From GPS and Virtual Globes to Spatial Computing - 2020*:
The Next Transformative Technology

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`Peggy Agouris, George Mason University`
`Walid Aref, Purdue University`
`Michael F. Goodchild, University of California - Santa Barbra`
`Erik Hoel, Environmental Systems Research Institute (ESRI)`
`John Jensen, University of South Carolina`
`Craig A. Knoblock, University of Southern California`
`Richard Langley, University of New Brunswick`
`Ed Mikhail, Purdue University`
`Shashi Shekhar, University of Minnesota`
`Ouri Wolfson, University of Illinois - Chicago`
`May Yuan, University of Oklahoma`

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*Spatial computing is used in a broad sense to include spatio-temporal computing and non-geographic spaces.

1 Proposal Description

1.1 Introduction

This proposal outlines an effort to develop and promote a unified agenda for Spatial Computing research and development across US agencies, industries, and universities.

Spatial Computing is a set of ideas and technologies that will transform our lives by understanding the physical world, knowing and communicating our relation to places in that world, and navigating through those places.

The transformational potential of Spatial Computing is already evident. From virtual maps to consumer GPS devices, our society has benefitted immensely from spatial technology. We've reached the point where a hiker in Yellowstone, a schoolgirl in DC, a biker in Minneapolis, and a taxi driver in Manhattan know precisely where they are, nearby points of interest, and how to reach their destinations. Large organizations already use Spatial Computing for site-selection, asset tracking, facility management, navigation and logistics. Scientists use GPS to track endangered species to better understand behavior and farmers use GPS for precision agriculture to increase crop yields while reducing costs. Virtual Globes (e.g., Google Earth, NASA World Wind) is being used in classrooms to teach children about their neighborhoods and the world in a fun and interactive way. Augmented reality applications [32] are providing real-time place-labeling in the physical world and providing people detailed information about major landmarks nearby.

Spatial Computing has also transformed how we access, store, visualize, and make use of geographic data. Imagine life without GPS-enabled smart phones, or emergency operations without interactive, dynamic maps. In the wake of many recent natural disasters, Google Earth has been used as a service to allow millions of people to access imagery to help in disaster recovery services [34]. After Hurricane Katrina, nearly 4,000 post-hurricane images were made available in Google Earth for the US Army Corps of Engineers to assess levee damage [11]. Within days of the 2010 Haiti earthquake, navigable digital roadmaps were available on OpenStreetMap [38]. Similarly, news media, educators, and activists use dynamic maps to help communicate with the public by adding spatial context to information. Learning about the environmental impacts of mining via mountaintop removal is much more powerful when one can see the visual context via a simulated 3-d map.

More recently, Spatial Computing has begun to transform the way we shop by identifying local services–ranging from home-maintenance providers (e.g., lawn services, remodeling, and locksmithing) to nearby deals and promotions for a variety of goods (e.g., flowers, clothes) and services (e.g., theater tickets, restaurant coupons). Many already use location-based services [43] to get recommendations and deals based on their current location [24]. For example, Walgreens has offered discounts to shoppers who check in on Foursquare. And in just over two years, location-based daily-deal website Groupon has accumulated 60 million subscribers and $760 million in annual revenue to become the fastest-growing Web company ever [7]. Even our socializing habits are being shaped by location-based social networks (e.g., Foursquare, Facebook check-in, Twitter), which allow us to locate our friends in real-time for impromptu get-togethers.

In addition, Spatial Computing has transformed public services. Epidemiologists use spatial analysis techniques to identify cancer clusters (i.e., locations with unusually high densities) and track infectious disease such as SARS and bird flu. Public safety professionals use spatial analysis to identify crime hotspots to select police patrol routes, social interventions, etc. Emergency managers use spatial analysis to identify routes to evacuate vulnerable populations to safety.

