Embodied Spatial Cognition in Tangible Computing

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CCS Concepts: •**Human-centered computing** → **Human computer interaction (HCI); Laboratory experiments;**

Additional Key Words and Phrases: Human-computer interaction, tangible interfaces, interaction design, physical computation, embodied cognition, spatial thinking, geospatial modeling

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1. INTRODUCTION

We have designed Tangible Landscape – a tangible interface powered by a geographic information system (GIS) – that gives spatial data an interactive, physical form so that users can naturally feel it, see it, and shape it (Fig. 1). Our aim was to iteratively design and empirically test a tangible interface that augments spatial thinking and improves spatial performance. Spatial thinking can be embodied – people can functionally think about space with their bodies by cognitively grasping objects and physically simulating it [Kirsh 2013]. Theoretically tangible interfaces should improve spatial performance through embodied cognition by enabling natural modes of interaction [Dourish 2001], offloading cognitive processes onto the body [Kirsh 2013], and computationally augmenting spatial thinking [Dror and Harnad 2008]. We designed Tangible Landscape to physically manifest digital data so that users can cognitively grasp the data as an extension of their bodies and automatically, immediately, and subconsciously interact with it. We conducted a series of experiments using quantitative methods including geospatial modeling, analysis, simulation, and statistics and qualitative methods including semi-structured interviews and direct observation to test whether tangible interfaces can improve spatial performance. We also explored how users approached spatial problem solving using Tangible Landscape in a serious gaming event.

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Fig. 1. Tangibly modeling the flow of water with Tangible Landscape

1.1. Spatial thinking and computation

Spatial thinking – 'the mental processes of representing, analyzing, and drawing inferences from spatial relations' [Uttal et al. 2013] – is used pervasively in everyday life for tasks like recognizing things, manipulating things, interacting with others, and way-finding. Spatial thinking is also used extensively in science, technology, engineering, the arts, and math for tasks like diagramming concepts, visualizing data, simulating physical processes, mapping and manipulating molecules, designing circuits, designing buildings, shaping sculpture, and studying topology. Given the importance of spatial thinking – personally, academically, and professionally – how can we effectively improve our spatial performance, our ability to perform tasks that require spatial thinking?

Many spatial tasks can be performed computationally enabling us to efficiently store, model, and analyze large sets of spatial data and solve complex spatiotemporal problems. In engineering, design, and the arts computer-aided design (CAD) and 3D modeling software are used to interactively, computationally model, analyze, and animate complex spatial forms. In scientific computing spatial patterns and processes can be mathematically modeled, simulated, and optimized. Geographic information systems, for example, can be used to computationally store, model, analyze, simulate, and represent geospatial patterns and processes. The open source Geographic Resource Analysis Support System (GRASS) GIS for example supports 'geospatial data management and analysis, image processing, graphics and maps production, spatial modeling, and visualization' [GRASS Development Team 2016].

Computing mediates and transforms spatial thinking, expanding, but also constraining what is possible. While spatial computing can augment spatial thinking – distributing or offloading cognitive processes through digital computation – the logic of implementation, the limits of what is computationally possible, and the modes of input and output constrain how we reason. Furthermore, when it is difficult to interact with a computer, to input commands and parse the resulting output, one has to think harder and risks frustration and demotivation.

Unintuitive modes of human-computer interaction constrain thought and add cognitive and emotional costs. The paradigmatic modes for interacting with computers today – command line interfaces (CLI) and graphical user interfaces (GUI) – require physical input from devices like keyboards, mice, digitizing pens, and touch screens, but output data visually as text or graphics. Theoretically this disconnect between intention, action, and feedback should make interaction less intuitive [Dourish 2001; Ishii 2008]. Furthermore, it can be challenging to parse data that is only presented visually. Spatial data – especially 3D spatial data – presented graphically can require sophisticated spatial reasoning skills such as mental rotation [Shepard and Metzler 1971], spatial visualization, and spatial perception [Linn and Petersen 1985] to parse and understand, much less manipulate.

