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III:Small: Information Integration and Human Interaction for Indoor and Outdoor Spaces

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Signature of Submitting Official (signature shall be submitted in accordance with agency specific instructions)	Nicholas Giudice

Accomplishments

*** What are the major goals of the project?**

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The NSF award abstract (amended Aug 18, 2011) can be found at: http://nsf.gov/awardsearch/showAward?

AWD_ID=0916219. The project website, updated November 13, 2014, can be accessed at: http://www.spatial.maine.edu/IOspace/

1. The primary goal of this work is to provide a unified informatic framework for static and dynamic indoor and outdoor spaces that supports seamless human navigation tasks in built indoor and outdoor environments.

A resultant collection of goals concerns the integration between models of outdoor and indoor spaces at:

2a: The formal level (e.g., ontological and mathematical)

2b: Data model level (e.g., extensions to GML)

2c: Functional level (e.g., experimental work and demonstrator systems taking into account both system and cognitive issues)

*** What was accomplished under these goals (you must provide information for at least one of the 4 categories below)?**

Major Activities:

Related to goals 2a and 2b, this year's work has focused more on the detailed integration of the indoor and outdoor ontologies, taking account of "microworld ontologies" operating at the upper ontology, domain ontology, and task ontology levels. We have developed extensions of the combinatorial maps, named the extended combinatorial maps and maptrees, which provide formal models of spatial configurations of integrated indoor-outdoor spaces. We also proposed a formal concept "dual map" and developed an approach to automatic generation of navigation graphs from building floor plans. Several computational algorithms (e.g., extended combinatorial maps, dual maps, maptrees, local kernels) were developed and have been implemented in Java. A case study based on a university building was conducted to illustrate these concepts and approach.

Related to goal 2C, extending last year's work on identifying the cognitive factors for why people get lost, a significant amount of work was done this year on characterizing the structure of multi-level cognitive maps, the mental representations of multi-level buildings, used to support spatial behaviors in complex multi-level environments. Previous work on indoor wayfinding has demonstrated that traversing between floors is a major cause for navigators to become disoriented or lost in complex buildings. However, most of the existing theories on cognitive map development relate only to 2D or 2.5D planes / floors. This is problematic as most indoor spatial structures are multi-floor and require development of multi-level cognitive maps for accurate human navigation. Last year we conducted three human studies relating to how different methods of spatial visualization and information rendering can be used to aid this process—this year we spent significant effort on analyzing the data and interpreting the empirical results in terms of the factors that most cause problems and identifying the cues that could be used in a navigation device to ameliorate them. The first significant component of this year's work was to formalize the parameters for developing multi-level cognitive maps by combining the factor of multi-level spatial structure and the factor of the navigators' view perspectives when learning multi-level indoor spaces. By analyzing performance data from our previous behavioral experiments we identified several factors that make the development of multi-level cognitive maps so hard and the integration of multi-level building information so challenging for human spatial cognition. Specifically, the challenges arise from the navigator's need to update and integrate their heading shift during vertical transition (the navigator factor), the spatial reference frame shift between floors (the spatial

structure factor), and the angular offsets between the navigator's heading direction and the spatial reference direction (the combination of the above two factors).

Studies of human spatial memory have suggested that global landmarks, salient objects or geometric features in the environment that are visible from a large field of view, play an important role in wayfinding. However, in most cases, global landmarks are rare in indoor environments due to poor visual access between floors. This motivated us to investigate the notion of vertically-aligned landmarks, which refer to a series of discrete local landmarks located on different floors but that are vertically aligned. If properly visualized, these landmarks could serve as a global landmark, as they can assist navigators to align cross-level spatial information and to unify the spatial reference frames between floors. Thus, the second significant part of this year's work was to run a human study to evaluate the effect of vertically aligned landmarks on the development of multi-level cognitive maps and to explore how different methods of visualization can be used to aid this process.

A major part of this year's work continued to broaden participation of the project to classes and other students. Co-Pi Giudice's VEMI lab has a large undergraduate component and many students were exposed to grant-related work as part of their training, including 2 REU students who worked on the project in Summer of 2014. Grant-related work was also incorporated in graduate-level courses at UMaine, including Human-computer Interaction (SIE 515) and Virtual Reality and research (SIE 516).

