 2019; Khemprasit & Esichaikul, 2011), and public services (Kurniadi et al., 2019), to providing sophisticated functions, such as 3D modeling and visualization functions (Yang, 2019; Teo, 2018; Hu et al., 018), and optimal routes (Shah et al., 2011). These systems were developed on various mobiles terminals (e.g., phones, tablets) and integrated with various technologies, e.g., LiDAR (Teo, 2018), VR (e.g., Hu et al., 2018), AR (e.g., Gazcón et al., 2018; Lo & Chang, 2019; Cron et al., 2019), computer vision (e.g., Fan et al. 2019), and cloud computing (e.g., Sánchez et al., 2018). Therefore, there are several important factors that need to be considered regarding the development of a mobile GIS:

1. User requirements, e.g., functions, and performances;
2. Mobile devices and associated OSs the app running on (Section 4.1);
3. Programming proficiency. For a given project, the easiest way is to use a ready-to-run mobile application, such as ArcGIS for Windows Mobile and Tablets, and ArcGIS App for Smart Phones and Tablets. These applications make it possible for field stuff that may not have any programming background to view, collect, and update geographic information on mobile devices. However, these systems only support fixed graphic UI with predefined functions. Next, app development tools, such as AppStudio for ArcGIS and Mapbox Studio, also allow the configuration and customization of an app through a UI without any coding. These tools also include runtime SDKs to further customize and create lightweight mobile GIS applications. Finally, developers can leverage various programming environments, mobile SDKs (Section 5.2) and programming languages (Section 4) to design and implement a mobile GIS from scratch; and
4. Mobile app type (e.g., web, native, and hybrid; Section 3), which in turn determines the programming languages to choose (e.g., Objective-C and Swift for iOS native apps whereas Java and Kotlin for Android native apps; Section 4.2).

6. Case Studies

The emergence of mobile technology has brought dramatic change to the GIS communities, and exciting opportunities in a large number of application domains, including disaster response and management. As example case studies, this section introduces how mobile GIS can be used to enhance the practices and operations in these domains.

6.1 Disaster Response and Management

Mobile GIS is one of the most vital technologies for the future development of disaster management systems because it extends the capability of traditional GIS to a much higher level of portability, usability and flexibility. Smart devices have enabled real-time situational awareness (SA) data and collection and dissemination by being connected to the internet and equipped with not only a GPS receiver but also a large number of other sensors (Lane et al., 2010; Farhadpour and Hosseinali, 2019). As a result, mobile GISs have been developed and incorporated in the disaster response and management efforts by academia, government and various industries. As an example from government and federal agencies, FEMA leverages the mobile platform to distribute information mostly collected from the authorities (Prentice, Huffman, & Alliance, 2008). AEGIS App is another operational mobile application to be used by firefighting personnel for wildfire information management, and prevention (Athanasis, Karagiannis et al., 2015). The Disaster Management and Decision Support System (AYDES) is designed to provide accurate and current disaster and emergency data, reports, statistics, job inspections, queries, analyses etc. for the National Disaster and Emergency Management Agency of Turkey (AFAD), collaborative Ministries, private institutions and provincial organizations (Keskin et al., 2018).

In academia, Baldegger and Giger (2003) envisioned a “wearable GIS” as a smart assistant in disaster management, where the user has only a head-mounted display in front of his eyes and earphones with a microphone on his head (Baldegger & Giger, 2003). AppPhyFire allows a quick visualization of the fire simulations through mobile devices by synthesizing both physical simulation models, and state-of-the-art communication and data processing technologies (Hérnández et al., 2019). Hu et al. (2018) constructed and optimized 3D disaster scenes in order to satisfy the high frame-rate requirements for the rendering of 3D disaster scenes in mobile VR. UN-ASIGN Crowd (UN-ASIGN, 2019) represents an industrial product regularly used in major emergency responses, including Haiti, Pakistan, Nigeria, Thailand, among others.

