Navigation Techniques for Large-Scale Astronomical Exploration

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ABSTRACT

Navigating effectively in virtual environments at human scales is a difficult problem. However, it is even more difficult to navigate in large-scale virtual environments such as those simulating the physical Universe; the huge spatial range of astronomical simulations and the dominance of empty space make it hard for users to acquire reliable spatial knowledge of astronomical contexts. This paper introduces a careful combination of navigation and visualization techniques to resolve the unique problems of large-scale real-time exploration in terms of travel and wayfinding. For large-scale travel, spatial scaling techniques and constrained navigation manifold methods are adapted to the large spatial scales of the virtual Universe. We facilitate large-scale wayfinding and context awareness using visual cues such as power-of-10 reference cubes, continuous exponential zooming into points of interest, and a scalable world-in-miniature (WIM) map. These methods enable more effective exploration and assist with accurate context-model building, thus leading to improved understanding of virtual worlds in the context of large-scale astronomy.

Keywords: Virtual environments, astronomy, interaction techniques

1. INTRODUCTION

Navigation among astronomical bodies is not a new concept. Independently in the West and the East, ancient astronomers grouped bright stars into constellations to form landmarks in the night sky; with these landmarks, they could locate and describe heavenly events. With advances in modern astronomy, our knowledge of the Universe is no longer limited to two-dimensional panoramic space. We now have highly detailed three-dimensional data not only for the solar system, but also for stars, the Milky Way, extra-solar planets, and distant galaxies. These exciting advances have transformed our perceptions and lifted us beyond the two-dimensional sky to a fully three-dimensional description of the physical Universe. However, simulating such a virtual environment is a very different task from that posed by conventional virtual environments at human scales. Due to the huge spatial range and the dominance of empty space intrinsic to astronomy, it is quite challenging for users to acquire spatial scale context and to perceive the spatial relationships among the astronomical bodies being simulated.

Navigating through a 3D virtual environment integrates two activities: a lower-level, motor activity for controlling the position and orientation of the viewpoint, called *travel*, and a higher-level, cognitive activity that constructs and retains mental models for paths through the environment, called *wayfinding*. Travel is the most common interaction technique for large-scale 3D environments, and has been widely studied. A major challenge of 3D travel is mapping the control values of the input device to the parameters of a virtual camera model. To address this need, a number of travel-interface metaphors have been developed, including: "walking" and "flying" interfaces,[1] target-selection methods,[2] and "world-in-hand" metaphors.[3,4] Bowman et al. have proposed a taxonomy for classifying the components of travel techniques along with methods for evaluating their effectiveness.[5] The issue of speed control is particularly important for environments that are very large or sparse. Mackinlay et al. were among the first to describe a general and effective method for rapid, controlled movement in such 3D environments.[6] Wayfinding, in contrast, is the cognitive process of defining a path through an environment while using and acquiring spatial knowledge; the work of Darken and Sibert,[7] for example, showed how environmental design principles are effective for designing large-scale virtual worlds to support wayfinding.

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Applicable wayfinding techniques for virtual environments include the following: providing integrated maps and markers; incorporating landmarks and cues into the environment; and providing a consistent hierarchical structure to organize the environment.

Position and orientation constraints are common and essential components of many computer interfaces, ranging from desktop window managers to 2D drawing programs and 3D modeling packages. Constraints are also a natural and important part of the human experience in navigating the natural world, providing the basis for walk-based viewers and forbidden domains based on collision detection. A more flexible constrained travel method was first described by Galyean, who proposed the use of an arbitrary 1D guide path for users to control orientation and distance from the path.[8] Hanson and Ma developed a method for context-driven control of viewpoint position and orientation as the user travels across the 2D surface of a mathematical manifold.[9] Hanson and Wernert later generalized these ideas into a family of methods that allow customized navigation through any 3D environment based on the design of an integrated set of auxiliary 2D navigation manifolds.[10]

This paper focuses on handling navigation in large-scale virtual environments, realized in the context of astronomy. Techniques are divided into two categories: *travel* and *wayfinding*. Section 3 focuses on techniques for *travel* in large-scale virtual environments, while Section 4 focuses on developing spatial cues for facilitating the *wayfinding* process. Section 5 presents the system implementation, and Section 6 presents the conclusions.

2. CHARACTERISTICS OF ASTRONOMICAL NAVIGATION

Before presenting our travel and wayfinding techniques, we discuss the characteristics of astronomical navigation to provide motivation, context, and justification, so the reader can better understand the nature of the problem. The real issues of scale are clearly exposed by examining Table 1, which helps us realize that the navigational environment involves objects placed at huge distances, huge ranges of distances, and with huge empty spaces between objects that are small relative to their separations. Curiously, these features are just as true for atomic and string-theory scales, where we find enormous empty scale ranges, as for astronomical objects.

Table 1. Base 10 logarithms of scales of typical objects in the physical Universe in units of meters.