1.2. Tangible interaction

Tangible interfaces – interfaces that couple physical and digital data [Dourish 2001] – are designed to physically manifest digital data so that we can cognitively grasp and absorb it, so that we can think with it rather than about it [Kirsh 2013]. Ishii and Ullmer envisioned that tangible interfaces would ‘take advantage of natural physical affordances to achieve a heightened legibility and seamlessness of interaction between people and information’ [Ishii and Ullmer 1997]. With a tangible interface both input and output are physical. Data can be felt as well as seen; data can be directly, physically manipulated, leveraging highly developed motor skills. Thus intention, action, and feedback should be seamlessly connected enabling automatic, subconscious, and intuitive interaction.

Tangible interfaces let users interact with computers while (functionally) thinking with their bodies. By thinking with their bodies, by embodying cognition users may be able to reduce their cognitive loads by offloading cognitive tasks like spatial perception and manipulation onto the body and physically simulating processes. In embodied cognition higher cognitive processes are grounded in, built upon, and mediated by bodily experiences such kinaesthetic perception and action [Hardy-Vallée and Payette 2008]. When people use tools they temporarily, contingently incorporate them into their body schema, feeling the perimeter, weight, and balance of the tool, sensing resistance when the tool touches something, as if the tool was an extension of the body [Maravita and Iriki 2004]. Because tools can be cognitively gripped and absorbed in ones body schema, they mediate embodied cognition – affording new bodily experience and action and thus extending ones capacity for thought. Tangible interfaces are designed to make computation tangible so that it can be cognitively gripped and absorbed, so that computation can be understood with the body.

It can be challenging and cognitively taxing to visually perceive and parse space, to for example visually judge distances and imagine volumetric form. Distance and physical properties like size, shape, volume, weight, hardness, and texture, however, can be automatically and subconsciously assessed kinaesthetically with the body [Jeannerod 1997]. By affording physical feedback tangible interfaces should, therefore, reduce the cognitive load needed to judge spatial distances, relationships, patterns, and forms.

. . . [Maravita and Iriki 2004]

Furthermore, some cognitive processes can be physically simulated, offloading the cognitive work onto the body [Kirsh 2013].

Architects massing models Office of Metropolitan Architecture foam massing models [Yaneva 2009] or Frank Gehry’s creative process of thinking through the movement of gestural drawing and exploratory form finding with massing models [Gehry 2004; Pollack 2006]

Professionals like designers develop creative ideas through ‘reflection-in-action,’ an iterative, exploratory process of framing the problem, ideation or making, and critical reflection [**?**]. This exploratory process may unfold in an instant in action, repeated continually through acts like drawing or model making. Frank Gehry for example develops his designs through exploratory form finding with massing models and by thinking through the movement of gestural drawing [Gehry 2004; Pollack 2006].

An ethnography of the Office of Metropolitan Architecture showed that architects in the firm used practices like reuse, adaption, and exploratory modeling to develop designs through iterative processes [Yaneva 2009]. The architects, for example, explored form by carving foam massing models with hot-wire cutters, reflecting on each model as they carved, while building up a library of forms. Ideas and forms set aside and unused in one project might show up in other projects, recycled and adapted [Yaneva 2009].

When tangible interactions are designed to be analogous to everyday, physical tasks like unscrewing a bottle top [Kirsh 2013], picking up and placing objects, or sculpting sand... users may already understand what to do. Such interaction should be highly intuitive, drawing on existing motor schema and cultural knowledge.

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1.3. Aim and objectives

1.4. Research questions

2. METHODOLOGY

2.1. Tangible Landscape

Concept. Tangible interfaces for GIS should ease the cognitive burden of visualizing, interacting with, reasoning about space by giving spatial data an interactive, physical form that users can cognitively grasp and kinaesthetically explore. Tangible Landscape – a tangible user interface for GRASS GIS – couples a physical and digital model of a landscape through a continuous cycle of 3D scanning, geospatial modeling, and projection so that users can intuitively interact with the modeled landscape in near real-time. Conceptually Tangible Landscape physically manifests geospatial data so that users can hold a GIS in their hands – so that they can, for example, feel the shape of the earth, sculpt its topography, and direct the flow of water with their hands. It enables users to 3D sketch – to naturally model forms such as topography, draw points and polygons, and interact with simulated physical processes – in a rapid, iterative process of observation, hypothesis generation and testing, and inference. Tangible Landscape is meant to fluidly, seamlessly combine computational science with exploratory modes of creative thinking.

