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Real-time collaborative GIS: A technological review

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ABSTRACT

Collaborative Geographic Information Systems (CGIS) have become an important research area over the past two decades. This paper provides a critical review of the development of real-time CGIS, which is a branch under Collaborative GIS study. A real-time CGIS system provides a multi-user, real-time collaborative work environment, i.e., what you see is what I see (WYSIWIS), for spatial decision support and problem solving. The research about this kind of system has mainly focused on system architecture and modelling, collaborative awareness, concurrent control, collaborative behaviour modelling and other related key issues. The paper presents a two-stage historic development process of real-time CGIS, summarizes major research progress and representative developments by analysing their key technical issues, and based on the review discusses some research problems that need to be solved and some future research directions.

1. Introduction

Spatial decision making has increasingly become a multidisciplinary process, involving people with different types of expertise and in many cases from different locations. Since 1992, a growing body of research has emerged in the use of geographic information systems (GIS) to support such group collaboration and to even encourage and promote more informed citizen involvement in various decision-making activities (Obermeyer, 1998). Among these efforts, an important area is on the design and development of collaborative GIS systems that support group-based sharing, exploration and interaction of geographical information for spatial planning and decision problems. Such collaborating systems, often termed as collaborative spatial decision-making systems, allow a group of people to work together with geospatial data over the Internet or corporate local area network (LAN)/wide area network (WAN), extranet.

GIS, as a system designed to capture, store, manipulate, analyse, manage, and present all types of geo-referenced data, has been widely used as a spatial decision support tool. However, the single-user interaction mode of traditional GIS limits the complexity of solvable spatial problems and the efficiency of problem solving. In reality, many spatial problems and decision-making tasks that involve geographic information require multiple users to work in collaboration to process and analyse geographic data. In the process of decision making and spatial problem solving, there is a trend of integrating real-time and collaboration, which has already become one of the crucial areas of research and development in GIS theory and applications (Armstrong, 1993; Balram and Dragićević, 2006). Terms such as "*collaborative spatial decision-making*" (NCGIA, 1996), "*geographic collaboration*" or *GeoCollaboration* in short (MacEachren and Brewer, 2004; Balram and Dragićević, 2008) and "*collaborative GIS*" (Balram and Dragićević, 2008; Chang and Li, 2013; Butt and Li, 2012), have emerged to represent this field of study.

On the other hand, computer-supported cooperative work (CSCW), as a research field studying the design, adoption and use of groupware technology, has long focused on understanding computer-mediated communication and collaboration using groupware which provides a set of software tools and technologies that facilitate group interaction (Coleman and Kbanna, 1995). Typical "non-spatial" groupware allows collaborators to work in a computer-supported virtual environment in either synchronous or asynchronous mode, depending on the arrangement of time and place of the use. For example, document-conferencing programs may offer support to synchronous collaboration in four different ways: whiteboarding, applications and data sharing, file transfer, and real-time text messaging (i.e., real-time chatting). To mimic traditional meetings, these document-conferencing programs are often integrated with an audio/video conferencing system.

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1.1. Defining collaborative GIS

Collaborative GIS (CGIS), not a well-defined and widely-accepted term, has historic links to CSCW-based groupware and spatial decision support systems. Built on CSCW concepts, a collaborative GIS system may possess a set of basic tools that permit: (1) shared view, control and object selection of geographical information; (2) annotation and mark-up of geographic (map) features with multimedia data in the form of text, graphics, photos, and audio/video clips; (3) interactive exploration of geographical data for spatial problems; and (4) awareness of other collaborators and their outcomes. Since the nature of collaborative GIS is to support group work, seamless integration of communication (e.g., email, real-time chatting, discussion forum and conferencing), and process coordination (e.g., workflow) tools will greatly improve collaboration processes. Depending on the application context, the system may also provide other tools. For example, in the context of spatial decision support, both decision-making (e.g., multi-criteria evaluation) and negotiation tools are deemed necessary. All these tools require efficient data access, integration and management as well as good mechanisms to handle outcomes from collaboration. While some of these tools are more generic to any collaborative GIS applications, some may be specific to a particular application. One of the efforts has therefore been on identifying which tools can be generalized and which tools are more application-specific. In the end, these tools may be developed gradually and categorized based on different GIS use cases to create a tool repository. This would need proper software specification frameworks, e.g., Open Geospatial Consortium (OGC) specifications, to deal with platform compatibility issues and interfaces.

CGIS tools, similar to general groupware, may be classified into four categories based on their time synchronization and users' locations (see Fig. 1): *same time – same location*, *same time – different location*, *different time – same location*, and *different time – different location*. While most CGIS falls into one or two of these categories, this paper focuses on "same time – different locations" tools, i.e., Real-time Collaborative Geographic Information System (RCGIS).

1.2. Real-time collaborative GIS

Early efforts focused on combining GIS with CSCW hardware systems and software (groupware), or at least applying CSCW concepts in developing collaborative GIS systems (see examples from Churcher and Churcher, 1999; Faber et al., 1997; Jankowski et al., 1997; Jones et al., 1997; MacEachren et al., 2001). These developments used either an existing commercial GIS system or in-house developed GIS viewer, and integrated it with a groupware system such as electronic meeting systems (EMS).