Specific Objectives:

Significant Results:

Key outcomes or Other achievements:

Related to goals 2a and 2b, a major breakthrough has been the formal representation of indoor/outdoor models using an extension of the combinatorial map structure, that we have called "maptrees". These results have been reported at two major conferences. We have also shown how Robin Milner's concept of the bigraph can be extended so that it can be used to formally represent topological constructs, and hence important aspects of indoor/outdoor space. These results have been published in a leading computer science journal.

An approach was developed to automatically generate a navigation graph from a building floor plan using extended combinatorial maps combined with semantics. In the final stage of the project, we developed a case study that demonstrates and evaluates our approach. We will be submitting these results to at least one major journal. Liping Yang, the PhD student associated with this project, is in the final stage of completing her PhD and should submit in spring 2015.

Overall, this project has demonstrated how a formal approach can have practical applications in spatial informatics.

Related to goal 2C, a significant outcome of this year's work was a formulation of how multi-story buildings lead to cognitive confusion, based on the spatial offset of elements on different floors and navigators' view perspectives when learning multi-level indoor spaces. This work was presented at the Mainly Data 2014 conference and the International Spatial Cognition Summer Institute (ISCSI 2013).

The effect of vertically aligned landmarks on the development of multi-level cognitive maps and the effect of different visualization methods to aid this process have been addressed in a behavioral experiment, where we found initial evidence that, in multi-level indoor wayfinding, navigators perceived vertically-aligned object

landmarks, which are helpful in providing vertical alignment information between floors. We also found that both of the two visualization methods tested (2D top-down view map and 3D bird's eye view map) promoted more efficient development of multi-level cognitive maps as compared to the control condition. These results can be used to help guide the information visualization and user interface used in developing portable navigation systems that will assist with spatial learning and navigation of combined outdoor environments with multi-level indoor spaces.

This work was presented at two international conferences, ISA2013 and Map Interact 2013. Time was also spent this year on writing up results and future studies for Co-PI Giudice's Ph.D. student Hengshan Li's dissertation proposal (successfully defended in May of 2014). Mr. Li is expected to complete his Ph.D. in Summer of 2015. As of Summer 2014, the design of three additional human studies, building on previous project-related work, have been designed. Data collection began in late Summer 2014 and will continue beyond the end of this project, ensuring that this work will progress into the future. Indeed, we have made significant headway on this project after a slow start while we found and trained students, and believe that the results of the empirical research conducted under this project will lead to the development of new theories in human spatial cognition of how people form and access multi-level cognitive maps and how these maps are integrated with those formed from outdoor spaces. They will also inform the development of new spatial visualization techniques for use on portable navigation devices supporting spatial learning and navigation of both complex indoor and outdoor spaces.

*** What opportunities for training and professional development has the project provided?**

We continue to work with our graduate students, and to link the work in with a wider graduate community in the School of Computing and Information Science at UMaine. For example, Worboys' PhD student Lisa Walton, has now almost completed her PhD in a closely related topic and Co-Pi has a Masters student who is working on similar visualization techniques supporting human spatial cognition.

PI Worboys has a PhD student, Liping Yang, to work on this project and she has now completed her dissertation proposal and is expected to defend her dissertation by May of 2015. In addition to class work on related areas to the research, she has gained experience, learning how to develop ontologies and data models as well as models of indoor localization. She has also constructed algorithms to implement combinatorial maps, and maptree formalisms, as well as making a start on algorithms using these structures to automatically convert conventional maps into data structures for navigation in integrated indoor-outdoor spaces. She continues to survey the most up-to-date and relevant literature on this quickly growing topic of indoor spaces.