Evolution. Tangible Landscape evolved from Illuminating Clay [**?**] and the Tangible Geospatial Modeling System (TanGeoMS) [**?**]. Illuminating Clay coupled a clay model and digital model of landscape through a cycle of laser scanning, spatial modeling, and projection. By enriching physical models of urban spaces and landscapes with spatial analyses such as elevation, aspect, slope, cast shadow, profile, curvature, viewsheds, solar irradiation, and water direction it enabled intuitive form-finding, streamlined analog and digital workflows, and enabled multiple users to simultaneously interact in a natural way [**?**]. Illuminating Clay had a very limited library of custom implemented spatial analyses. Since many of analyses were adapted from the open source GRASS GIS project [**?**] there was a call to integrate it with GRASS GIS in order to draw on GRASS GIS's extensive libraries for spatial computation [**?**]. The effort to couple a physical landscape model with GRASS GIS [**?**] led to the development of TanGeoMS [**?**]. TanGeoMS coupled a physical model and GIS model of a landscape through a cycle of laser scanning, geospatial computation in GRASS GIS, and projection giving developers and users assess to a sophisticated library for spatial modeling, simulation, visualization, databasing. It enriched freeform hand modeling with geospatial simulations like diffusive water flow and erosion-deposition so that users could easily explore how changes in topographic form affect landscape processes. Tangible Landscape – the next generation of this system – was inspired by the open source Augmented Reality Sandbox [**?**] which couples a sandbox with a digital model of a landscape through a real-time cycle of 3D scanning with a Kinect sensor, spatial modeling and simulation, and projection. While TanGeoMS used an expensive terrestrial lidar scanner for 3D scanning [**?**], Tangible Landscape uses a low-cost 3D sensor like the Kinect for real-time depth and color sensing. The 1st generation of Tangible Landscape [**?**] used the 1st generation Kinect with structured light sensing [**?**], and the 2nd generation of Tangible Landscape [**?**] used the 2nd generation Kinect with time-of-flight sensing [**?**] .

Design. Tangible Landscape was designed to let users naturally explore spatial data, models, and simulations in an engaging, playful way by 3D sketching (Fig. 3). As users sculpt the physical model the model is 3D scanned as a point cloud, georeferenced, imported into GIS, and either binned or interpolated as a digital elevation model. The digital elevation model is used to compute geospatial analyses, models, and simulations, which are then projected back onto the physical model – all in near real-time (Fig. 2). This enables users to tangibly interact with digital models and simulations either by shaping topography with their hands or by placing markers that are identified through object detection. As the digital models and simulations update the results are projected back onto the model for the users to see.

Because the model is continually scanned users hands will be digitized as they sculpt or place objects. Scanning users' hands as topography can be distracting; it also, however, helps users understand how the system works – by seeing how direct interaction is – and encourages play. Users can, for example, cup their hands over the model and see them fill with simulated water.