Distinctive from other CGIS systems, RCGIS seeks real-time, synchronized natural and harmonious interactions that are concurrent, responsive and flexible (Kanzawa et al., 2008; Luo et al., 2004; Shao et al., 2010). RCGIS focuses on providing an object-oriented, multi-user collaborative work environment, i.e., what you see is what I see (WYSIWIS), to achieve interaction and collaboration between stakeholders and professionals. It has applications in disaster and emergency response, e-government, resources management, data production, and collaborative mapping and spatial modelling (Cai, 2005; Cheng et al., 2012; Lu, 2004; Quinterot et al., 2005; Sun et al., 2009). RCGIS possesses features common to general real-time systems, and the ability for users from different domains to collaborate on solving spatial problems and making spatial decisions simultaneously from different locations. It provides decision-makers with a virtual interaction space to overcome space and time limitations. RCGIS shares not only geospatial data, but also users' visual images and even their operating behaviours; it is therefore much more complicated to implement than asynchronous collaboration systems. RCGIS often involves supporting intensive discussions within a small group.

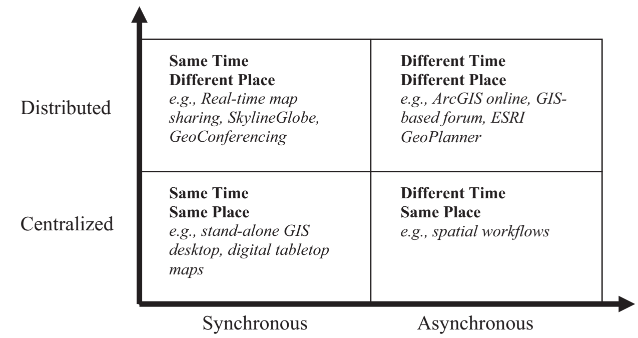

Fig. 1. Groupware classification based on time and place dimensions (Armstrong, 1993).

RCGIS has increasingly drawn attention of researchers in computer science, geographic information science, and urban planning, among other related fields. On one hand, we have seen increasing research and commercial interests in developing tools and applications that provide real-time collaborative methods for working with geospatial data. On the other hand, insufficient understanding of theories, designs and insights on related social issues pose challenges for researchers and developers to generate solid outcomes. This paper presents a review of the development of real-time collaborative GIS, aiming at not only mobilizing the study in this subject field but also providing an overview of historical background as well as state-of-the-art of the field. It begins with a brief history of RCGIS in Section 2, followed by detailed review of research on RCGIS in Section 3 and applications in Section 4. Section 5 discusses some open issues and proposes future works. Section 6 concludes the paper.

2. A history of RCGIS development

The development of RCGIS has gone through stages starting from conceptualisation through development of tools and systems to exploration of different applications. From a research point of view and for the purpose of this review, we break down the whole development process into two overlapping phases: (1) conceptualisation and proof of concepts; and (2) theoretical frameworks and research methodology.

2.1. Conceptualisation and early experiments

The basic CGIS concepts may have their root in the National Centre for Geographic Information and Analysis (NCGIA) Initiative 17 on collaborative spatial decision-making (NCGIA, 1996). The purpose of the initiative was to extend conceptual frameworks for spatial decision support systems (SDSS) to support groups of decision-makers in order to generate solutions, with a specific emphasis on integrating SDSS with CSCW environments. The initiative envisioned that this kind of integrated environment should provide group users with a set of generic tools to complete decision-making tasks. In the following 10 years, the development of RCGIS mainly focused on formulating concepts, research prototyping for proof of concepts, and exploration of simple GIS/CSCW integration. Work done by some early pioneer researchers, such as Marc P. Armstrong, Neville Churcher, Clare Churcher and Alan M. MacEachren, among others, has been widely refereed by others.

Marc P. Armstrong, University of Iowa, was one of the earlier researchers involved in the research of RCGIS. Building on the inability of GIS in supporting group work, he suggested the integration of group work with GIS for spatial decision support, developed the WYSIWIS image-sharing application mode (Armstrong, 1993), discussed "shared graphics" or maps that analogue to a traditional whiteboard in a group environment (Armstrong, 1994), and addressed issues about potential misuse of RCGIS tools (Armstrong and Densham, 1995). These concepts contributed to the early development of RCGIS.

Churcher and Churcher (1996, 1999) and Churcher et al. (1997) developed GroupARC, a collaborative GIS browser that enabled participants to simultaneously browse and annotate maps. Developed using the GroupKit toolkit, the application supported group awareness by using colours, multi-user scrollbars and telepointers, provided simple attribute-based query functions, and allowed participants to work on multiple map layers. The system, however, required the installation of GroupKit on each participant's computer, which did not make it easy to deploy and maintain. More GIS functions other than simply browsing and annotating maps were provided by a stand-alone commercial GIS system, installed at least on one of the participants' computer. GroupARC was a preliminary attempt of integrating GIS with an earlier electronic meeting system (EMS), and led to discussions on *collaborative awareness* using *fisheye views* to assist in visual information overloading management (Churcher et al., 1997). In Churcher and Churcher (1999), two design scenarios were proposed for the integration of GIS and CSCW systems. The first one involves expansion of single-user GIS systems by incorporating groupware functions. The second one keeps GIS and groupware functions in separate systems but provides data conversion between them and relies on groupware to take care of intergroup communication and presentation.

