**Summary of Revisions and Responses to Reviewer’s Comments:**

We have carefully gone over the comments from reviewers 4 and 6 on last two versions of our paper and thought hard about various ways to address those. We have tried to follow the spirit of the comments as much as possible.

Overall, the major comments from reviewer 6 are addressed by increasing coverage of Computer Science concepts in sections 2, 4 and 5. These are highlighted in blue color in the revised version attached at the end of this document. It did require a depth vs. breadth trade-off due to word limit. As a result, some of topics in sections 2 and 4 in the previous version were moved to appendices.

Reviewer 4’s major request is for a “well-structure review.” This paper being a contributed article, we believe that the word-count limit prevents us from addressing this comment to the fullest. Nevertheless, section 2 has now been expanded to increase coverage of “*significant applications and research results of high significance and broad interest*,” which is also expected of a contributed article. For example, section 2 describes spatial database management systems with specific results of R-tree, OGIS Simple feature types, etc. The new text is highlighted in blue color. To further comply with CACM guidelines for contributed articles, we also describe societal impact (opening section), technical visions (section 4) and open challenges (section 5).

 Reviewer 4 also critiqued the structure of this paper without providing a specific alternative. We have structured our article using example of the following CACM contributed article: “*Compiler research: the next 50 years*, CACM, 52(2), 2009” by Mary Hall, David Padua, and Keshav Pingali.

Next, we provide a detailed table listing reviewer comments (left column) and summary of revisions/responses (right column). After the table, we also provide a new version of the paper for the convenience of editors and reviewers. This version highlights the next text in blue color.

**Reviewer 4:**

|  |  |
| --- | --- |
| **Comment** | **Response** |
| Comments to the Author: My original comments stand. The tweaking of the language does not make a useful contribution. This is just a very poorly structured paper and has no place in Communication.Original comment reproduced from previous review:“It would be useful to the general CS community to have a **well structured review** of the present status of developments in the area of spatial and spatiotemporal databases, visualization and analysis as well as specific discussions on the current scientific challenges found in these areas. Both the CS and non-CS components in this summary discussion should be clearly pointed out and interesting examples of current research identified.” | Thanks for suggesting the need for a well-structured review of present status of developments in the area of spatial and spatio-temporal databases, visualization and an analysis on their current scientific challenges. We couldn’t agree more, having co-authored survey papers [A,B] ourselves. However, with due respect, we would like to mention that this manuscript is not submitted as a review article. We structured this article as a “contributed article” (<http://cacm.acm.org/about-communications/author-center/author-guidelines>). We used a structure similar to a recent contributed article [C] [A] Shekhar, S. and et. al.: "Spatial databases-accomplishments and research needs," Knowledge and Data Engineering, IEEE Transactions on , vol.11, no.1, pp.45,55, Jan/Feb 1999[B] Shekhar, S. and et. al.: “Identifying patterns in spatial information: A survey of methods,” WIREs Data Mining Knowl Discov, 1: 193–214, 2011[C] Mary Hall, David Padua, and Keshav Pingali. 2009. Compiler research: the next 50 years. Commun. ACM 52, 2 (February 2009), 60-67As per the guidelines given on the site “***Contributed Articles*** *cover the wide and abundant spectrum of the computing field—its open challenges, technical visions and perspectives, educational aspects, societal impact, significant applications and research results of high significance and broad interest.*”Following is a brief summary of how each of the desired aspects of a contributed CACM article (mentioned in the quote from the CACM website) were covered in our article. **Societal Impact** 🡪 Section 1 of the document (Introduction) covers this aspect.**Significant applications and research results of high significance and broad interest** 🡪 Section 2 (Transformative Accomplishments) and Appendix B (Other Transformative Accomplishments) of the new document covers this aspect. These Sections include text on some of the seminal accomplishments of research done in the area of spatial computing. In this article, we included Geographic Information Systems, Spatial Database Management Systems, Spatial Statistics, Global Positioning Systems, Location Based Services and Digital Earth. For each of these accomplishments, we have now included text (in the new version) on the significant computer science research results behind their success. This new text appears at the end of the paragraphs describing these accomplishments (Section 2 and Appendix B in the new version)**Technical visions, perspectives and educational aspects** 🡪 Section 4 (Short-Term Opportunities) and Appendix C (Other Short-term Opportunities) of the new document covers this aspect. These Sections describe 11 different emerging opportunities/applications which would need novel research in the coming future. For these opportunities we have now included (in the new version) few sample research questions highlighting a technical vision of possible new directions for computer science research. This new text appears at the end of the paragraphs describing these opportunities (Section 4 and Appendix C in the new version)**Open Challenges** 🡪 Section 5 (Long-Term Research Needs) of the new document covers this aspect. This is done by putting forth open challenges in the following four broad sub-areas: (a) Spatial Computing Sciences, (b) Spatial Computing Systems, (c) Spatial Computing Services and (d) Cross-cutting Issues in Spatial Computing. While revising the paper, we felt that the open challenges in the area of Spatial Computing Sciences and Spatial Computing Services could be further improved. To this end, we added the following text to strengthen is further. Following text was added as the second last sentence in the second paragraph (spatial computing sciences) of Section 5. “For example, volunteers often use place-names (e.g., silicon valley) and prepositions (e.g., near, in, at, along, etc.) instead of numerical coordinates (e.g., latitude-longitude). This raises the challenge of porting the current numerical-coordinate based data-structures and algorithms to spatial data with place-names and spatial prepositions.”Following text was added at the end of fourth paragraph (spatial computing services) of Section 5. “How do humans represent and learn cognitive maps? How may spatial cognition concepts improve usability of spatial computing services? How can we create user interfaces that bridge the gap between spatial computing “in the small” (typically on indoor desktop systems with stereo displays and precise 3D tracking) and spatial computing “in the large” (typically outdoors using coarse GNSS on mobile/wearable devices)?” |