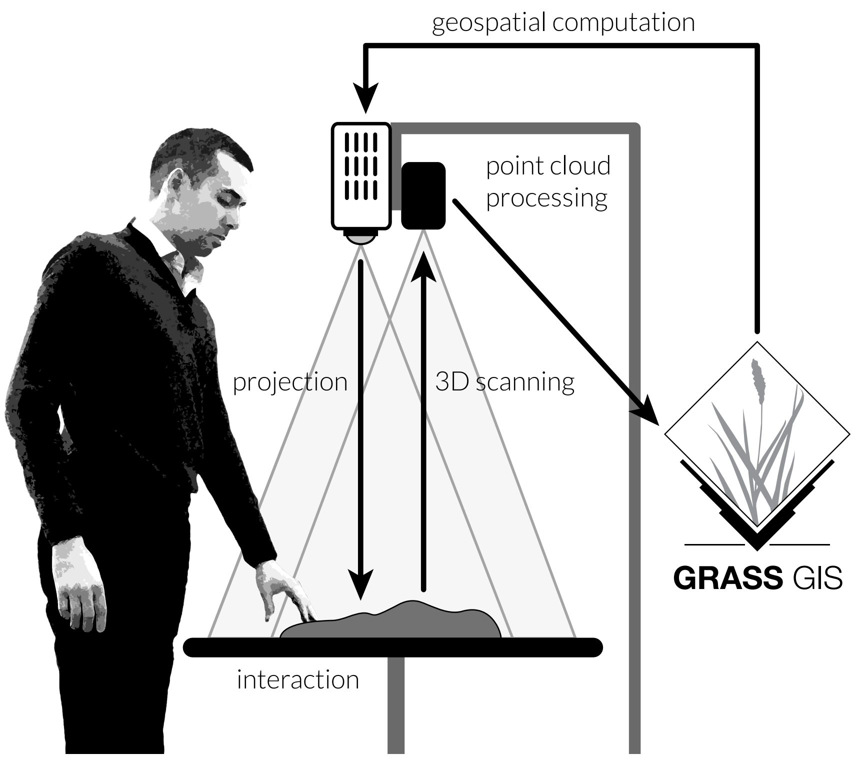

Fig. 2. How Tangible Landscape works: a near real-time feedback cycle of interaction, 3D scanning, point cloud processing, geospatial computation, and projection

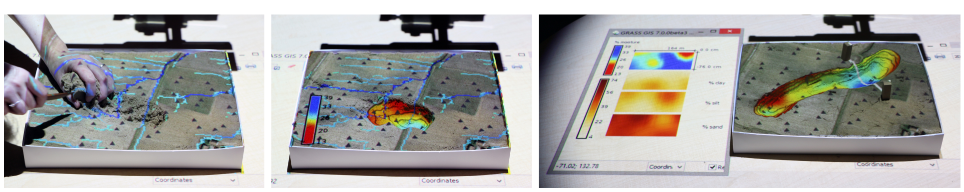

Fig. 3. Naturally exploring subsurface soil moisture and soil types with Tangible Landscape

Fabrication. The physical model is often made of polymer-enriched sand so that users can easily sculpt forms in a medium that will hold its shape, has good plasticity, and has a familiar feel and aesthetic.

Tangible Landscape typically uses familiar, everyday materials – like sand and wooden blocks – for modeling. Interactions – sculpting sand and moving wooden blocks – are analogous to everyday tasks so users should subconsciously knows what to do and how to do it, leveraging existing sensorimotor schemas. The materiality – the feel, look, and physics – of the media matters. The choice of material can afford different interactions and mediate meaning, emotion, and motivation. We typically use a polymer-enriched sand for the physical model so that users can easily sculpt forms in a medium that will hold its shape, has good plasticity, and has a familiar feel and aesthetic. Because polymeric sand can easily be cast in molds and will be hold its form, we use computer-numeric control (CNC) machined or 3D printed molds to cast polymeric sand into precise models (Fig. 4.

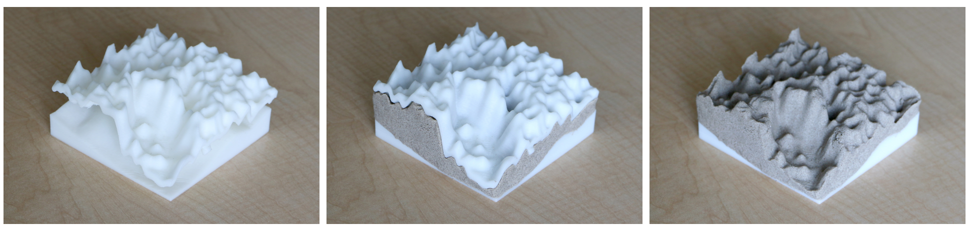

Fig. 4. Casting polymeric sand with 3D printed molds

Applications. Landscape planning applications include stormwater management, flood control, landscape management and erosion control, trail planning, viewshed analysis, the assessment of solar potential, and subsurface visualization. Landscape change applications including urban planning, sea level rise adaption, wildfire management, disease management, and invasive species management [**?**]. These applications draw upon GRASS GIS's libraries of sophisticated models and simulations such as the FUTure Urban – Regional Environment Simulation – a patch-based, stochastic, multi-level land change modeling framework [**?**; **?**].