MacEachren (2001) coined the term "geographic collaboration". Since then, the work done by his group has mainly focused on collaborative geo-visualization based on multimodal interfaces (MacEachren et al., 2005), e.g., for data exploration and decision-making (MacEachren et al., 2003), knowledge construction (MacEachren et al., 2001) and emergency response. Most of these studies are related to human aspects of geocollaboration, e.g., human-GIS interaction under "same time and same place" and "same time and different place" dimensions (see Fig. 1), using for examples tabletop large screens and specially-design desktop software (e.g., DAVE_G – a natural, Multi-modal interface) (MacEachren et al., 2005).

2.2. Theoretical frameworks and research methodology

Since the beginning of the 21st Century, several theoretical frameworks have been proposed and many have been working on establishing research methodologies, with a focus on experimenting with some key technologies required to develop real-time collaborative GIS with a certain level of synchronisation. As more researchers became involved, the scope of research has been expanded, and studies have been moved towards more in-depth, detailed investigations on integrating a variety of different technologies to enhance real-time collaborative GIS capabilities.

On the collaboration framework and model side, an early effort was a decision task model developed by Nyerges et al. (1997). The model summarizes the need for information technology support for transportation site selection and is still useful in handling decision-making aspects in RCGIS environment. MacEachren and Brewer (2004) developed a conceptual framework for visually-enabled geocollaboration. The framework included six important aspects for the evaluation and development of a collaborative system. Three of them involve interaction between users and collaborative environment, including problem context, collaborative tasks, and commonality of perspective. The remaining three aspects focus on collaborative system support, including spatial–temporal context, interaction, and tools for mediating group work. Antunes et al. (2009) developed a model for designing geo-collaborative artefacts and applications, which consists of spaces (virtual, physical, social and awareness) and places (artefacts, teams and tasks). Recently, Chang and Li (2013) proposed a geo-social model that is a conceptual framework for real-time geocollaboration emphasising geospatial, social and technological aspects. While there have been a number of other studies on collaboration frameworks, all these developments basically examine CSCW and related taxonomies and relationships between key concepts described by taxonomies in the context of geographically-based collaborations.

On the research methodology side, Convertino et al. (2005) explored a multi-view method to strengthen expressivity of real-time collaborative GIS. For real-time collaborative spatial planning, they developed a synchronous visualization prototype system based on real-time collaborative behaviours. The system supports role-based and shared visualizations, in which user operations can be transferred to each other (see Section 3.3.2 for details), to help experts reach consensus. Schafer and Bowman (2006) conducted an in-depth and detailed study on collaboration awareness between users. Based on 2D maps, they compared and analysed methods such as continuous navigation, discrete navigation, traditional radar view and fish-eye radar view, to find collaborative awareness methods most suitable to users. Chang and Li (2008, 2009, 2012) carried out studies on methodologies for developing 3D real-time collaborative GIS, e.g., they explored the use of multi-agent technology to create a shared 3D environment to support group collaboration. Wu et al. (2009) suggested that geographic collaboration should involve not only shared data but also shared GIS processes, and utilized Google Maps to prototype a web-based geospatial collaborative visualization system. The system provides public–private maps, and has functions of grouping, inspecting and analysing data entered into the system.

Other distinctive studies include an application developed by Lee et al. (2006). The development studied the use of hybrid P2P structure to support small group discussions. The application was created for the purpose of collaborative work in spatial data analysis and determination of spatial relationships between geographic phenomena. Marion and Jomier (2012) tried new techniques, WebGL and WebSocket, in developing a 3D real-time collaborative visualization and performed assessment in terms of average latency, synchronization rate (per second), master rendering rate (per second). Delipetrev et al. (2014) studied open source software and Web GIS technology to develop a water conservatory system. It provides a work environment that supports multiple-user interaction, and allows users from different locations to discuss water conservatory issues simply using a web browser at the same time in a shared group workspace.

From the above review, real-time collaborative GIS has evolved from loosely-coupled groupware and GIS in earlier days to more tightly-integrated collaborative spatial decision support systems, real-time GIS data production, and GIS-enabled teleconference, and from two-dimensional to three-dimensional synchronization. New technologies such as P2P, multi-agent, open source, web service, and web socket have been constantly tested and adopted in its development. Over the last two decades, we have also seen progress in theoretical development, e.g., conceptual frameworks and models, as well as increasing consideration of social and organizational issues in collaborative GIS design and development. Finally, it becomes clear that the system development has shifted from early simple integration of CSCW and GIS to more fine-grained, code-level integration, accompanied by more in-depth study on key technical problems such as collaborative awareness, concurrent control, and collaboration modelling.

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3. Main research and development work

A RCGIS system allows users (e.g., experts, stakeholders, decision makers, interested citizens, etc.) from different professional domains to simultaneously work together from different locations. It provides users with a shared, distributed, cooperative workspace. Over the past two decades, research work in this area has mainly focused on system development and integration, architecture design, concurrent control mechanisms, and collaborative awareness in shared environments.