Co-Pi Giudice's Ph.D. student working on this project is Hengshan Li. Hengshan has now successfully passed his proposal defense and is working on his dissertation (expected completion of Summer 2015). in addition to continued training through class work in related areas to his research, he has presented his findings at several conferences and been part of several papers (see later in this report). This experience has provided him with critical insight in formulating research results and in the writing process. He has also spent significant time learning about information visualization techniques and about the union of human cognition and information presentation. Armed with this knowledge, he has developed multiple visualization interfaces using interactive 3D virtual software packages used in the lab (e.g., Unity and Vizard) and integrated these products into his behavioral experiments. Hengshan has gained important experience conducting empirical research and has completed a course sequence on statistical analysis, which he has directly incorporated in the analysis and interpretation of data from his projects this year.

Hengshan and co-PI Giudice meet one or two times per week to discuss relevant literature, research questions, experimental design, and data analysis for ongoing and future research.

*** How have the results been disseminated to communities of interest?**

Our results have been disseminated via Journal papers, conference presentations, invited keynotes, seminars, workshops, and panels. (as elaborated later in this report).

Products

Books

Book Chapters

Conference Papers and Presentations

Li, H. & Giudice, N.A. (2013). *Determining the Optimal Visual Interface Supporting Multi-level Indoor Wayfinding*. Talk given at the International Spatial Cognition Summer Institute (ISCSI). Santa Barbara, CA, USA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Giudice, N.A. (2012). *Moving beyond the vision-only bottleneck: Using multimodal information in virtual reality research. When is virtual reality real enough? Workshop on Using VR in spatial cognition research*. Spatial Cognition 2012. Kloster Seeon, Germany. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Li, H. & Giudice, N.A. (2013). *The Effects of 2D and 3D Maps on Learning Virtual Multi-level Indoor Environments*. Proceedings of the 1st ACM SIGSPATIAL International Workshop on Interacting with Maps (MapInteract 2013). Orlando FL, USA.. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Li, H. & Giudice, N.A. (2013). *The Effects of Immersion and Body-based Rotation on Learning Multi-level Indoor Virtual Environments*. Proceedings of the 5th ACM SIGSPATIAL International Workshop on Indoor Spatial Awareness (ISA 2013). Orlando FL, USA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Giudice, N.A. (2012). *Using multimodal information displays in spatial cognition research. Keynote Speaker*. CINACS Summer School Workshop on Multimodal Information Processing. University of Hamburg, Germany. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Inventions

Journals

Nossum, A.S., Giudice, N.A., & Li, H. (2013). Vertical color maps: A data independent alternative to floor plan maps. *Cartographica*. 48 (3), 225. Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

Worboys, M. (2013). Using bigraphs to model topological graphs embedded in orientable surfaces. *Journal of Theoretical Computer Science*. 484 56. Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: http://dx.doi.org/10.1016/j.tcs.2013.02.018

Yang, L. and Worboys, M. (). Automatic generation of navigation graphs for indoor space. *International Journal of Geographic Information Science*. . Status = SUBMITTED; Acknowledgment of Federal Support = Yes

Licenses

Other Products

Other Publications

Worboys, M. (2013). *A brief survey of indoor spaces*. Invited talk, University of Bremen, Germany, July, 2013.. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Worboys M. (2013). *A brief survey of indoor spaces.*. Invited talk, University of Bremen, Germany, July, 2013. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Worboys M. (2014). *A theoretician's-eye view of GIS research.*. Keynote address, GISRUK (GIS Research UK), University of Glasgow, Scotland, April, 2014.. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Worboys, M. (2013). *Bringing Urban Data Management Indoors*. Keynote Address, Urban Data Management Symposium, University College London, June 2013. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Worboys, M. (2013). *Bringing geographic information science indoors.*. Invited talk, University of Muenster, Germany, July, 2013.. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Li, H. & Giudice, N.A. (2013). *Determining the Optimal Visual Interface For Indoor Wayfinding*. Talk presented at the UMaine Graduate Expo, March 2013, University of Maine. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Li, H. & Giudice, N.A. (2013). *Evaluating the effect of 2D and 3D indoor interfaces for facilitating navigation of multi-level buildings*. Poster presented at the UMaine Graduate Expo, March 2013, University of Maine. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Worboys, M. (2013). *International Jury*. Funding Programme of the Austrian Academy of Science (New Frontiers Group). Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Li, H. (2014). *Multi-level cognitive maps for supporting indoor wayfinding.*. Talk at the 5th Annual Mainely Data Conference. May, University of Maine, Orono, ME.. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Giudice, N.A. (2014). *Space is the common denominator: From human information processing to multimodal interface design.*. Keynote talk at the Workshop on Empowering Blind Students in Science and Engineering (EBSSE). University of Washington, Seattle WA, USA.. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Worboys, M. (2012). *Space-time Panel*. GIScience 2012, Columbus, OH, 2012. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Worboys, M. (2012). *The Role of the Qualitative in Spatial Computing*. Position paper and presentation to the CCC Workshop "From GPS and Virtual Globes to Spatial Computing-2020", Washington DC, 2012. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Worboys, M. (2013). *Using maptrees to characterize topological change.*. Spatial Information Theory, (Proceedings of the International Conference on Spatial Information Theory, England, 2013). In Tenbrink et al., editors, Lecture Notes in Computer Science, 8116, pp. 74-90, Springer, Heidelberg.. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Patents