**Reviewer 6:**

|  |  |
| --- | --- |
| **Comment** | **Response** |
| To **get an** **overview of these Computer Science methods and techniques** would be interesting for CACM readers. This has been promised by the title but not been performed in the manuscript. | Thank you the guidance. With due respect, we would like to mention that we have structured this article as a contributed article rather than a review article for CACM and the space limitation prevents us from including a more detailed overview of computer science methods. Nonetheless, we followed the spirit of this advice and have increased the coverage of Computer Science contributions to the interdisciplinary field of Spatial Computing. This was done by adding new text pertaining to computer science contributions in Section 2 and Section 4. In addition we have also added an additional appendix (Appendix A on page 14) containing computer science research questions in the area of Spatial Computing.  |
| The **paper mainly presents a classification of spatial application areas that have profited by spatial computing techniques. But are these applications unknown or surprising? The answer is no**. **Most applications are known to computer scientists** and to people in everyday life. From this perspective, it is not clear what this paper can offer to the reader except for a classification of applications. | Thanks for the guidance. It is important to think about CACM readership and their knowledge about spatial computing. While the material presented in Section 2 appears as common knowledge to spatial experts, it is not common knowledge for 100,000+ readers of CACM. For example, vast majority of computer scientists are not familiar with spatial statistics or even OGIS simple features types, even though they have experienced Google Maps and Navigation Services.  |
| If one reads the title "Spatial Computing: Accomplishments, Opportunities, and Research Needs" of the manuscript and compares it to the contents of the manuscript, then one must come to the conclusion that the intended goals manifested in the title have been missed in the manuscript. This manuscript almost exclusively deals with spatial applications or spatial application areas that have benefited from methods provided by spatial computing. However, the title promises a description of the accomplishments, opportunities, and research needs of the spatial computing methods that have been deployed for these applications. This is a big difference, and this second aspect is especially interesting for computer scientists and thus CACM readers. The first aspect only serves as a motivation.**What are the fundamental methods and techniques of spatial computing** that have led to the success of the spatial applications broadly described in the manuscript? Some are mentioned but rather as a marginal aspect.  | The goal of Section 2 (Transformative Accomplishments) is to introduce research results of high significance and broad interest. Since an average reader of CACM is not familiar with topics such as spatial statistics, OGIS simple features types in a spatial database, etc., we have focused on such topics in Section 2. Due to space constraints, we have moved the last two paragraphs of Section 2 (Location-based Services and Digital Earth) to Appendix B in the new version. Following are the details of the new text inserted for each of the transformative accomplishments described in Section 2 and Appendix B.Added the following text at the end of second paragraph (**Geographic Information System (GIS)**) in Section 2. “GIS has greatly benefited from computing advances in algorithms (e.g. plane-sweep), data-structures (e.g. triangulated irregular network) related to map rendering, map overlay, etc.”Added the following text at the end of fourth paragraph (**Spatial Statistics**) in Section 2. “However, spatial statistical techniques are orders of magnitude more computation and data intensive than traditional statistical ones. Increased availability of inexpensive high performance computing and data technologies (e.g., sensors, SDBMS, GIS) in recent decades have facilitated a wider interest and adoption of spatial statistical methods [10].”Added the following text at the end of fifth paragraph (**Global Positioning System (GPS))** in Section 2. “Wide spread proliferation of GPS systems was possible by VLSI implementations (e.g., SiRF www.csr.com) which could easily be integrated into mobile phones and tablets.”Text pertaining to following two “transformative accomplishments” have been moved to Appendix B (page 15 in the new document)Added the following text at the end of first paragraph (**Location-based Services (LBS)**) in Appendix B. “Efficient algorithms for analytics over spatial networks (e.g., nearest neighbor techniques and hierarchical routing for road networks [37, 36, 34]) have been one the most central pieces for a successful realization of Location-based services. These techniques help build large scale systems which can cater to the core services of a LBS.”Added the following text at the end of second paragraph (**Digital Earth**) in Appendix B. “Development of SDBMS, large capacity (terabyte size) storage devices, multi-resolution map rendering algorithms were the key computational techniques behind this revolution.” |