3.1. System development and integration

A careful literature review indicates that current RCGIS system development mainly follows two methods. The first method is to integrate the traditional single-user GIS system with some groupware systems – CSCW implementations. There have been three different approaches of integrating GIS and CSCW: (1) extending GIS interfaces with CSCW functions; (2) building GIS functions in groupware systems; and (3) enabling communications between GIS and CSCW tools in a separate system via a common set of protocols, interfaces and data formats, which realises loosely-coupled integration. The first two approaches require all users to have a local installation of either GIS or groupware system, which is not a cost-effective or easy-to-maintain approach. Further, users need to learn how to use these systems, mostly with their own complicated interfaces on top of collaborative GIS components.

Representative systems that used this first method to achieve real-time collaboration include GroupARC (Churcher and Churcher, 1996), Habanero (Chabert et al., 1998), and Toucan Navigate (Shon, 2004). Other examples are real-time GIS work environments developed for solving specific practical application problems. Medeiros et al. (2001) developed a collaborative GIS system for environment preservation and changes by integrating GIS technology, workflow technology and multi-media conferencing system. Lu (2004) developed a collaborative environment for emergency medical rescue by combining Web GIS, CSCW and multi-media technologies.

The second method is, based on characteristics of spatial data, to decompose and analyse GIS operations and explore how messages can be expressed and transmitted to establish a RCGIS system using messaging technologies. Other group collaboration functions such as instant messenger and audio/video communication can then be added into the established system. A potential benefit of this method is independence, i.e., RCGIS systems developed can be independent of any existing groupware and GIS systems by taking advantage of the state-of-the-art technology of both CSCW and GIS through their software development kits (SDK) or components.

Not much development work has been done based on this method so far. Sun et al. (2010) used ArcEngine 9.3, C# Language and MSMQ (Microsoft message queue) information, and developed a real-time collaborative GIS system prototype to support collaborative work with functions of spatial query and buffering zone analysis. Chang and Li (2013) utilized information messaging mechanism, and designed and developed an Internet-based three-dimensional collaborative GIS system. This system provides simple GIS functions that allow for collaborative browsing, magnifying and scaling. Considering characteristics of geographic information services, Cheng et al. (2012) proposed a GIS collaboration method based on message queue, and developed a prototype for multi-user GIS collaboration and collaborative map annotation based on some techniques such as OpenLayers and ExtJS framework.

Comparing these two methods for real-time collaborative GIS system development, the first method allows easy and fast development of RCGIS systems; however, the integrated systems tend to be inflexible, often with limited collaboration functionality due to the constraints imposed by both independent integrating systems. Further, the systems developed based on this method do not support, for example, GIS/map feature level collaboration. With the second method, collaboration may be realised at GIS operation or feature level, e.g., real-time synchronization of operations and feature-level changes. Although it is much more difficult to develop systems based on the second method, the effort can be balanced by gaining more flexibility and easy integration of more powerful collaboration functions.

3.2. Architecture design

From a distributed computing perspective, most RCGIS systems in earlier days adopted a client–server (C/S) architecture, which was progressively developed into browser–server (B/S) architecture. Depending on its configuration, C/S architecture allows optimal utilization of client-side and server-side computing resources to share data, support user interaction through an interface, and balance data control, network bandwidth usage and computation requirements. With the rise of the Internet, two problems have emerged with C/S architecture. One problem concerns performance and reliability due to various communication issues. This is especially important to real-time collaborative systems. The second problem is related to client-side software installation and maintenance (e.g., plug-ins) due to the widely distribution nature and diversity of users on client side (Zheng, 2013). B/S architecture is an upgraded version of C/S architecture for the Web. Under this architecture, user interface is implemented completely through web browsers. Some business logics can be implanted on client (browser) side, while the main ones are realised on the server side. Application systems based on B/S architecture enjoy "zero maintenance", thus can further lower the cost for maintenance and execution of the system.

Both architectures have been used in developing RCGIS systems. Manoharan et al. (2002) designed and developed a C/S based prototype system for supporting collaborative urban planning. This system supports shared visual analysis of geospatial data and user interaction. Other C/S-based developments include Kanzawa et al. (2008), Sun et al. (2010) and so on. Tan and Sun (2010) used FME (Feature Manipulation Engine) technology based on B/S architecture to develop a synchronous GIS display system. RCGIS systems based on B/S architecture were also reported in Butt and Li (2012) and Chang and Li (2008).

From the way the data and collaborative application are shared, RCGIS architecture design can be built on the understanding of the concepts of the following system architectures:

Centralised architecture: depends on one central process to serialize (strictly order) all events. Serialization plays an important role in making sure that actions performed by multiple participants in a session are in a single consistent order, so that they share consistent views. Both data and collaborative applications are deployed on the server, and the server handles all collaborators' requests. The collaborator side provides only user interface to collaborative applications.