Typical objects	Powers of 10 (m)	Typical objects	Powers of 10 (m)	Typical objects	Powers of 10 (m)
Known Universe	27	Distance to nearby stars	17	Human	0
Super-cluster	25	Solar system	13	Micro-Organisms	-4
Clusters of galaxies	24	Orbit of Jupiter	12	DNA Structure	-8
Within Virgo cluster	23	Venus, Earth, and Mars	11	Carbon Atom	-9
Distance to Andromeda	22	Earth-Moon distance	9	Carbon Nucleus	-14
Milky Way diameter	21	Earth diameter	7	Quarks	-16
Distance to Orion arm	19	San Francisco	4	Planck length (string theory)	-35

◇ *Adaptive Navigation Speed* The first challenge of astronomical navigation is the conundrum of navigation speed. To make transitions from nearby objects to reach faraway targets, we have to radically adjust the simulated navigation speed for different situations and user goals. Although there are very interesting issues involved in correctly simulating special relativity and the effects of the finite speed of light, this is a distinct issue from that of designing effective astronomical travel: the sheer practical necessity of providing the user with spatial context within reasonable times and with comprehensible geometric images means that we essentially have to ignore the finite physical speed of light and allow arbitrary speeds during navigation to accomplish our principal objectives.

◇ *Losing Spatial Context in Empty Spaces* Since the Big Bang, the Universe has expanded through several eras, and is now a thousand times larger than it was when the "first light," now the 3-degree cosmic microwave background radiation, was emitted to find its way to our instruments. Because of this enormous expansion, as well as the gravitational clustering of matter into dense regions, cosmological space is mostly empty; as a result, unlike conventional environments in which we can typically identify landmarks and paths, it is very hard for users to assimilate spatial context knowledge in astronomical environments. Furthermore, scale context is difficult to handle because it is easy, even natural, in a simulation to make it seem that the distances among planets are the same as distances among stars if the travel speeds are exponentially scaled for convenience and flexibility.

◇ *Data are Earth-Centered* Because we are restricted to capture astronomical data from Earth, Earth-orbiting satellites, or spacecraft inside the solar system, datasets such as the Hipparcos star catalog[11] and the Nearby Galaxies Catalog[12] are essentially Earth-centered. This feature of the real data makes it natural to actually navigate in an Earth-centered (or at least Sun-centered) space.

◇ *Field-of-view and Motion Sickness* Finally, we have to pay attention to the field-of-view during the navigation. When using a narrow field-of-view in a virtual exploration, we have to slow down the panning speed so that our view on the computer screen does not change too rapidly and produce motion sickness.[13,14] The other extreme occurs for a very large field-of-view such as a planetarium dome; since a dome image fills most of the human visual field, small changes in the viewing direction are very obvious in the dome and we also have to carefully limit the panning speed and viewing parameter changes to avoid motion sickness.

3. TECHNIQUES FOR TRAVEL

3.1. Navigation Models in the Context of Large-scale Travel

In the previous section, we pointed out various problems concerning astronomical navigation with the intent of convincing the reader that an unaided or unconstrained navigation model is indeed inadequate for astronomical travel. To resolve the noted problems, we must now address the question of designing appropriate constraints and visualization systems for this context. This section goes over a series of five navigation models in the context of astronomical navigation. The first two are conventional models available in most applications, while the last three are models we tailored specifically for large-scale travel. Note that the chosen order corresponds to the complexity of these models, and models with higher complexity can be implemented in sequence on top of the lower models.

◇ *The Unaided Navigation Model*[1] The first model is the "unaided navigation model," or the "walking and flying viewer." We avoid calling it a "free" or "unconstrained" model because there are still significant constraints imposed by the user interface (2D mouse-based controls, selection of center of rotation, etc.). On the other hand, the word "unaided" does not mean that there is no navigation restriction in the model. Rather, it refers to the fact that no specific aid is given for large-scale navigation. One familiar example of such an interface is the VRML browser,[1] whose basic navigation controls include *Walk*, *Fly*, and *Examine* (or *Study*); in practice, using these controls is fairly effective for navigation in common 3D environments or when examining individual 3D objects. However, in the context of astronomical navigation, this navigation approach is definitely inadequate due to the navigation speed problem and the spatial context perception problem.