6.2 Agriculture

Accurate, reliable and real-time agricultural information is paramount to achieve digital agriculture and higher productivity (Brugger, 2011; X. Chen et al., 2012). Mobile GIS for agriculture is primarily used to record agricultural information in the farmland, including both spatial information (i.e., longitude, latitude and elevation), and attribute information, such as pest monitoring data, soil water, organic matter, nitrogen, phosphorus and potassium content, crop growth and yield (X. Chen et al., 2012). As such, the applications of mobile GIS mostly focus on agricultural information collection, plant disease monitoring, plant management, and crop mapping development and evaluation. For example, Zhao et al. (2015) proposed an information collection system for cotton pests and diseases. Users can plot the location where cotton pests and diseases locate by drawing points or polygon graphics on the map. Some mobile systems provide extended services and functions to enable the capability of mLearning and mFarming by sharing information, knowledge and experiences to and among farmers (Brugger, 2011). Fu et al. (2018) introduced an intelligent supervision system for monitoring and management of farm on mobile phone terminals based on BeiDou Satellite Navigation System (BDSNS), GIS, and GPRS technologies.

6.3 Public Health

Defined as medical and public health practice enabled by mobile devices, mobile health (mHealth) has been used to improve access to health care, engagement and delivery, and health outcomes (Heerden, Tomlinson, & Swartz, 2012). mHealth supports a variety of medical and public health applications ranging from the improvement of point of service data collection, care delivery, and patient communication with the use of mobile devices, to using alternative wireless devices to support real-time medication monitoring and adherence (Tomlinson et al., 2013). For example, an mHealth system was suggested to help pregnant women select adjacent care center or hospital maternity at online registration after they send SMS via GPRS network containing their ID and coordinates (Chu et al., 2012). Ismaeel (2012) introduced an emergency system for succoring sick child. The proposed system is the first tracking system works online (24 hour in the day) but only when the sick children requiring the help using mobile GIS (Ismaeel, 2012). Khasha et al. (2018) developed a mobile GIS tool with maps of monitoring asthma attacks based on environmental factors, such as air pollutants and meteorological factors, to enable self-managing asthma attack.

6.4 Forestry

Mobile GIS synthesizes cutting-edge science and technology such as GPS, wireless communication technology, and mobile database technology to advance forest digitalization, monitoring, management, and protection. Common applications include forestry information collecting, forest fires monitoring, resource survey, lands consolidation, water and soil conservation, and forestry e-government (Dong et al., 2010). For example, a mobile GIS was developed for forest resource inventory based on portable devices, remote sensing, GPS and embedded technology (Li & Jiang, 2011). Mobile GIS was developed to run on the PDA with ArcPad software and connected to a GPS to record indigenous knowledge in community managed forests in developing countries, such as Tanzania, India and Mali (Verplanke, 2004). Recently, Roberts et al. (2019) introduced mobile terrestrial photogrammetry to enhance municipal forest management by collecting georeferenced imagery of urban roadway to create photogrammetric point cloud datasets suitable for measuring stem diameters and attaining positional x and y coordinates of street trees. Based on web services, Cloud Computing, simulation models and geographic information systems, Sánchez et al. (2018) developed a mobile application for sharing, processing and exchanging quantitative information of the bovine meat production system to support decision-making in the bovine meat production system through grazing in the tropics. With the development of mobile technologies, mobile GIS will provide more powerful functions to support forestry planning decisions, protect wild animals, upgrade the quality of forestation and the level of monitoring plants, improve the efficiency of forestry e-government resource management, reduce the invasion of pests and diseases, calculate indicators of environmental assessment, decrease the pollution of atmosphere, soil, vegetation and other resources, and maintain ecological balance (Dong et al., 2010). Fan et al. (2019) presented the design and implementation of a ground measurement tool based on terrestrial photogrammetry, LBS, and computer vision technologies to support forest surveys for obtaining important forest structure factors, such as tree position, diameter at breast height, tree height, and tree species.