Peer-to-peer architecture: is a novel approach in the architecture and system design of collaborative GIS applications by sharing client's computer resources (Krek and Bortenschlager, 2006), and allows anyone to establish a collaboration session using a certain port number and invite other participants to join the session. All participants share the same view, for instance, a map display model and have control of that view. The session manager who sets up the session has the super right to exclude other's right of controlling the view.

Replicated architecture: supports distributed applications that have identical copies of software running on each participant's computer with the same views of the application. The shared data may also be replicated. The replicated application is responsible for handling local user operation events, sending operations to other replicas through, for example, messaging mechanisms, and receiving operations from other replicas and presenting them to the user.

Hybrid architecture: the main problem with centralized and replicated architecture is that they view the application as a whole, meaning that no component-division is provided and no attention is given to different aspects such as specific group-oriented services and GUI-specific services (Roth and Unger, 2000). Since applications are often decomposed into many components, this architecture allows some components to be shared while others to be replicated according to functionalities. Hybrid architecture does not represent a "pure" new category, but represent the combination of the centralized and replicated architecture. It helps solve "server bottleneck" problems of the centralised architecture and potential implementation issues of the replicated architecture (Xu, 2005).

We have also seen developments based on all of the above architectures. For example, Zhou et al. (2005) developed a distributed collaborative cartography system based on GIS using a replicated architecture to reduce network load, provide rapid response and enhance stability of the system. MacEachren (2001) used the same architecture in developing a long-distance synchronized analysis system to effectively lower network data usage. Chang and Li (2008) developed a 3D synchronous collaborative GIS system using a hybrid architecture to deal with shared components (e.g., large images and databases) and components that can be easily replicated. The hybrid architecture was also adopted by Wu (2008) to develop a system for collaborative editing of geographic features. To satisfy real-time requirements, both data in editing and applications are replicated to each collaborator's computer, so collaborators can use a local program to edit data, and pack the GIS operations into messages that are then passed on to other collaborators. The centralised architecture was used for collaboration control, role and privilege management, collaboration message database, and concurrent GIS operation conflict rules for overall coordination and management.

3.3. Key design issues

Due to the nature of supporting real-time and group collaboration, RCGIS system design often requires special consideration of issues such as concurrent control and group awareness, which are further discussed in the following sections.

3.3.1. Concurrent control

Concurrent control is one of the main problems of the cooperation mechanisms required by any CSCW systems. It is widely used in general multi-user systems and real-time groupware systems (Ellis and Gibbs, 1989). In real-time collaborative GIS, all participants can perform GIS operations on shared spatial data and the coordination of this kind of group activity is essential for resolving inevitable conflicts. Concurrent control aims to solve such conflicts. Similar to other CSCW systems, RCGIS requires concurrent control to: (1) support and allow for multi-users to freely interact; and (2) be able to detect and resolve any concurrent conflicts. A few concurrent control approaches (e.g., lock, token, transaction, etc.) have been used in RCGIS developments. The choice depends on consideration of its potential effect on collaborative work and user interface design, in addition to application specific requirements.

Lock Mechanism: provides concurrent control by locking and unlocking shared objects. The benefits of a lock mechanism are its simple design and implementation; however, there are also some problems when applied in real-time collaboration systems (Ellis and Gibbs, 1989). First, the requests for a lock and unlock can affect the speed of user feedback, and it is difficult for the system to determine when to lock and unlock and for the user to get control. Second, it is hard to determine the granularity of the locked data. Granularity that is too small can add burden to the system, but too large can affect concurrency of user's operations. Third, at the operation level, it is even difficult to decide who gets the right to operate the shared environment and to move the cursor, for example. Thus, in order for effective use of lock mechanism, it is important to determine when to add the lock mechanism and how to use it in the collaborative environment (Xu, 2005).

Experiments have been done on utilising this mechanism. Ross (2010) in developing a real-time collaborative spatial query environment used a fine-grain lock mechanism, which controls concurrent user operations by locking required interactive interface elements. Guo et al. (2006) used object lock and multi-level lock methods to solve concurrent control on data in a synchronized spatial data editing platform to maintain consistency of spatial data. In a similar collaborative data editing system, Li et al. (2005) used object lock to control the visibility and operability of different granularity objects, in order to avoid conflicts in collaborative editing from occurring when multiple users concurrently access it. Zhan et al. (2005) proposed a real-time shared lock mechanism to account for both concurrency and synchronization in collaborative GIS applications. The main idea was to allow conflicts to certain extent and solve them, based on certain level of collaborative awareness.

Floor Control: sometimes called "token" or "single active participant" method, this method controls who has the right to operate. The person who gets the floor or token has the right to operate on and manipulate the collaborative environment. As such, floor control can be seen as a lock at a coarse-grain level. The process of floor control includes requesting, assigning and releasing the floor. Schafer et al. (2007) designed floor control based on social conventions for more smooth interactions in a group for emergency contingency planning. Chang and Li (2004, 2008) used floor control mechanism to maintain consistency between collaborators of a 3D synchronous collaborative GIS system, and pointed out the need for floor search and floor control mechanism for coordinating user concurrency. In developing a multi-user synchronous/asynchronous collaborative 3D GIS, Hu et al. (2013) used "leader-and-follower" method as the mechanism to control concurrency. In any collaboration session, only one leader has the highest control and operation power. Followers can interact with other followers but have no control power. The leader role can be changed through sending a request.

