Multi-touch Techniques for Exploring Large-Scale 3D Astrophysical Simulations

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ABSTRACT
Enabling efficient exploration of large-scale virtual environments such as those simulating astrophysical environments is highly challenging. Astrophysical virtual worlds span exceptionally large spatial scales occupied mostly by empty space, and this makes it difficult for the user to comprehend the spatial context during exploratory navigation. Public exhibits, where novice users have little experience using complicated virtual navigation interfaces, pose additional challenges.

To address these issues, we propose multi-touch techniques to deliver an effective interface to navigate the unique features of large-scale 3D environments such as astrophysical simulations. In this work, we carefully study conventional multi-touch methods and adapt them to the practical requirements of this application. A novel technique called the powers-of-ten ladder is introduced to support efficient movement across huge spatial scales using multi-touch interactions. We also investigate user experiences with various multi-touch finger gestures on our prototype digital planetarium.

Author Keywords
Multi-touch interaction, large spatial scale, navigation control, astronomy

ACM Classification Keywords
H.5.2 Information interfaces and presentation: User Interfaces—*Interaction Styles*; J.2 Computer Applications: Physical Sciences and Engineering—*Astronomy*

General Terms
Design, Human Factors.

INTRODUCTION
Multi-touch is a user interaction technique typically used to manipulate graphical entities with multiple fingers at the same time. Due to their efficiency and ease of use, multi-touch methods have been rapidly commercialized in a number of products, including the Microsoft Surface, the Apple iPhone, the MacBook, and the DELL Latitude XT2. Multi-touch technologies revolutionize the way we can interact with information. Taking the Microsoft Surface [2] as an example, we see a replacement for traditional WIMP (window, icon, menu, and pointing device) interfaces; we can apply multi-touch to directly manipulate a wide range of digital content via physically-motivated contact and gestures.

1. Multi-touch contact: The surface can simultaneously recognize multiple contact points and actions;
2. Direct interaction: Users can actually grab digital information through touch and gesture;
3. Object recognition: Users can also place physical objects (with certain labels), such as cell phones or digital cameras, and trigger corresponding digital responses;
4. Multi-user experience: A large surface can allow multiple users to interact simultaneously on the same surface.

Multi-touch interactions can be seen as a significant step towards tangible user interfaces and ubiquitous computing. In particular, multi-touch interactions help to support direct manipulation of graphical entities on the screen so that users can more rapidly master interface control requirements for complex applications. Researchers and practitioners from a wide range of domains have started experimenting with and applying multi-touch methods; these include tabletop large map exploration [19], tabletop games and electronic entertainment [16], manipulation (and animation) of 2D graphical objects [24, 33], social learning and interactions [36] via a very large multi-touch screen, and interactions on handheld device interfaces such as the Apple iPhone [1].

While these are exciting examples demonstrating the effectiveness of multi-touch interactions in various application domains, most of the work we are aware of focuses on the manipulation of objects in 2D or 2.5D domains. Though some recent works [26, 40, 11, 9, 27, 13, 38] extend multi-touch methods to 3D objects and 3D scenes, the 3D virtual simulations being manipulated are still typically homogeneous in spatial scale.

In this paper, our main focus is to explore and design multi-touch methods for navigating in a very large-scale virtual environment such as the simulation of the astrophysical Universe. Note that the term “large-scale” in this paper typically refers to large spatial scale, such as the enormous spatial scale spanned by astrophysical data. Since the universe is gigantic in size and yet dominated mostly by emptiness

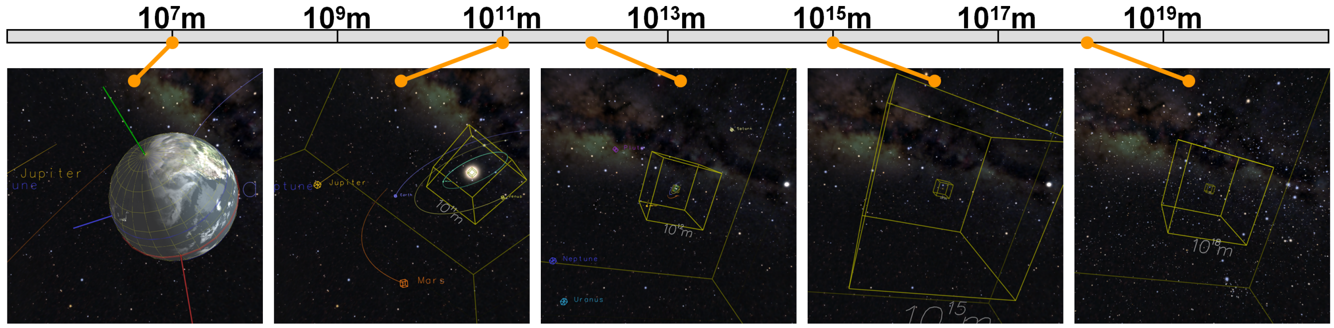

Figure 1. The spatial scale range covered by our experimental virtual simulation ranges from 10^7m to 10^{19}m. Environments include the Earth, the inner planets and outer planets of the solar system, as well as stars with three-dimensional positions at the local galactic interstellar scale (from left to right).