Spatial Computing has revolutionized national defense [9, 33, 35] as well. From stealth route selection (i.e., the practice of navigating through terrain without detection) to precision-guided weapons, spatial technologies permeate through every aspect of national security. Situational awareness in battle starts with maps of locations, environments, terrains, and intelligence about adversary placement and movement. Recently, the US-DoD has started a GPS modernization (GPS-III) effort due to rising concerns of adversarial jamming [46].

Unique contributions of spatial thinking to computer and information sciences include map projections, scale, auto-correlation, heterogeneity, non-stationarity, etc. [45]. The first two impact computation of spatial distance, area, direction, shortest paths, etc. Autocorrelation refers to the observation that nearby locations tend to be similar. Such spatial and temporal auto-correlation violate common-place independence assumptions in traditional statistics and data mining and have led to spatial statistics and spatial data mining [44]. Heterogeneity (and non-stationarity) refers to the observation that no two geo-locations (or calendar-days) are alike. Thus, the ranking of candidate solutions for a problem may vary across location and time–violating the stationary assumption underlying dynamic programming, a popular algorithm design paradigm. To address this challenge, Spatial Computing has provided new algorithm design paradigms [18].

Forthcoming Age of Spatial Computing: The above examples are all early indicators of the likely impact of Spatial Computing. The US Department of Labor has identified geospatial technologies, along with nanotechnology and biotechnology, as one of the three most important high-growth industries for the 21st century [16]. The Congressional Research Service published a recent report on GIS [15] listing 19 federal agencies who consider Spatial Computing a mission-critical technology. The United Nations published 15 Global Challenges to "provide a framework to assess the global and local prospects for humanity." Many of these challenges are inherently spatial problems, such as maintaining clean water, sustainable development, energy production, and peace and conflict [22]. Spatial Computing is essential to computational advances in addressing the global challenges. The Association for Computing Machinery (ACM) in 2008 created a new Special Interest Group (SIG) for Spatial Computing (SIGSPATIAL). A variety of other representative professional organizations are listed in Appendix A.

A National Agenda: There is an international competition for leadership in Spatial Computing. While the United States started out extremely strong in this area, with the deployment of Navstar GPS satellites, development of Google Earth and digital roadmap databases, foreign countries are investing heavily to surpass our capabilities. The European Union, Russia, China, India and Japan are all forming their global navigation satellite systems (GNSS), some with newer capabilities such as indoor location services. NAVTEQ, a former American company and the leading global provider of digital roadmaps, traffic and location data was recently bought by Nokia, a European company. A recent revolution in mapping with help from volunteers, OpenStreetMap, came from England and has allowed many countries to develop US-quality digital roadmaps for navigation, emergency management and other purposes.

The proposed program would develop a Spatial Computing research agenda that relates strategic applications to underlying basic research, defines the roles of various different funding agencies, and lays a path forward that serves the economic and social needs of the nation.

1.2 Context

Today, Spatial computing researchers and developers operate in a landscape increasingly defined by two global trends.

Societal Context - A Growing Burden on Earth's Resources: Since the beginning of the 2000s, the oil market has undergone a major shift - raising the price of gasoline in the United States by roughly a factor of three, severely straining the economy. The rise of China's economy signaled that the developing world was becoming an increasingly important consumer of oil. Between 1998 and 2008, China accounted for a third of the growth in global oil demand. Its consumption, which reached 8 million barrels a day, rose more than five times faster than the rest of the world. As developing countries like China, India, Russia and Brazil grow their middle class, the demand for oil and other resources (e.g., food, water) will grow much faster than supplies, straining our world in many ways. According to the Happy Planet Index, if the developing nations across the world want to live a western lifestyle, we will need 4.5 planets to sustain everyone [2]. This will make it critical to efficiently manage Earth's natural resources by addressing issues such as the following: How Is the Movement of People, Goods, and Ideas Transforming the World? How Might We Better Observe, Analyze, and Visualize a Changing World? [36]. Spatial Computing is a crucial aspect for aiding in management of these resources. IBM began a project entitled Smarter Planet to do just that, aiming to increase efficiency of energy and resource use by building 'smarter' cities [37]. In addition, ESRI is working to answer the question, "How do we utilize spatio-temporal concepts to design sustainable places and alternative futures?" via a new initiative called GeoDesign [5]. These systems can be used for monitoring a variety of Earth resources (e.g., agriculture fields, fresh water lakes, etc.) and trends (e.g., deforestation, pollution, etc.) for timely detection and management of problems such as impending crop failures and crop-stress anywhere in the world. NSF GEO and OCI Directorates are developing research visions in this area under the EarthCube initiative [40].