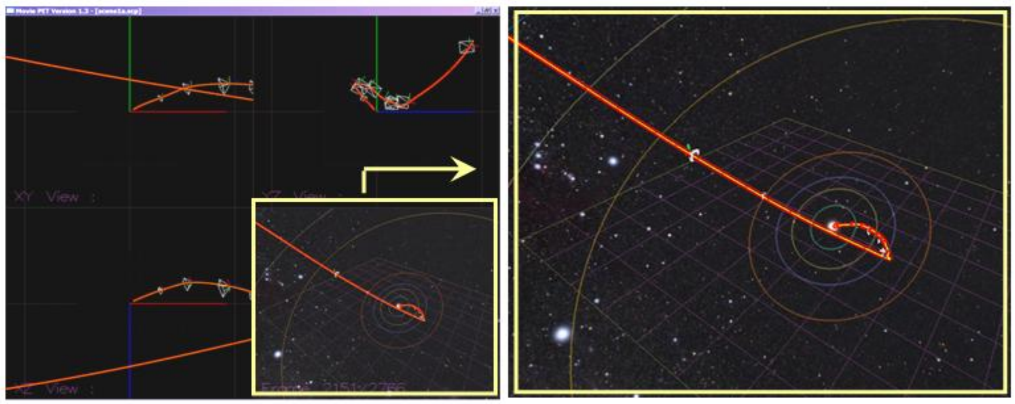
◇ *The Select-and-Go Navigation Model* To carry out large-scale navigation in a simulated Universe, most applications such as Celestia[15] and the Digital Universe (based on partiview)[16,17] provide the *select-and-go* function in the user interface: Users can select target objects through a menu or the mouse, and the system smoothly interpolates the user's viewpoint from the current position to the target object during the next few seconds. This is a productive approach for large-scale travel as a supplement to an unaided model. However, because the user is transported directly to the target, there is still a nontrivial loss-of-spatial-context problem when traveling across large distances. An add-on feature to this model is *tethering*, which attaches the user viewpoint (as a virtual camera or spacecraft) to the selected target and maintains a virtual orbit at fixed distance from the target.

◇ *The Spatial Scaling Navigation Model* Although the basic user controls provided by the spatial scaling model are generally the same as those in the unaided model, our approach adds a powerful functionality to support large-scale navigation — *spatial scaling*. Our principal spatial scaling paradigm is embedded in large-scale rendering strategy through an enhancement of the OpenGL transformation framework. By introducing a scale variable $s_{\rm mv}$ as a relative spatial (logarithmic) scale associated with the generic modelview transformation, we can generalize the translation component of the modelview matrix as follows:

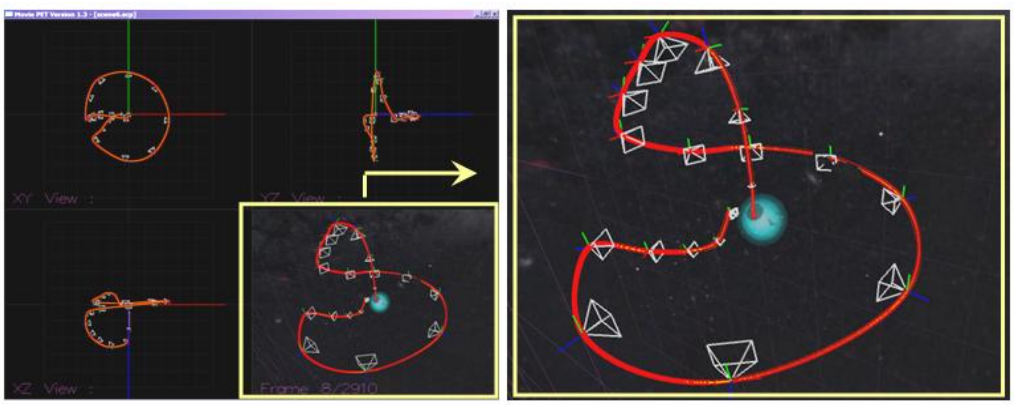
$$\text{Modelview translation, } \mathbf{T} \quad = \quad (T_x, T_y, T_z)^t \times 10^{s_{\rm mv}} \ .$$

Thus, a distance of one abstract unit in the virtual environment corresponds to $10^{s_{\rm mv}}$ physical units (typically meters) in real space. In other words, by adjusting $s_{\rm mv}$, we scale the entire simulated Universe's data space relative to the virtual space.

During large-scale travel, this method allows interactive traversal of datasets with vastly different spatial scales. Users can directly adjust $s_{\rm mv}$ to a specific appropriate value to look at the Earth, the local stars, or the galaxy clusters. Though this scaling method looks similar to the object scaling method in Mine, et al.,[18] the spatial scaling method is performed in logarithmic scale relative to any object defined in the global physical space. Furthermore, since we scale the entire data space relative to the navigation space (where the camera travels), we never have to worry about the navigation speed; we always navigate at a reasonable abstract (rescaled) speed in the virtual navigation environment while all models are scaled relative to this fixed camera scale. Another appealing feature is that this spatial scaling framework meshes perfectly with the previous two models; we can employ the tethered target in the select-and-go model as the fixed point for spatial scaling, so whenever the user switches the tethering target, we alter the fixed point accordingly.



(a) From the solar system to the Milky Way Galaxy



(b) Around the Loop I Bubble ($\sim 10^{18}$ m)

Figure 1. Editing navigation paths in a large-scale astronomical environment.

◇ *The Path-based Navigation Model* The path-based navigation model further enhances the previous models by providing navigation paths in the virtual environment. Unlike camera paths in conventional animation systems, the paths offered by the path-based model must span enormous scales to support guided tours[8] across the cosmos. Particular care is required for position representation and interpolation so that the guide paths are smooth and well-defined in the entire cosmological space. Figure 1 shows our path editing program with some typical navigation paths. The path shown in (a) starts from the Sun, passes the Earth, and extends beyond the Milky Way galaxy. The path shown in (b) is a local path around a supernova remnant at a scale of 10^{18} meters. Note that the spatial scaling method serves as a powerful tool in the path editing process because it enables us to quickly traverse different scales between successive keyframes.