6.5 Law Enforcement and Crime Control

Mobile GIS has significantly advanced the solutions for electronic policing (ePolicing; Steiniger & Weibel, 2009), by offering optimized access to relevant information with each case, and facilitating communication among relevant stokeholds for law enforcement officers, which in turn enables quicker and more accurate response to crime scenes and accidents (Saravanan et al., 2013; Steiniger & Weibel, 2009). For example, Jensen et al. (2012) presented a mobile GIS to enable law enforcement officers to report crime on location and incident details in real-time with built-in sensors in mobile devices to capture location and other contextual information together with rich media in the forms of pictures, audio and videos (Jensen et al., 2012). The increase in use of mobile phones as a means of communication among the people and also among those involved in committing a crime, makes it possible to trace crimes by analyzing the mobile digital footprints, which are the individual's call detail records and spatiotemporal aspects of the cell tower details. Saravanan et al. (2013) proposed a rapid response system which can identify the most probable local suspects involved in a crime case, by analyzing the relevant case histories (Saravanan et al., 2013). Next, the current location of the probable suspects is then tracked and visualized by using mobile GIS.

In addition to enhance the effectiveness and efficiency of law enforcement officers, mobile GIS for crime solutions has also been used to improve the safety of the public by enabling the report (Manazir & Rubina, 2019) and access of crime information (Khemprasit & Esichaikul, 2011), and helping schedule a safe and convenient travel plan (Shah et al., 2011). CROWDSAFE, a mobile GIS application, was developed to integrate Internet crowdsourcing and mobile devices to support real time, location based crime incident searching and reporting (Shah et al., 2011). It allows the users to report crime information, and then leverages such crowdsourced data to provide novel features such as a Safety Router and crime analytics. Similarly, My Safetipin, a mobile e-participation platform, was created for women in India to identify and report locations unsafe for them (Manazir & Rubina, 2019).

6.6 Navigation and Tourism

Equipped with GPS, mobile GIS makes us easy to navigate from one location to another quickly. Chen et al. (1999) introduced a 3D mobile GIS with an AR interface by integrating camera, GPS, inertial navigation system, magnetometer, gyroscope and image navigation technology (T. Chen & Shibasaki, 1999). The system potentially can support personal navigation, disaster investigation, update of a spatial database, daily inspection of infrastructures, etc. In addition, mobile GIS can significantly promote tourism, enhance cultural and historical heritage, and improve tourist experiences. For example, mGuiding as an android based mobile GIS integrates tracking and location functions using GPS coordinates, multi-media guiding (e.g., descriptions of scenic spots, videos, photographs and audio presentations), suggested tour selection and searching, to guide tourists (Chu et al., 2012). Bartie et al. (2018) introduced a virtual tour guide system that could respond to questions through a spoken dialogue user interface and notify the user of interesting features in view while navigating the tourist to various locations. AR technologies are widely incorporated in the mobile GIS to enhance navigation (Cron et al., 2019) and tour services (Lo & Chang, 2019). For example, Lo and Chang (2019) developed a mobile app that installed on the AR glass to provide directive location-based landscape tour service that provides the audio guide service for a location, and helps users to understand what they see without searching.

6.7 Survey and Inventory

The advantages of mobile GIS are increasingly being acknowledged and used in the survey, audit, inventory and mapping of landscaping (Tian & Tong, 2007), built-in environment (Lafontaine et al., 2017), water supply networks (Aloys, Delphine, Moha & Joseph, 2019), public services (e.g., health facilities, and education institutes; Kurniadi, Mulyani, Septiana & Akbar, 2019) and physical infrastructures, such as road (EL-Sheimy & Schwarz, 1998; Teo, 2018), buildings (Sawada et al., 2014), archaeological sites (Tripcevich, 2004), coal mine (Wang et al., 2011), land use and change (Fu, Wang, & Li, 2005), entertainment sites (de Abreu Freire & Painho, 2014), to name a few.

VISAT (Video, Inertial, and SATellite GPS) is a mobile survey system for road inventory and general GIS applications. Equipped with a set of digital video cameras, an inertial navigation system, and GPS satellite receivers, the system includes a data collection component, and a measuring and processing component (EL-Sheimy & Schwarz, 1998). Lafontaine et al. (2017) presented and evaluated a novel built-in environment audit method that combines VEs for auditor training and mobile GIS technology for real-time data collection at randomly audited locations and efficiently assessing neighborhood aesthetics over large urban areas. Further, Teo (2018) introduced a mobile LiDAR system for road inventory. Within this system, a data preprocessing component is used to improve the accuracy of trajectory using co-registration and 3D similarity transformation, and a feature extraction component to select road point, and extract road mark. Similarly, Want et al. (2011) developed a mobile GIS system which employed state-of-the-art technologies including GIS, GPS, wireless networks and a smart phone for pipeline inspections of coal bed methane (CBM) field. m-SportGIS is currently being exploited by Mozambican government staff to inventory all kind of sport facilities, which feeds a WebGIS platform to manage Mozambican sport resources (de Abreu Freire & Painho, 2014).