2.2. Coupling experiment

2.3. Analytics experiment

2.4. Case studies

We hosted a participatory modeling workshop using Tangible Landscape as part of North Carolina State University Library's Coffee & Viz series. In this interactive seminar participants explored complex environmental problems by playing serious games. In the games participants used simple tangible interactions to computationally steer simulations, to drive simulated environmental processes. In one game participants managed the spread of termites across a city by treating city blocks. To treat a city block they placed wooden cubes representing preventive treatments on the game board leveraging basic motor skills from childhood play (Fig. **??**). In the other game participants tried to save houses from coastal flooding by building coastal defenses. To build defenses they sculpted dunes out of polymeric sand again leveraging motor skills from childhood play (Fig. **??**). Participants were able to naturally interact with a statistical epidemiological model and a flood simulation. Because the interactions were so simple

they were able to iteratively explore the behavior of multidimensional environmental processes unfolding in time and space.
(Fig. 5)

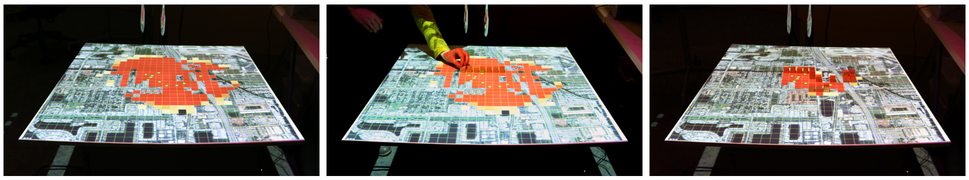

Fig. 5. Managing the simulated spread of termites through a city with Tangible Landscape

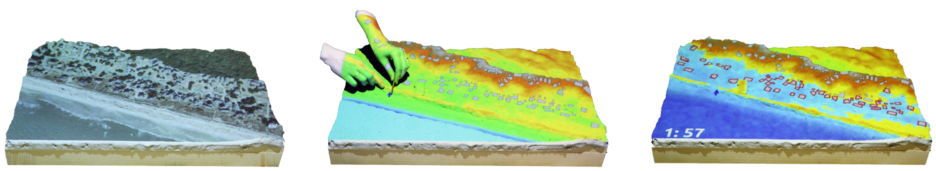

Fig. 6. ...

3. RESULTS

4. DISCUSSION

4.1. Design guidelines

[**?**]

5. FUTURE WORK

Figure 7 . . .

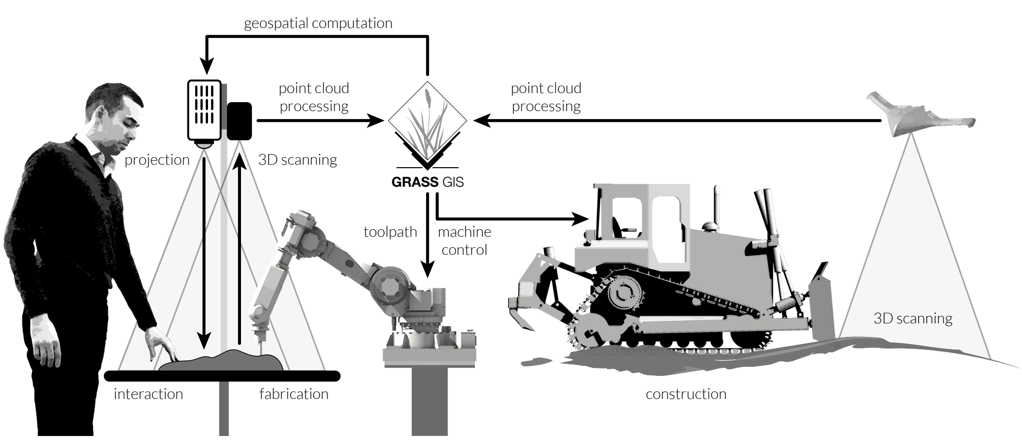

Fig. 7. Tangible Landscape with robotic fabrication, robotic construction, and real-time field data

6. CONCLUSION

APPENDIX

In this appendix ...

ELECTRONIC APPENDIX

The electronic appendix for this article can be accessed in the ACM Digital Library.

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REFERENCES

Paul Dourish. 2001. *Where the action is: the foundations of embodied interaction*. MIT Press, Cambridge, MA.