The advantage of using navigation paths for astronomical exploration is obvious. First, it helps to alleviate the lost-spatial-context problem because addition spatial context for wayfinding is provided at each step of the navigation path. Furthermore, users can choose to stay on the path, and let the system guide them along their way, or they can detach their virtual spacecraft from the canonical path and navigate around any selected object of interest. The tethering target is no longer restricted to a particular object in the space. Rather, it can be any point along the navigation path. Finally, the use of navigation paths in large-scale exploration enables astronomers to plan and share the exploration context more efficiently.

◇ *Constrained Navigation: The Manifold-based Model*[10] The constrained navigation model[10] can be understood as a generalization of the path-based model offering the design of one or more 2D "sidewalks" that define the 3D spatial motion of the camera (viewpoint) parameters in response to inputs in a limited controller space such as that of a mouse or the CAVE joystick. Since the response of the user displacement to a unit of controller motion can be completely controlled and customized by the fields stored with the navigation manifold, we can easily adapt the motion response to meet the user requirements of large-scale navigation.

In particular, it is obvious that a "Powers of ten," i.e., logarithmic, scaling of the response is the natural choice: the farther we get from the tethering target, the lower the density of detailed observational data, and the larger the scale of the visible structures that are interesting to depict. Furthermore, using two-dimensional navigation manifolds brings additional flexibility to astronomers when sharing exploration context and visualization information.

3.2. Moving the Camera in Large-scale space

In order to implement the above navigation models for large-scale travel, particular care is needed for both position representation and position interpolation.

◇ *Position Representation* It is easy to arrive in situations in systems such as Celestia that trigger arithmetic precision errors and, e.g., cause orbiting bodies to jump back and forth in the scene due to the state of the hardware matrix computation. Our design addresses and solves this problem. To handle the demands of scenes with extreme spatial scales and to avoid floating-point precision limitations, spatial quantities such as coordinates and vectors are stored in an extended logarithmic form using a data representation we called *power homogeneous coordinates* (PHC).[19] Similar in apparent form to homogeneous coordinates, power homogeneous coordinates are a four-tuple,

$$(x,y,z,s) \textit{ representing } 3D \textit{ position } (x,y,z)\times k^s \ ,$$

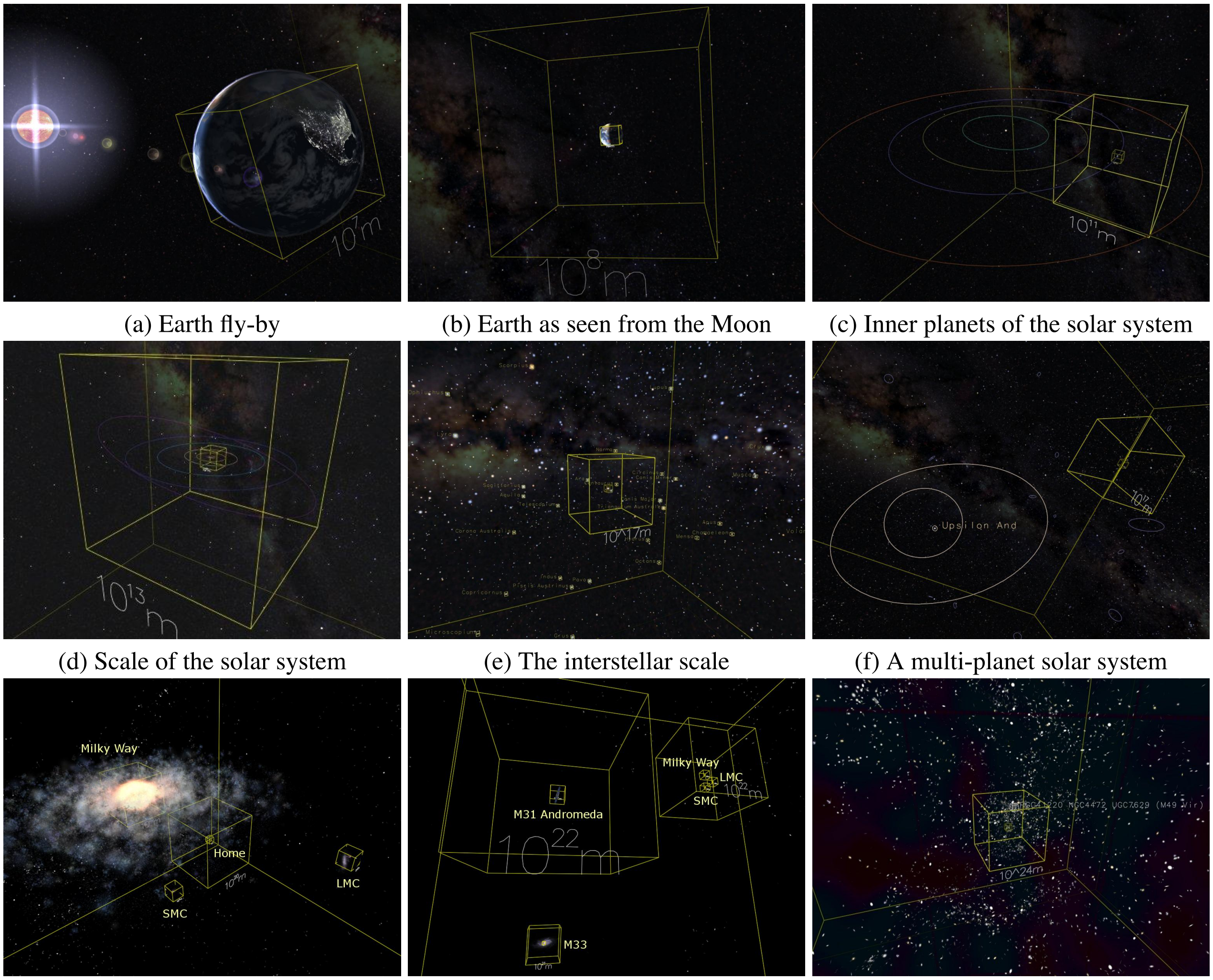
where k is any positive exponent base, usually chosen as 10. Using this representation, we can nicely decouple the *directional term* (x,y,z) and the *exponential term* s from the given 3D coordinate so that we can effectively represent digital models of objects at super-galactic or sub-atomic scales in a uniform fashion. Note that a PHC is said to be *normalized* if its *directional term* is a unit vector.