Floor control allows only one active user and does not support concurrent control. Thus, it is not suitable for many real-time collaborative environments, because the essence of collaboration is to support multi-user concurrent activities. Although lock and floor control are two mostly used mechanisms in concurrency control in the development of real-time collaborative GIS systems, they are actually very inflexible control methods. Real-time collaborative work requires local and remote users to be able to quickly see operation results to prevent delay in interaction. Although these two mechanisms are easily implemented, they have relatively poor interactive responsiveness, and violate the free and non-restrictive characteristics of real-time collaboration. Because real-time collaboration systems support human–human interactions, in comparison to other distributed systems user-centred design should be considered when dealing with concurrent control, in addition the effect of the selected control mechanism on collaborative work and user interfaces.

In addition to the above commonly-used techniques, other techniques such as operation transformation (Ellis and Gibbs,

1989) have also been proposed and tested. For example, Hu (2004) tested the operation transformation technique in developing a general collaborative GIS and found that the original algorithm was not suitable to geographic data because it was designed for collaboration on simple data structure such as text.

3.3.2. Group collaborative awareness

Synchronized collaborative work often needs a shared environment, where users can share the same visual images and become aware of other users' information including name, role, location, voice, image, and even their behaviours and activities. In other words, synchronized collaborative work needs to have a "WYSIWIS" work environment. In this environment, users can work on individual views while simultaneously observing the activity and work of others, and also work together to complete group tasks using collaborative tools. Group awareness is an important feature to ensure the users are fully informed in a collaboration session. For general real-time collaboration systems, tools such as user list, instant messenger, voice messenger and electronic whiteboard have been used for group awareness. In addition, some special tools or techniques have been developed for RCGIS, including telepointer, radar view, and multiple views, which are described and analysed below.

Telepointer can record the user's location on the shared map, focus and operation trajectory (Convertino et al., 2005; Schafer et al., 2007). It is an extremely effective collaborative awareness tool. During a collaboration session, many pointers can be seen simultaneously on the local map interface. One pointer ("current pointer") is controlled by the local user, and the other pointers ("remote pointer") are controlled by other users. The user names are often labelled under these pointers, which may be further distinguished by different colours and shapes of mouse pointer. Fig. 2 shows an example use of telepointer – the grey and blue pointers that belong to two different users. For guest 1's view (left), the grey one is his/her pointer and the blue one marked as "guest 9" is his/her collaborator's pointer. For examples, Wu et al. (2009) used telepointer to identify other user's information in a web-based collaborative map-based decision support system. Convertino et al. (2007) used telepointer and role colouration to differentiate different user's operation information to achieve knowledge sharing between users in geographic collaboration planning.

Radar view is a class of widgets based on miniature overviews of a whole workspace for awareness (Gutwin et al., 1996). In RCGIS, it provides an overview of the shared map space. Radar view can be used to display the mouse location and the map visual extent (view outline) of other users. As illustrated in Fig. 3, the right is the map-based, shared workspace and the left is the overview. In the

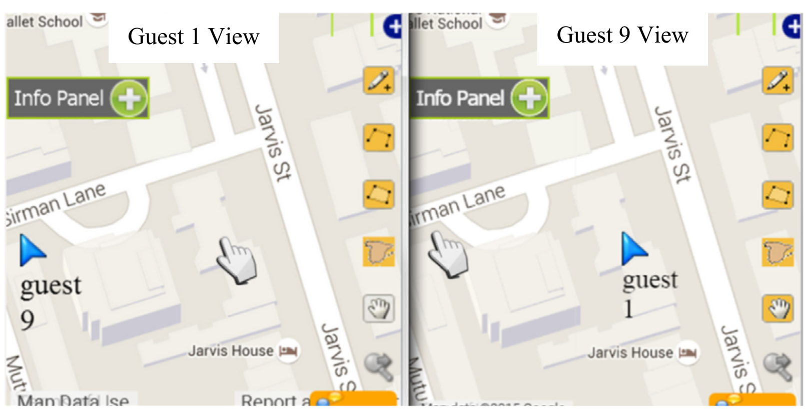

Fig. 2. Use of telepointers for collaborative awareness.