International Context - Worldwide Investment Surpasses the US: Our foreign colleagues are organizing strong coherent R&D programs. In China, the government has recognized the dramatic impact of Google Earth on a number of industries, along with its military and defense applications. They are creating an advanced version of the software for internal purposes, leapfrogging Google Earth's capabilities by providing data analytics and simulation models for predicting alternative futures for issues ranging from climate change to population growth [19].

In Russia, Moscow State University boasts the largest scientific and educational center for Geo-Spatial Science in the world and has dedicated massive funds for spatial research. The Faculty of Geo-Information Science and Earth Observation (ITC) at the University of Twente, The Netherlands is a major GIS powerhouse in Europe and the developing world. China has a similar large center at Wuhan University devoted to geospatial science and technology. Each of these universities boast hundreds of faculty members devoted to Spatial Computing research, surpassing comparable research centers in the United States.

In South Korea, the government and industry recently funded a large study on the development of indoor spatial awareness technologies [25] and smart cities (e.g., Sangdo [28]). Japan's Aerospace Exploration Agency (JAXA, like the US NASA) is designing a regional GNSS system that surpasses ours in capability, allowing for "seamless indoor and outdoor positioning" [20]. Recognizing that people spend most of their day indoors without GPS signals, the goal of such innovation is to provide GPS-like location and routing information for pedestrian travel through building and structure interiors. Information and technologies such as this will prove invaluable for emergency services, homeland security and even businesses, which can use indoor location-based services to entice customers or track inventories in warehouses and stores.

In Brazil, technology for monitoring illegal logging in the Amazon rainforest via a Google Earth-like system shows almost real-time satellite imagery to detect anomalous events. Change-detection algorithms monitor land cover and highlight temporal changes in foliage cover. In Denmark, the Copenhagen Wheel project was announced that treats cyclists as moving sensors, allowing for spatial information about weather, climate, pollution, transportation, etc., to be collected anonymously and aggregated for civil projects and informatics. With the capability of today's smartphones, one can easily see the potential of citizen sensors enabling the next generation of informatics.

International competition is leapfrogging the United States through heavy investments in Spatial Computing. We need sustained support and investment to remain at the forefront of Spatial Computing research and development, as it has implications for prosperity, national security, and civil society.

1.3 Vision

Spatial Computing encompasses a number of technologies to enable sensing, monitoring, and analyzing in order to provide better understanding for decision-making. Computers need spatio-temporal context to make informed decisions. Decisions based on location require an understanding of the place: history, topography, government, crime, climate, etc. Spatial Computing is more than just maps, it is a means for synthesizing information about places to help people understand the world, as illustrated by the following examples.

Spatio-Temporal Computing: Adding the temporal dimension to Spatial Computing opens up exciting possibilities. For example, commuters may ask for the best start time to reach a scheduled meeting while minimizing the time spent on the highway or public transportation. Epidemiologists and public safety professionals may identify emerging hotspots and intervene proactively before problem gets severe. Emergency planners may explore spatio-temporal evacuation plans using spatio-temporal ideas like phased evacuation and contra-flow via reversible lanes. Bigger impacts are likely in areas such as global change, demographic studies (planning), event detection, etc. Spatio-temporal computing raises many questions: How do we conceptualize the spatio-temporal world? How do we use spatio-temporal concepts to think about spatio-temporal phenomena, and to seek explanations for spatio-temporal patterns and phenomena?