◇ *Position Interpolation* We now exploit the PHC representation to interpolate camera locations precisely along our navigation path (or manifold). If we convert PHCs to standard 3D coordinates and move by applying linear interpolation in 3D, we have a problem when positions span large spatial ranges, since linear interpolation in 3D may produce abrupt acceleration or deceleration with exponentially separated keyframes. The following three methods address this interpolation problem:

- Linear Interpolation in 4D — This scheme is an intuitive solution in which camera locations are stored as normalized PHCs and interpolated as if they are 4D coordinates. As a result, we can effectively smooth the interpolation between keyframes having large scale differences; whenever we return to local path navigation, we can revert to ordinary 3D interpolation.

- Speed Parameterization — Although linear interpolation in 4D smooths large-scale transitions across spatial ranges, the points at which we switch interpolation schemes are non-differentiable and the motion could be very jumpy. The speed parameterization method avoids the interpolation switch by 1) applying uniform speed parameterization to the navigation path and 2) re-sampling the path by using additional speed-time information provided by the user. In this way, the navigation speed can be smoothed and tuned.

- Tension Control — If camera animation is needed, the camera has to pass through specific keyframes at some specific moments so that the animation can properly tell its story. However, if we use the speed parameterization method, the consistency between keyframes and time could be lost, and so this is not feasible for animation. We therefore propose the tension control method to control speed along a large-scale animation path. This method is based on the tension control mechanism[20] used for Catmull Rom splines, and the designer can adjust the speed or step sizes locally in the animation path by tuning tension values at the keyframes.



(a) Earth fly-by (b) Earth as seen from the Moon (c) Inner planets of the solar system

(d) Scale of the solar system (e) The interstellar scale (f) A multi-planet solar system

(g) The Milky Way, LMC, and SMC (h) The Local Group (i) The Near Galaxies Catalog

Figure 2. Powercubes: revealing spatial context in a powers-of-ten journey from Earth, to the solar system, to the Milky Way Galaxy, and finally to the intergalactic scale. The journey goes from 10^7 meters up to 10^{24} meters along the navigation path shown in Figure 1(a).

4. TECHNIQUES FOR WAYFINDING

Our techniques for large-scale travel must be accompanied by visualization strategies to maximize the exploration power both in terms of performance and spatial perception. This section presents three visualization methods to facilitate the wayfinding process.

4.1. Powercubes: Power-of-10 Reference Cubes

In 1977, Charles and Ray Eames produced a ten-minute film, "Powers of Ten,"[21,22] showing a virtual journey across the scales of the Universe, from nuclear scales up to extra-galactic scales; the film itself was a motion picture version of the 2D images in an earlier book, *Cosmic View,* by Kees Boeke.[23] The film employs a hierarchy of nested squares to mark regions of space at each powers-of-ten scale. Inspired by this elegant idea, we extend the use of nested squares to nested cubes, namely powercubes, for virtual exploration in large-scale three-dimensional space. The major advantage of using cubes to enrich spatial context is that since all sides have the same length and neighboring sides are orthogonal, we can nicely expose the spatial context enclosed by the cubes and compare spatial scales using concentric cubes. Figure 2 presents an abbreviated powers-of-ten journey through a simulated Universe to demonstrate the advantages of powercubes. In general, there are three ways of using powercubes:

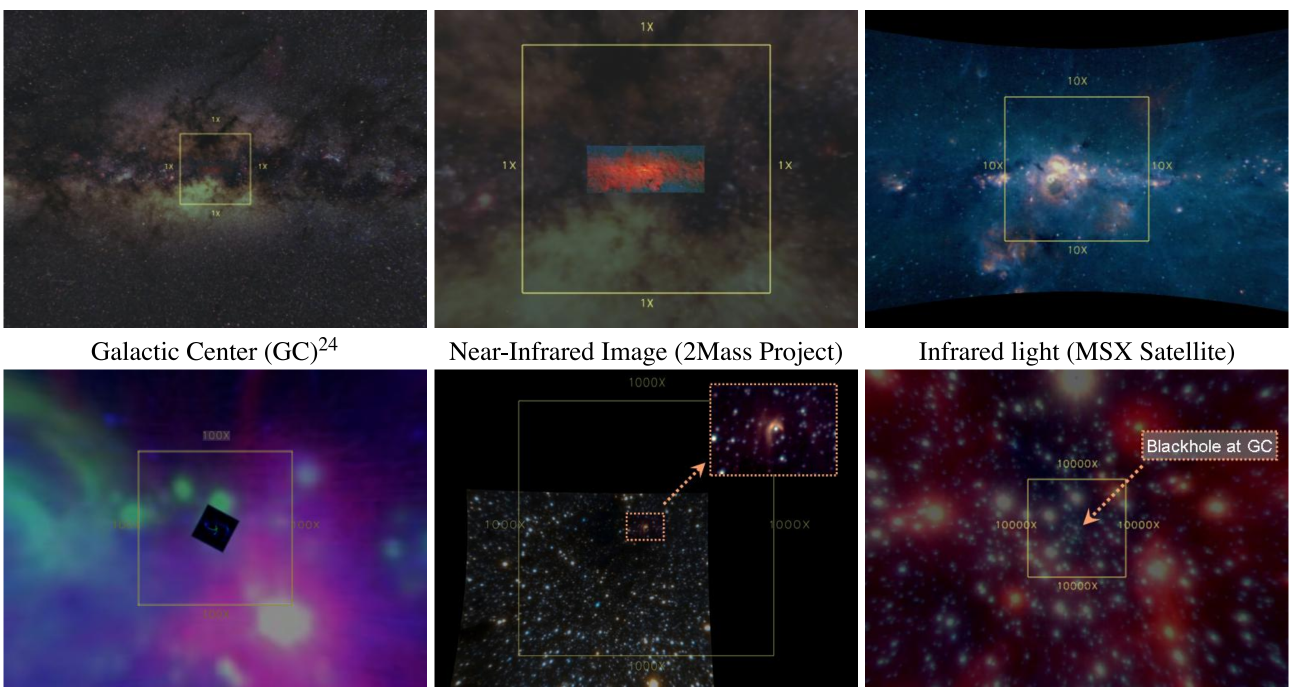
◇ *Earth-centered (or Solar-centered) Powercubes* First, based on the Earth-centered property of astronomical data (see Section 2), we can center the powercubes at the Earth or at the Sun. In this way, during the spatial scaling process, we can readily explore the spatial context related to datasets at different scales.

◇ *Tethering-Target-Centered Powercubes* Second, powercubes can annotate spatial context around the tethering target. During a target switch in the select-and-go model, we can display one set of powercubes around the source object while we are departing from it, and during the journey, we can gradually fade out the powercube set around the source and fade in another set around the destination. This method helps reveal the context of otherwise empty space.

◇ *Eccentric use of Powercubes* Third, multiple sub-cubes can be arranged within a common powercube at a higher hierarchical level, see Figures 2(g) and (h). More spatial information within the space enclosed by the larger powercube can be exposed, and spatial proximity information can be emphasized by the eccentric cubes. This technique can be further extended to include road signs to different navigation paths or manifolds in a large-scale navigation tree.

4.2. Powerzoom: Powers-of-Ten in Field-of-View

The Powerzoom visualization technique addresses the field-of-view problem in astronomical exploration. With recent advances in imaging technology, very high resolution images of many significant astronomical objects have become available. By analogy to powers-of-ten scaling in space, we propose the related *powerzoom* approach to explore rescaling in the angular field-of-view domain. Figure 3 displays a typical powerzoom sequence toward the Galactic center from 10 degrees down to 0.001 degrees. The powerzoom warping is particularly spectacular when we apply it in a planetarium environment; however, in order to implement the effect correctly, we have to take into account the precision limit in the projection transformation, and this may require warping images of small angular sizes so the projection transform never falls below the matrix computation limit.