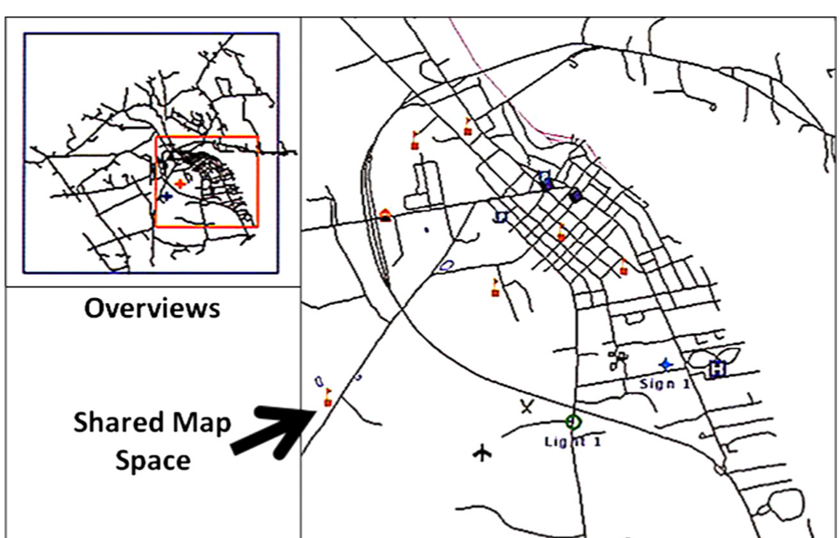

Fig. 3. Radar view shows collaborator's map view and current cursor location (modified from Schafer et al. (2005)) to better show how radar view works).

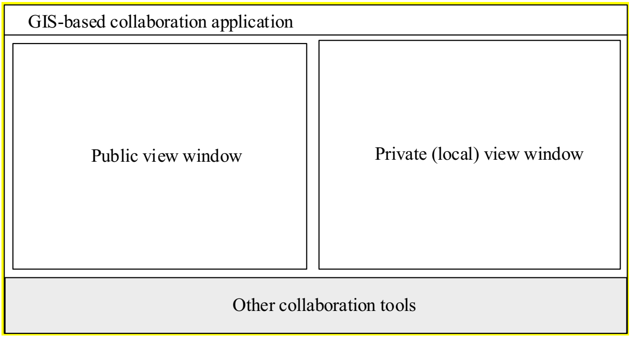

Fig. 4. Multiple views for collaborative awareness.

overview, each transparent rectangle with a different colour represents the current mouse location and map visual extent of a user. For example, the blue rectangle means that the user is currently viewing the full map, and the blue cross is this user's current mouse location. At the same time, the red rectangle represents the current map visual extent of another user, and the red cross shows that user's current mouse location. Schafer et al. (2005) further studied traditional radar view image and fisheye radar image as tools for collaborative awareness. Depending on the content displayed in the shared workspace, other types of radar views were also explored, e.g., structure radar (Gutwin et al., 1996).

Multiple views technique uses multiple view windows to handle awareness in a collaborative workspace. Typically, two view windows as shown in Fig. 4 are used, one for public view and the other one for private view. Every collaborator has a public view and a private view. The public view provides a shared space where synchronised operations are performed and displayed to support group discussions. The private view on the other hand provides a private workspace where the user can operate and display individual (private) work. A mechanism is necessary to be able to transfer and/or switch between public and private views (Convertino et al., 2005; Wu et al., 2009). For example in RCGIS, every user can transfer operations performed on their private map onto the public map, and also take operations on the public map done by other users and perform them on the local private map. Multiple views technique may be combined with telepointer to gain better collaborative awareness results, which will make implementation more difficult.

Telepointer, radar view, and multiple views can all be used to support group awareness in real-time collaborative GIS. Each technique has its advantages and disadvantages. Telepointer can reflect collaborators' location, activity trajectory and work process. However, when there are many collaborators the shared view may be messy, especially when the collaborators' map views are far away from each other, not all pointers may be shown. Radar view can identify collaborators' view range and current location, but when their map scale differs greatly, the collaborators with large map scale may have blurry view range and view point. The main benefit of using multiple views technique is to separate public view and private view, which gives collaborators a private space to work while maintaining his/her awareness of group work. A potential issue is that some of the private views may not show on the public view, when the scale and view range differs greatly between collaborators.

In general, telepointer, radar view, and multiple views techniques all can be implemented with fair effort. They can be further combined to provide better collaborative awareness, towards a rich "WYSIWIS" shared work environment.

4. RCGIS applications

Real-time collaborative GIS have been developed and used to support applications in many areas, with emergency response and disaster management as the mostly-studied area. Examples include school closure due to severe weather conditions using big board for shared situational awareness (Heard et al., 2014), civil public security (Siegel et al., 2008), community emergency planning (Schafer et al., 2007), RCGIS for radiological disaster management (Quinterot et al., 2005) and collaborative sense-making in emergency management (Wu et al., 2013). Another area that has drawn much attention is planning and management of natural and built environments. Stock et al. (2008) developed an immersive online environment for 3D landscape environment for exploring and decision-making purposes. Medeiros et al. (2001) developed a decision support cooperative system for environment design. Faber et al. (1997) developed an active response GIS for interactive resources modelling. Other areas include public participation, e-government, spatial data editing and production, and tourism. For example, Hu et al. (2013) used RCGIS, and Butt and Li (2012) used real-time map sharing for supporting public participation. Sun et al. (2009) built a collaborative GIS that supports electronic government workflows.