6.8 Smart Cities

Smart cities are designed to build up spatial data infrastructure, and use data to optimize resources, maintain sustainability, enhance service delivery, increase management efficiency, and improve people's quality of life (Loo & Tang, 2019). At present, public agencies in many countries have launched a variety of smart city initiatives to establish e-governance (Wang, Zhang & Zhong, 2019). Mobile devices, along with GIS, GPS, digital media, and computing technologies, enable smart data collection and immediate transformation to smart information and knowledge. To promote smart and evidence-based decision making, Mokoena & Musakwa (2018) develop a mobile GIS system to conduct an occupancy audit for Ulana, an informal settlement in Ekurhuleni Municipality in South Africa, with tablets collecting the geographic and socio-economic attributes of the informal dwelling units, and spatial analysis producing the occupancy audit. As a 3D city model allows urban planners and the public for a better understanding of city environment and planning in the urban design-context. Yang (2019) developed a mobile mapping systems that enables the modeling of 3D buildings and urban environments using both aerial images and ground-based sensing techniques.

7. Mobile GIS Challenges

The success of a mobile GIS mostly depends on three factors: spatial functions, user interface design, and system performance (Charland & Leroux, 2011; de Abreu Freire & Painho, 2014; Roth, 2017). While web GISs have been widely implemented to integrate geospatial resources and deliver powerful information analysis for end users through geovisualization or animation with interactive, web-based spatial web portals (P. Yang et al., 2007), mobile portals are rarely available. This has resulted from the constraints of mobile devices, including screen size, computing power, and battery, to support geospatial processing, mapping, visualization, and analysis that often are computing intensive to perform on a mobile system, and require a moderate screen size to be visually effective (Gao & Mai, 2018; Kumar & Lu, 2010). Besides, these mobile devices vary widely in terms of the manufacturers, hardware, OS, and technologies. Therefore, it is challenging for mobile GIS taking such diversity into consideration to develop UIs and spatial functions compatible and running in various mobile terminals. Additionally, limited geospatial tools, libraries, and methodologies also hinder the utilization of mobile technology in geospatial fields.

To achieve better performance, a mobile GIS can more extensively leverage offline and distributed storage and computing capabilities, animations on the UI, and backend services that retrieve and send data through web services and web servers (Charland & Leroux, 2011). In addition, high performance computing based rendering methods are critical to enhance the mapping and visualization of spatial data (Li et al., 2019). This is especially paramount for high-dimensional datasets, such as oblique photogrammetry, building information model (BIM), and laser point cloud.

As cloud computing can enhance the computing capability of mobile systems by offloading computation into the clouds, Mobile cloud computing has emerged as a new computing model to support various applications, such as mobile commerce, mobile learning, mobile healthcare, and mobile gaming (Dinh et al., 2013; Qi & Gani, 2012). In addition, mobile edge computing is expected to provide a foundation for new mobile applications and services by making cloud computing closer to users (Syamkumar et al., 2018). Similarly, a new IT paradigm in which cloud computing and Internet of Things (IoT), a concept that envisions all objects around us as part of Internet, are two complementary technologies that together will dramatically change both current and future Internet (Botta et al., 2014; Rao et al., 2012), and therefore shape how mobile GIS can be used in real-world applications. However, existing work on cloud computing for GIScience is primarily focused on developing a web-based framework and architecture to enable spatial data analysis, computing, and dissemination (Huang, Cervone, & Zhang, 2017; C. Yang et al., 2017). Therefore, an urgent need exists to explore the challenges, solutions, lessons, and the role of cloud computing, edge computing, and IoT for spatial data analysis, mining and visualization of GIScience through mobile devices.

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