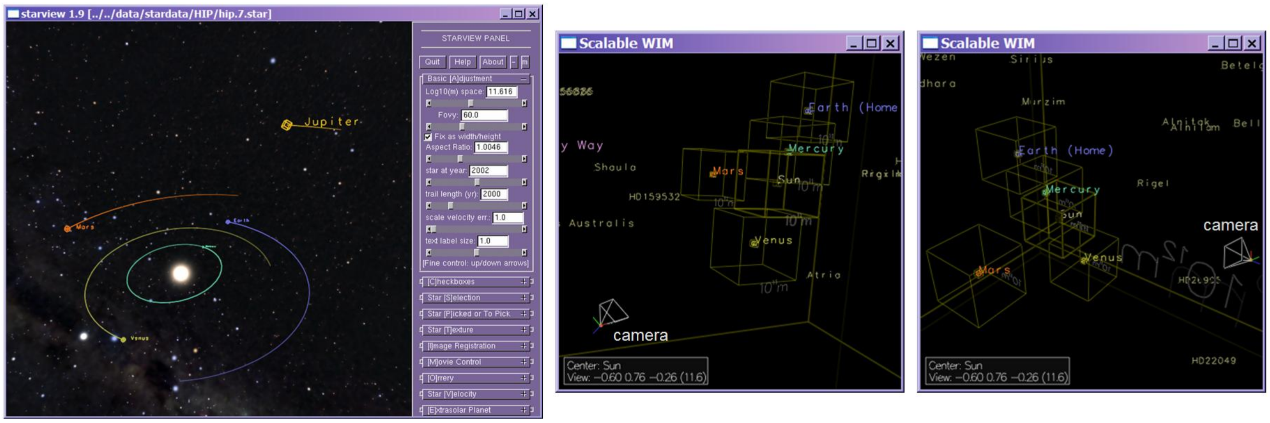
Galactic Center (GC)[24] | Near-Infrared Image (2Mass Project) | Infrared light (MSX Satellite)

Multiwavelength Image (Chandra) | Bow Shock Near GC | Central Black Hole at GC

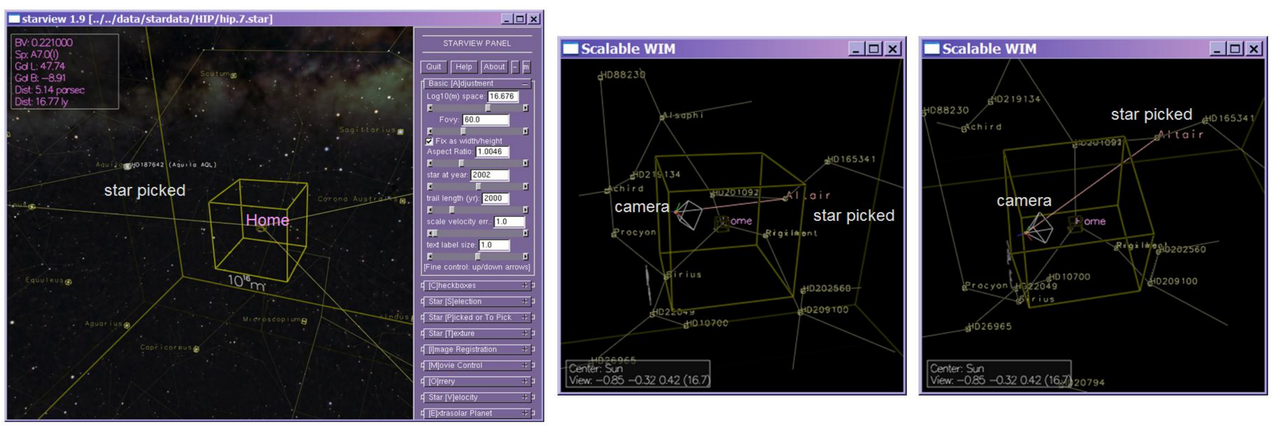
Figure 3. Powerzoom: Touring toward the Galactic Center (`1X` = 10 degrees field-of-view, `10X` = 1 degree, etc.).

4.3. Scalable WIM as a Navigation Map

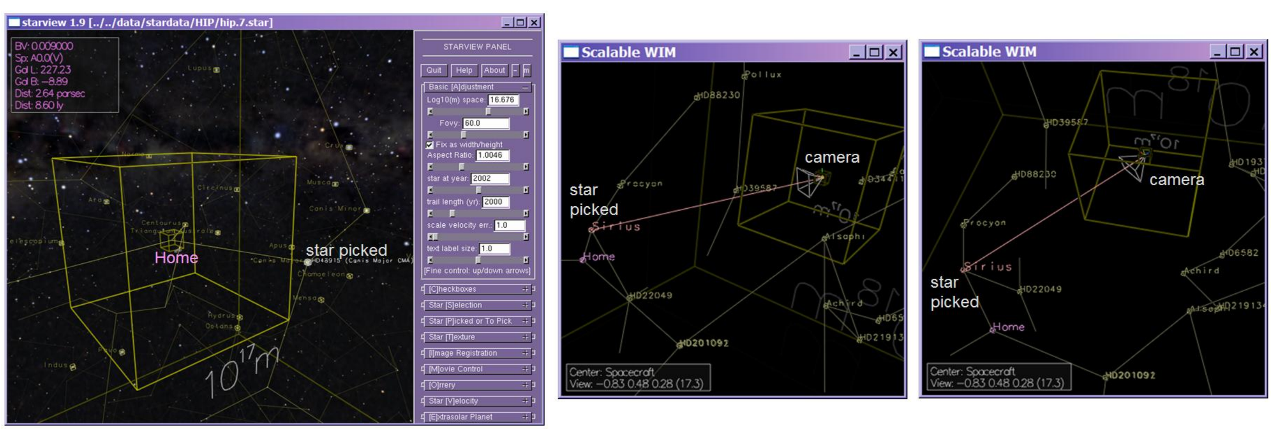
The scalable world-in-miniature (WIM) technique[3,4] abstracts the structure of the virtual space around the camera in the form of a visual map. Users can look into the virtual space around the camera from a third person perspective, and make use of the WIM to control the camera view in the virtual simulation as well as to navigate through the virtual space by manipulating the camera icon in the WIM. For ease of identification, objects such as planets and stars are represented as text labels or icons in the WIM space.