Technologies or Techniques

Thesis/Dissertations

Websites

Participants/Organizations

Research Experience for Undergraduates (REU) funding

Form of REU funding support: REU supplement

How many REU applications were received during this reporting period? 1

How many REU applicants were selected and agreed to participate during this reporting period? 1

REU Comments:

What individuals have worked on the project?

Name	Most Senior Project Role	Nearest Person Month Worked
Worboys, Michael	PD/PI	1
Giudice, Nicholas	Co PD/PI	1
Li, Hengshan	Graduate Student (research assistant)	6
Yang, Liping	Graduate Student (research assistant)	6

Full details of individuals who have worked on the project:

Michael Worboys
Email: worboys@spatial.maine.edu
Most Senior Project Role: PD/PI
Nearest Person Month Worked: 1

Contribution to the Project: overseeing students and research, please see accomplishments

Funding Support: None

International Collaboration: No
International Travel: No

Nicholas Giudice
Email: nicholas.giudice@maine.edu
Most Senior Project Role: Co PD/PI
Nearest Person Month Worked: 1

Contribution to the Project: overseeing students and research, please see accomplishments

Funding Support: None

International Collaboration: No
International Travel: No

Hengshan Li
Email: Hengshan.Li@umit.maine.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 6

Contribution to the Project: working on cognitive models and information visualization supporting indoor wayfinding

Funding Support: graduate stipend

International Collaboration: No

International Travel: No

Liping Yang
Email: liping.yang@umit.maine.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 6

Contribution to the Project: working on seamless integration of informatics of indoor and outdoor spaces

Funding Support: graduate stipend

International Collaboration: No
International Travel: No

What other organizations have been involved as partners?
Nothing to report.

What other collaborators or contacts have been involved?

NO

Impacts

What is the impact on the development of the principal discipline(s) of the project?

Impacts from our project will relate to a number of disciplines, includeing formal data structures and ontologies, data visualization and human spatial cognition, and the design of interfaces to support spatial learning and navigation of both indoor and outdoor spaces.

What is the impact on other disciplines?

Due to the broad and general nature of this research--theoretical and formal models of spatial data, human spatial behavior, and systems to facilitate integrated navigation of both indoor and outdoor spaces, there are many impacts of all these project elements to many disciplines.

What is the impact on the development of human resources?
Nothing to report.

What is the impact on physical resources that form infrastructure?
Nothing to report.

What is the impact on institutional resources that form infrastructure?
Nothing to report.

What is the impact on information resources that form infrastructure?
Nothing to report.

What is the impact on technology transfer?
Nothing to report.

What is the impact on society beyond science and technology?
Nothing to report.

Changes/Problems

Changes in approach and reason for change
Nothing to report.

Actual or Anticipated problems or delays and actions or plans to resolve them
Nothing to report.

Changes that have a significant impact on expenditures
Nothing to report.

Significant changes in use or care of human subjects
Nothing to report.

Significant changes in use or care of vertebrate animals
Nothing to report.

Significant changes in use or care of biohazards
Nothing to report.