Transforming the Internet: Perhaps the most profound change will be an extension to the Internet - transforming our way of living and social interactions. The incorporation of location information for Internet entities such as users, documents and servers will allow a flourishing of services designed around enhanced usability, security and trust. For example, the way information is categorized on the Internet can be augmented with spatial information. Currently we access information based on keywords and references, but a large portion of information has an inherent spatial component. Storing and referencing data by location may allow for more intuitive searching and knowledge discovery. It would then be possible to draw correlations and find new information based on relative locations, rather than keywords.

However, this is just the beginning. Spatial Computing will take the Internet beyond cyberspace, enabling connections among moving objects such as cars, pedestrians, and bicycles, to help avoid collisions or coordinate movement using Dedicated Short Range Communications (DSRC). Transportation agencies and automotive manufacturers are pursuing this vision under the IntelliDrive initiative [14]. For example, the USDOT recently announced a challenge to explore the question: "When vehicles talk to each other, what should they say?", aiming to make driving safer and more efficient [1].

Impact on Science: One may address broader questions related to the philosophy of science. Many traditional scholars look for unified theories across all locations, time frames, scales and phenomena. However, many spatial thinkers believe that place-based models may be more accurate and effective due to spatial heterogeneity, at least in the early stages of a new field of knowledge. Spatial Computing may facilitate a debate comparing global theories and place-based (or time-based) theories and their place in evolving fields of knowledge, e.g., understanding the impact of climate change for different cities and countries.

Eco-routing: Logistics companies such as UPS are exploiting smarter routing decisions (e.g., avoiding left turns) to save over three million gallons of fuel and associated green house gas emissions annually [29]. Imagine the savings in fuel-cost and greenhouse gases if other fleet owners (e.g., public transportation) and consumers utilized this technology. GPS navigation services are just beginning to experiment with providing eco-routes which aim to reduce fuel consumption, as compared to reducing distance traveled, or time spent. The McKinsey Global Institute recently published a report estimating that Smart Routing could have a global worth of "about $500 billion by 2020" in terms of fuel and time saved [30]. These techniques along with smarter suggestions for ride sharing and public transportation will enable significant fuel conservation. The rise of Spatial Big Data may enable computers to suggest not only compatible ride-share partners, but they may lead to retooled bus routes based on the spatio-temporal movements of individuals. With these new data sources, can we develop efficient and privacy-preserving techniques to automatically suggest public transportation, compatible ride-share partners and smart driving routes?

Relieve Air-Traffic Congestion: Current air-traffic control systems rely on radar. Due to the imprecision of this technology, large gaps between aircraft are required to ensure safety and avoid collisions. Consequently, the air space over America has become more and more congested, with the military needing to open up reserved air space over holiday weekends. If air traffic control systems were switched to a GPS-based system, the large gaps between aircraft would no longer be needed as the traffic controllers would have much more precise data. The Federal Aviation Administration (FAA) is actively exploring this vision to relieve congestion in many air corridors [13].

Increase Prosperity: The above mentioned McKinsey report states that location-based services will be a significant portion of an estimated 150,000 new deep-analytical jobs and 1.5 million data-savvy manager and analyst positions needed for the upcoming push by companies into big-data analysis [30]. Along with that, a potential consumer surplus of "$600 billion annually" is possible through using personal location data. However, the use of geospatial information in commerce is in its infancy. Great opportunities lay ahead in the leveraging of users' locations and expected routes in proactive services and assistance, ad impressions, and healthcare. Even though preliminary work in mobile commerce has explored the potential of computers enhancing commerce between mobile buyers and businesses based on geolocation [23], next generation bidding systems enabling ideal matches between mobile buyers and sellers continue to pose challenging research questions such as the following: How can computer systems efficiently pair mobile buyers and geo-located sellers while minimizing overall trip delay and transportation costs? This vision involves many advances in the basic foundations of Spatial Computing, and many new technologies. It also requires substantial continuing investments by the business community, and potentially significant training and re-training of the human workforce.