a) WIM of the solar system



b) WIM centered at the Sun



c) WIM centered at the spacecraft

Figure 4. The Scalable WIM is a large-scale three-dimensional visual map providing camera viewing and control from a third person perspective. By showing a minimum spanning tree for stars around the camera (see (b) and (c)), the spatial proximity among nearby objects can be nicely exposed to the users while they manipulate (rotate or scale) the WIM.

Unlike conventional WIMs that are mostly two-dimensional and work in a uniform spatial scale, the proposed scalable WIM is a large-scale three-dimensional map equipped with spatial scaling control. Users can center the WIM at the Sun, at the camera position or at any selected target, and perform spatial scaling so that the entire WIM space is scaled logarithmically. The WIM approach provides a third person perspective to the users so that they can control the camera view in the virtual simulation while examining the large-scale virtual environment surrounding the camera. To effectively represent the changing spatial domain in proximity to the camera, we construct a minimum spanning tree through all objects in the virtual world. Just like a 3D search light, when the camera moves in the space, the part of the tree connected to objects near to the camera is rendered in the WIM, while distant objects beyond the local domain are culled. Thus we can expose the spatial neighborhood of the camera without information clutter. Figure 4 shows screen shots of scalable WIMs at different scales. The left column shows the renderings of the virtual simulation, while corresponding scalable WIMs on the right represent the same environment but from a third person perspective. Note that in order to have proper rendering in the WIM space, we also have to incorporate PHC representation and computation for objects in the WIM space.

5. IMPLEMENTATION AND DISCUSSION

In order to serve as a flexible development platform for making applications and animations, the structure of the visualization system we developed for astronomical exploration is module-based. There are four kinds of modules in the system:

The PHC Module This module offers a library API for large-scale representation and transformation using PHCs. Two versions are provided: a GPU-based implementation using OpenGL shaders and a software implementation mimicking the shader computation.

Modeling and Rendering Modules For efficiency and scalability, we maintain individual modules for different types of astronomical objects, e.g., galaxies, the Milky Way Galaxy, stars, the solar system, etc. Each module contains its own data loader and a corresponding PHC-based renderer.

The Navigation Module The navigation module implements the travel and wayfinding strategies presented in this paper:

- Travel: Built upon the PHC module, this sub-module supports the navigation models mentioned in Section 3 and allows large-scale camera placement and movement without encountering floating point precision problems.
- Wayfinding: This sub-module implements the wayfinding strategies presented in Section 4: Powercubes, Powerzoom, and the Scalable WIM control for camera manipulation are included.

The Interface Module The main purpose of the interface module is to connect the rendering and navigation modules with the application layer (desktop computer, CAVE environment, etc.), and to optimize the rendering and navigation performance while efficiently processing user requests.

6. CONCLUSION

This paper presents a careful combination of navigation and visualization techniques for large-scale astronomical exploration. The techniques are divided into two categories: travel and wayfinding. In terms of travel, we proposed and implemented the spatial scaling method and the constrained navigation method for large-scale travel based on power homogeneous coordinates. These methods allow us to effectively position and interpolate camera coordinates without encountering floating point precision problems. On the other hand, to facilitate wayfinding in large-scale astronomical spaces, we created the powercubes and powerzoom techniques for exploring the spatial and angular context in terms of powers-of-ten scale annotation. Finally, we proposed the scalable world-in-miniature technique to create a user-friendly visual map. Users can quickly examine the camera parameters with respect to the local environment, and manipulate the camera view from a third person perspective.

There are many remaining refinements of our overall framework to investigate in the future. The travel–oriented methods would benefit from extending the concept of navigation paths and manifolds to be dynamic so that we can properly support complex object motions such as orrery motion in the solar system. As an enhancement to wayfinding, we would like to further explore the applicability of the scalable WIM, e.g., by separating the WIM from the main display, and implementing it on a tablet device or even a cell phone, permitting control of the virtual simulation on a large display system through remote manipulation on a pocket-sized WIM.

Acknowledgements

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Appendix: Web Availability

Interested readers are encouraged to visit the following web-site for accompanying videos demonstrating a powers-of-ten journey with powercubes and a powerzoom visualization sequence.

`http://www.cs.ust.hk/~cwfu/papers/largenav`