| Further, the manuscript addresses future innovative applications that will require new sophisticated spatial computing techniques. It would be very interesting for the CACM reader to get a vision what the new sophisticated spatial computing techniques might be. **In which directions do we have to perform research in spatial computing to develop the innovative applications presented?** The manuscript does not give an answer to this.It is important to sketch future applications to which computing methods has been applied and will be applied. The manuscript contains a large number of such applications. But it is even more important to describe and **give a vision what the nature of the required computing methods will be to fulfill the requirements of the future applications**. This part is missing in the manuscript and therefore reduces its value essentially. | Thanks for the suggestion to include a list of new directions to perform research in spatial computing to develop the innovative applications presented. To this end, we have refined Section 4 (Short-Term Opportunities) by adding the sample computer science research questions highlighting the new directions for research in spatial computing. Due to space constraints, we have moved some of the opportunities described in Section 4 to Appendix C in the new version. Below are the details of text inserted for the short-term accomplishments described in Section 4 and Appendix C.Added the following text at the end of second paragraph (**Augmented Reality Systems)** in Section 4. “New spatial computing research challenges in this space stem from the need for new algorithms as well as cooperation between users and the cloud for full 3D position and orientation pose estimation of people and devices and registration of physical and virtual things. What are natural interfaces leveraging all human senses (e.g., vision, hearing, touch, etc.) and controls (e.g., thumbs, fingers, hands, legs, eyes, head, and torso) to interact with augmented reality across different tasks? How can we capture human bodies with their full degrees of freedom and represent them in virtual space?”Added the following text at the end of third paragraph (**Spatial Predictive Analytics)** in Section 4. “Questions that need to be answered in this area include: How may machine-learning techniques be generalized to address spatio-temporal challenges of auto-correlation, non-stationarity, heterogeneity, multi-scale, etc.? How can frequent spatio-temporal patterns be mined despite transaction-induced distortions (e.g., either loss or double-counting of neighborhood relationships)? What are scalable and numerically robust methods for computing determinants of very large sparse (but not banded) matrices in context of maximum likelihood parameter estimation for spatial auto-regression model?Added the following text at the end of fourth paragraph (**Geo-collaborative Systems, Fleets and Crowds)** in Section 4. This raises the challenge of “trust” while using a group of spatial agents for computation and decision making: How may geographically distributed agents (e.g., smart signals and cars) cooperate in a trustworthy manner (e.g. despite GPS spoofing)?Added the following text at the end of fifth paragraph (**Moving Spatial Computing Indoors and Underground)** in Section 4. Indoor localization opens several new research questions such as: What scalable algorithms can create navigable maps for indoor space from CAD drawings? What about buildings without CAD drawings? How can we perform reliable localization in indoor spaces where GPS signals are usually attenuated?Text related to following six “short-term opportunities” have been moved to Appendix C (page 16 in the new document)Added the following text at the end of first paragraph (**Spatial Abilities Predict STEM Success)** in Appendix C. “Questions that need to be pondered in this area include: How do we improve STEM learning and spatial thinking using spatial computing? How may spatial computing be designed to further strengthen spatial abilities of interest to STEM disciplines?”Added the following text at the end of second paragraph (**Emerging Spatial Big Data)** in Appendix C. “Spatial Big Data spurs several new opportunities for computer science research: Can SBD be used to remove traditional issues with spatial computing, such as the common problem of users specifying neighborhood relationships (e.g., adjacency matrix in spatial statistics) by developing SBD-driven estimation procedures? How might we take advantage of SBD to enable spatial models to better model geographic heterogeneity, e.g., via spatial ensembles of localized models?”Added the following text at the end of third paragraph (**Time-Travel and Depth in Virtual Globes)** in Appendix C. “However, In order to support all of these tasks, it will first be necessary to develop representations that capture both the data and any associated metadata about multiple views of past, present, and future. How can we incorporate provenance, accuracy, recency, and the semantics of the data? Given a rich representation of the data with diverse views, what new techniques are needed to exploit all of this metadata to integrate and reason about the diverse available sources?”Added the following text at the end of fourth paragraph (**Persistent Large Area Environmental Monitoring**) in Appendix C. “Such exposure data can analyzed for better decision support, planning and emergency preparedness. One of the key challenges in realizing an efficient monitoring of an large geographic area is effective use of limited bandwidth between the sensors and the central computational infrastructure. What is optimal division of analysis between computing at sensor level-which is locally available but limited in computing power (e.g. smart-phone processor)-and remote data-center based computing-which is more powerful but require communication bandwidth?”Added the following text at the end of fifth paragraph (**Localizing Cyber Entities)** in Appendix C. “Localizing cyber entities poses significant challenges to the geo-coding techniques. Can the current techniques-which are limited to textual information-can scale-up to handle images and videos over internet? How may we geo-locate cyber entities such as images and videos?”Added the following text at the end of seventh paragraph (**Beyond Geographic Space)** in Appendix C. Non-geographic spaces raise some fundamental questions for spatial computing. Example, what reference coordinate systems (e.g., latitude-longitudes for Earth) are most suitable for queries in non-geographic spaces? For instance, inside a human body, we may use rigid structures (e.g., skull and bones) for reference but, we would also have to accommodate the variation in these structures across humans. What is the computational structure of routing problems (e.g. least invasive path to a brain tumor that minimizes tissue damage) in a non-geographic space such as the human body? |