Itiel E Dror and Stevan Harnad. 2008. Offloading cognition onto cognitive technology. In *Cognition Distributed : How Cognitive Technology Extends Our Minds*. John Benjamins Publishing Company, Chapter 1. http://discovery.ucl.ac.uk/48379/

Frank O. Gehry. 2004. *Gehry draws*. MIT Press, Cambridge, MA.

GRASS Development Team. 2016. GRASS GIS. (2016). https://grass.osgeo.org

Benoit Hardy-Vallée and Nicolas Payette. 2008. *Beyond the Brain: Embodied, Situated and Distributed Cognition*. Cambridge Scholars Publishing, Newcastle, UK.

Hiroshi Ishii. 2008. Tangible bits: beyond pixels. In *Proceedings of the 2nd international conference on Tangible and embedded interaction - TEI '08*. ACM Press, xv–xxv. DOI:http://dx.doi.org/10.1145/1347390.1347392

Hiroshi Ishii and Brygg Ullmer. 1997. Tangible bits: towards seamless interfaces between people, bits and atoms. In *Proceedings of the SIGCHI conference on Human factors in computing systems - CHI '97*. ACM Press, 234–241. DOI:http://dx.doi.org/10.1145/258549.258715

Marc Jeannerod. 1997. *The Cognitive Neuroscience of Action*. Blackwell, Cambridge, MA. 236 pages.

David Kirsh. 2013. Embodied cognition and the magical future of interaction design. *ACM Transactions on Computer-Human Interaction* 20, 1 (2013), 3:1–3:30. DOI:http://dx.doi.org/10.1145/2442106.2442109

Marcia C Linn and Anne C Petersen. 1985. Emergence and Characterization of Sex Differences in Spatial Ability : A Meta-Analysis. *Child Development* 56, 6 (1985), 1479–1498. DOI:http://dx.doi.org/10.2307/1130467

Angelo Maravita and Atsushi Iriki. 2004. Tools for the body (schema). *Trends in Cognitive Sciences* 8, 2 (2004), 79–86. DOI:http://dx.doi.org/10.1016/j.tics.2003.12.008

Sydney Pollack. 2006. Sketches of Frank Gehry. (2006).

Roger N Shepard and Jacqueline Metzler. 1971. Mental Rotation of Three-Dimensional Objects. *Science* 171, 3972 (1971), 701–703. http://www.jstor.org/stable/1731476

D. H. Uttal, D. I. Miller, and N. S. Newcombe. 2013. Exploring and Enhancing Spatial Thinking: Links to Achievement in Science, Technology, Engineering, and Mathematics? *Current Directions in Psychological Science* 22, 5 (2013), 367–373. DOI:http://dx.doi.org/10.1177/0963721413484756

Albena Yaneva. 2009. *Made by the Office for Metropolitan Architecture: an ethnography of design*. 010 Publishers, Rotterdam, Netherlands.

Online Appendix to: Embodied Spatial Cognition in Tangible Computing

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A. HOW-TO-BUILD

A.1. Hardware

Table I. Hardware

Type	Product	Cost
Computer	System 76 Oryx Pro	$1500
Projector	Optoma ML750 WXGA 700 DLP LED	$500
3D sensor	Xbox One Kinect	$100
	Kinect Adapter for Windows	$50
Stand	Avenger 40-Inch C-Stand with Grip Kit	$200
	Avenger 40-Inch C-Stand with Grip Kit	$200
	Avenger F800 3-Inch Baby Wall Plate	$10
	Avenger F800 3-Inch Baby Wall Plate	$10
Peripherals	HDMI cable	$10
	Extension cord	$10
Modeling media	Waba Fun Kinetic Sand 11 Lbs	$50

A.2. Data sources

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Table II.
Data
sources

Data type	Data source	Link
Lidar	United States Interagency Elevation Inventory	http://coast.noaa.gov/inventory/
	Earth Explorer	http://earthexplorer.usgs.gov/
	Digital Coast	http://coast.noaa.gov/dataviewer/
	Open Topography	http://www.opentopography.org/
Digital Elevation Models	National Elevation Dataset	http://viewer.nationalmap.gov/viewer/
Orthoimagery	USGS EROS Orthoimagery WMS	http://raster.nationalmap.gov/