Geo-Privacy and Geo-Security: Privacy of geographic information is an important topic. While location information (GPS in phones and cars) can provide great value to users and industry, streams of such data also introduce spooky privacy concerns of stalking and geo-slavery [10]. Computer science efforts at obfuscating location information to date have largely yielded negative results. Thus, many individuals hesitate to indulge in mobile commerce due to concern about privacy of their locations, trajectories and other spatio-temporal personal information [27]. Spatio-temporal computing research is needed to address many questions such as the following: "whether people reasonably expect that their movements will be recorded and aggregated..."? [39]. How do we quantify location privacy in relation to its spatio-temporal precision of measurement? How can users easily understand and set privacy constraints on location information? How does quality of location-based service change with variations in obfuscation level?

Geo-Sensing: Another challenge area is in the use of geospatial reasoning in sensing and inference across space and time. Multiple tradeoffs (including those arising in privacy considerations) can come to the fore with attempts to sense and draw inferences from stable or mobile sensors. New challenges arise from crowd-sourced sensors. For example, the ubiquity of mobile phones presents an incredible opportunity for gathering information about all aspects of our world and the people living in it [26]. Already research has shown the potential for mobile phones with built-in motion detectors carried by everyday users to detect earthquakes mere seconds after they begin [12]. Navigation companies frequently utilize mobile phone records to estimate traffic levels on busy highways [47]. How can computers efficiently utilize this prevalent sensing power of mobile phones without drastically impacting battery life or personal privacy concerns? This raises many computer science questions related to sensor placement, configuration, etc.

Geo-Informatics: Support is needed for the constellation of problems in the geosciences – the core evolving basic and applied sciences of understanding the entire Earth and its physics (e.g., ocean, atmosphere and land), biology (e.g., plants animals, ecology), sociology (e.g., sustainable economic development, human geography), etc. For example, there is a growing need for a cyber-infrastructure [6] to facilitate our understanding of the Earth as a complex system. Technological advances have greatly facilitated the collection of data (from the field or laboratory) and the simulation of Earth systems. This has resulted in exponential growth of geosciences data and the dramatic increase in our ability to accommodate complexity in models of Earth systems. These new data sources, referred to as Spatial Big Data, surpass the capability of current spatial computing systems to process efficiently. New research into massively scalable techniques for processing and mining Spatial Big Data via novel cyber-infrastructures (e.g., EarthCube [40]) will be key for Geo-Informatics.

Beyond Geo: Spatial computing need not only apply to geographic space. Other spaces, such as the human body in medicine or micro and nano structures in material science may benefit immensely from spatial computing. Spatio-temporal datasets in medicine include 3-D images (e.g., CT and MRI) and spatial networks in the body (e.g., circulatory system). New research problems include: defining a frame of reference for the human body [42], determining spatial changes in lesions, and finding minimally invasive routes for neurosurgery to remove a malignant tumor. In material science, spatial ideas such as point processes and spatial autocorrelation may help characterize the spatial distribution of defects on silicon wafers [48].

Prediction: Geospatial information can also be used to make predictions about a broad area of issues including the next location of a car driver, the risk of forthcoming famine or cholera, or the future path of a hurricane. Models may also predict the location of probable tumor growth in a human body or the spread of cracks in silicon wafers, aircraft wings, and highway bridges. Such predictions would challenge the best of machine learning and reasoning algorithms, including directions with geospatial time series data. We see rich problems in this realm. Many current techniques assume independence between observations and stationarity of phenomena. Novel techniques accounting for spatial auto-correlation and non-stationarity may enable more accurate predictions.

How can new techniques remain computationally efficient while incorporating auto-correlation and non-stationarity while remaining computationally efficient?

Additional computer science questions can be found in Appendix C.

1.4 Process

Project Goals, Metrics and Expected Outcome: The objective of the proposed activities is to formulate a broad research program on Spatial Computing and engage the broader community. Focused attention from key leaders in the field will illuminate important areas of research and study for various programs. A key outcome would be a set of critical research issues and a broad research program, which would describe the research directions to understand and address the problems, and describe the benefits to society from the research.