Although effort has been made to study RCGIS applications and there may be many other anticipated application areas, little has been done on developing application frameworks and/or models, which express the conceptual and implementation architectures of an application by notation and rules, and testing and evaluating developed application systems. Based on the literature review, we believe that the following application scenarios may be a good starting point for further studying application models, testing and evaluating RCGIS systems and tools using a mix of platforms and supporting technologies:

- A public meeting is held for interested citizens to provide input on a newly planned urban development (e.g., a park), using a large interactive wall display system to facilitate the meeting. Simultaneously, those citizens and stakeholders, who are not able to physically attend, share the display and meeting conversations from their homes or offices using a Web browser or a mobile device. A group of specialists may respond to questions from participants and interact with the shared display of the meeting using their desktop PCs that possess powerful GIS capabilities.
- An emergency operations centre is working on a disaster or emergency occurred. Location-based onsite information and guidance from the centre to the onsite front-line workers are critical in emergency operations. A collaborative session is setup which connects front-line workers, specialty teams (perhaps located somewhere else), and staff at the operation centre. Onsite information is captured by front-line workers using mobile mapping (including video mapping and GPS components) devices and communicated with others in real time. Analysis results and corresponding detailed operation instructions are sent back to front-line workers.
- A small group of urban, transportation and environmental specialists and design engineers work on the review and assessment of a particular development project that may have impact on a variety of environment factors. Due to their work schedules and locations, they cannot have a face-to-face meeting to discuss these impacts. A web-based collaborative GIS application is then used; allowing them to collaboratively visualize and manipulate related information based on spatial data, and to explore different plans.

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5. Recommendation for further development

Research on RCGIS technologies has evolved from the initial phase to further research and development phase, and has increasingly drawn great attention of researchers in computer science, geographic information science, and urban planning, among other related fields. After initial conceptualization phase, the field has so far primarily been technology driven, i.e., developing and upgrading systems and tools using newly emerged information technology, hardware and software platforms. Less attention has been paid on related theories (e.g., semantics, ontology, frameworks and application models), system evaluation, and applications. As technologies continue to advance and new applications become apparent, it is not surprising that the development will continuously be driven by technology, but gradually shifted to application-driven.

Given the interdisciplinary nature of this field, future directions are always hard to predict precisely. Nevertheless, the further developments in real-time, collaborative GIS may be towards the following:

3D-enabled collaborative workspace: real-time collaborative 3D GIS system is still in the early phases of research. However, a high number of 3D objects in the shared scene could lead to longer loading and updating time (Stock et al., 2008).

Support of multi-platforms: current developments for single platform need to be expanded to support multiple platforms because collaborators use a variety of terminals (e.g., PC, tablet, smart phone, pad, etc.) on different platforms (e.g., Windows, Mac, Android, etc.). Specially, the current trend is to move everything onto the web and mobile platforms. Due to the performance and screen size, synchronization of views, operations and awareness will be much more difficult, which calls for further studies in personalization, semantics, data and message transmitting, and visualization of collaborative artefacts.

More open source based: open source technology has now become more acceptable and mature after long debate about its downsides comparing with proprietary and commercial technologies. Further, open source is likely to provide complete implementation of open standards (Li, 2008) with low cost and potentially high quality due to the large number of people working on fixing bugs in codes. Current developments through integrating existing systems or programing based object codes rely heavily on proprietary/commercial technologies, which often results in "heavy" system with many unwanted functions, issues with license and upgrading, and potentially high cost for development and implementation. Open source technology proves to be a viable alternative to tackle these problems.

Flexible concurrent control: concurrent control in RCGIS needs to consider characteristics of spatial or map data and GIS operations. Current work mainly uses lock and floor control approaches to ensure operations may only be performed on data by a single user at any time, which makes group work very inefficient especially when many users are presented. New mechanisms need to be developed to allow control at different granularity levels in more flexible manner.

More performance evaluation: evaluation of collaborative systems involves assessing systems/tools from a software engineering perspective and assessing cooperation objectives reached (Li, 2006). Although current RCGIS developments lack empirical studies on system and application performance, some studies have been done on individual aspects, e.g., usability study of awareness widgets (Gutwin et al., 1996) and online real-time map sharing (Butt and Li, 2012).

Better understanding of applications: existing efforts have been focused very much on developing various systems to support real-time GIS-based collaboration. Case studies are common to show the usefulness of the developed systems. Little has been done, however, on modelling different applications. Well-developed application frameworks/models can ensure RCGIS systems meet requirements of different application areas and even the interests of different types of users in the same area (Stock et al., 2008).

Research on the above aspects may also provide useful enabling technologies to support geodesign, which is an emerging field of study in geography and GIS (Goodchild, 2010). Geodesign is meant to solve large, complicated and significant design problems that are "beyond the scope and knowledge of any one individual person, discipline or method", for which collaboration is the key (Steinitz, 2012, p.3). Further studies are therefore needed to investigate how RCGIS might fit into the overall geodesign framework and support collaborative geodesign processes.

6. Conclusions

Real-time, collaborative GIS is a vibrant early-stage research field. Through an extensive literature review, together with authors' long-term research in the field, this paper discusses the key technologies needed for RCGIS developments, examines status of current research and development, and proposes some further study areas. It is hoped that the paper presents an overall picture of the field and will provide a good starting point and reference for researchers stepping into this area.

We believe the field of real-time collaborative GIS will attract more researchers, and along with further advancement of technology and R&D activities, RCGIS will continue to make progress, especially resulting in practical applications that serve society in critical situations of disaster response, management and policy decisions.

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