Engaging key participants: We plan to engage about 100 researchers across academia, industry and government for this project. We will consult the various professional societies, industry members, and government agencies listed in Appendix A. A sample of representative participants can be found in Appendix B and the acknowledgement section. A key goal will be to diversify participation across: career stages, validation methodologies (theory, systems, etc) and disciplines (e.g., computer science, geography, social science, navigation, remote sensing, and engineering).

We have already started engagement with the Spatial Computing community via the 12th International Symposium on Spatial and Temporal Databases [3]. Sponsored by the CCC, the symposium featured a new Vision and Challenge track. There were 21 submissions to this track, reviewed by key people in academia, industry and government. Eight were selected for presentation and publication in the proceedings [3] and the 80 people in attendance selected the top 3 papers to receive the CCC Headwaters Awards [17]. The symposium also featured a panel-discussion on "Envisioning 2020 Spatial Research" and a keynote titled "Under-explored Research Topics from the Commercial World."

Proposed Activities: We propose to build a research agenda for Spatial Computing through a workshop designed after the 2009 Discovery and Innovation in Health IT workshop [8], in an effort to stimulate innovation from opposing directions: market pull and technological push. The first two sessions will explore these directions in successive sessions on the first day. The second day will have a session on generating grand challenges for spatial computing along with a synthesis session which will record the common competency and theoretical needs determined from the previous reports.

Session on Needs Assessment: Our first session will invite leaders from industry and mission-centric government agencies to identify both short and long term needs and opportunities, including core requirements, bottlenecks and stretch-goals. This session will be structured by user communities illustrated in Appendix A to understand common needs across multiple communities. For example, spatio-temporal models may be needed by many user communities.

Session on Science and Technology Trends: A session will be organized to identify the key science and technology results expected in the coming decade based on the current state of the art. What are key anticipated inventions and discoveries that may significantly change the use of Spatial Computing in industry and government? The report from this symposia will identify key science results expected to appear over the next decade based on extrapolation from current work in Spatial Computing.

Session on Formulation of Spatial Computing Grand Challenges: On the second day, a session designed to brainstorm and formulate grand challenges of geo-driven computer science will be held.

Examining the needs and trends from the previous sessions, attendees will be split into discipline-diverse subgroups to discuss potential grand challenges in spatial computing, with a moderator facilitating integration and exploration of ideas at the conclusion of the session.

Synthesis Session: Finally, a synthesis process will be used to identify core findings from earlier workshops to prepare a report to be shared with the wider community for comments and suggestions. We plan to present the report at annual meetings of selected professional organizations for wider feedback.

Based on the full set of reports and community feedback, a proposal for a research program will be put forward for presentation to the CCC and to the wider community. It is anticipated that a number of different program proposals will be generated. Each of them will target a different agency, such as: NSF, DHS, US-DoD, etc. However, all proposals will be aimed at incorporation with a common vision for the future of Spatial Computing.

1.5 Timeline

The effort will begin Summer 2012 with an initial organizational meeting between core leaders as indicated in Table 1. An online web presence will be established and a Call for Participants form will be drafted and distributed. The workshop itself will be held in late summer, followed by a summarization and broad report on the findings in Fall 2012. Following a peer review among program members and interested parties in Spring 2012, we will submit the research agenda to the CCC.

Table 1: Proposed Timeline

April 2012	Finalize Participants, Finalize workshop date
May 2012	Finalize Symposium Agenda, Facilities, Catering, etc
June 2012	Create website, provide background reading material, solicit position papers, travel arrangements
July 2012	Potential Symposium Dates, e.g., 9th-13th
Sept 2012	Potential Symposium Date, e.g., 10th-11th or 13th-14th
Oct 2012	Prepare Report
Nov 2012	Peer Review
Dec 2012	Revise Report
Jan 2013	Begin Community Outreach (reports in society magazines, conference panels)
Feb 2013	Begin visits to federal agencies