(see Figure 1), controlling 3D navigation in such a space involves various problems of motor control for spatial travel as well as the mental processing in wayfinding [10, 30]. Moreover, since such navigation controls usually involve elaborate mouse and keyboard actions, a traditional user interface is of limited suitability for a public exhibit, where the user control must be intuitive and quickly learnable. Hence, typical navigation/exploration controls are employed by domain experts, e.g., by having a show director to "drive" a real-time planetarium show. Users from the general public are normally provided only with simple controls such as touch-and-go or view rotation.

Aiming at enhancing the efficiency and user-friendliness of large-scale navigation, we propose to exploit multi-touch techniques for controlling the 3D navigation in virtual environments, containing physical data whose scales span many orders of magnitude. Major contributions of this work include the following;

- To our knowledge, this is the first multi-touch implementation supporting large-scale navigation; our target applications are virtual simulations of the astrophysical Universe;
- We introduce the powers-of-ten ladder method for efficient and intuitive navigation across huge spatial scales, along with five other multi-touch gestures tailored for navigation through large-scale simulated spaces;
- A complete working system for multi-touch astrophysical visualization has been developed; it includes the multi-touch hardware, a software system for multi-touch tracking and gesture interactions, and the astrophysical visualization system that delivers the rendered images.

RELATED WORK

While multi-touch methods are growing rapidly in popularity due to advances in recent commercial technology, it has a long history [6]. One early example is the work of Mehta [32] in 1982, which combined finger pressure, image capture, and simple image processing to create a drawing system supporting multi-touch input. Later on, Boie at Bell Labs engineered the first multi-touch screen using capacitive technology and numerous developments were reported [7, 28, 44, 18, 29, 12, 45, 39, 46, 22]. Among these, Wellner [44] built an environment that demonstrated tangible manipulation of virtual documents on a physical desk. Esenther et al. [15, 16] then developed the DiamondTouch SDK that supports multi-user and multi-touch interactions simultaneously on the same physical surface, which enables effective collaborative work among groups of people. Rekimoto [39] introduced a new sensor architecture called *SmartSkin* that makes interactive surfaces sensitive to both human hand and finger gestures, while Blaskó and Feiner [5] presented novel uses of a pressure-sensitive pad that simulates sliders and spinning wheels with their multi-strip design. Han [22] presented a novel design for multi-touch sensing using frustrated total internal reflection. The design is simple-to-implement, inexpensive, and scalable; and it also enables high resolution sensing. Subsequently Benko et al. [4] suggested a screen feedback mechanism to enhance the selection precision on multi-touch screens and Wang et al. [42, 43] devised a simple detection algorithm enabling the determination of both finger locations and their 2D orientations on the screen.

Recent work on multi-touch interaction focuses on the application of multi-touch to various display platforms as well as its adaptation to high-level applications. Jung et al. [26] presented a comprehensive hardware and software design that integrates multi-touch interactions into the framework of X3D. Steinicke et al. [40] explored the potential of multi-touch interactions in a stereoscopic display system, while Grossman et al. [21] presented a collection of hand gestures for interacting with a 3D volumetric display. More recently, Kim [27] applied multi-touch interactions on an iPhone to control walking movements in a 3D virtual environment, and Chang et al. [9] designed and implemented a very interesting origami modeling interface employing specially-designed multi-touch gestures. Reisman et al. [38] presented 2D screen-space multi-touch methods to realize traditional 3D Rotate-Scale-Translate controls. De la Rivière [11] built an interesting cube-shaped multi-touch device allowing users to perform Rotate-Scale-Translate multi-touch interactions independently on each cube face, where the resultant interaction applies to the 2D subspace corresponding to the orientation of the cube face being manipulated by the user. Edelmann [13] presented the DabR system, which is a robust multi-touch hardware environment exploring direct interaction to control 3D navigation.

Our main efforts in this work involve navigation, which typically involves two basic processes: *travel*, which controls the position and orientation of the virtual viewpoint, and *wayfinding* [10], the cognitive process that allows users to perceive landmarks and paths in the virtual environment. Basically, *travel* involves the mapping of control values from the input device to the parameters of a virtual camera model. A number of travel metaphors have been studied in the research community, including the select-and-go method [3], walking and flying [37], and the world-in-miniature (WIM) approach [41, 35]. Recently, Li et al. [30] adapted the WIM method to support large-scale navigation in astrophysical simulations. They applied indirect manipulation of an iconic object, called the Scalable WIM, which shows the third person view of the abstract local environment surrounding the viewer. Such methods can be quite effective at enhancing navigation efficiency for high-end users; however, the user controls are not highly intuitive user controls and are often hard-to-learn, particularly when the target users are from the general public.

CHARACTERISTICS OF LARGE-SCALE NAVIGATION

Navigation in large-scale virtual environments such as a simulation of the astrophysical Universe is very different from that in conventional virtual environments. Important unique features for this class of problems include:

- **Spatial scale.** Conventional virtual environments are mostly homogeneous in spatial scale, and the sizes of objects and the distances of camera movements are more or less within the same spatial scale, typically 10^{-1}m to 10^{1}m for a virtual apartment and 10^{1}m to 10^{3}m for a virtual campus. The spatial scale that a typical astrophysical simulation spans can, however, be much larger than that (see Figure 1), spanning dozens of orders of magnitude, as demonstrated in the Eames "Powers of Ten" animation [8]. The virtual world constructed for our application includes planets with a scale of 10^{7}m, solar systems [25] spanning 10^{13}m, and the Hipparcos stars [17, 31] encompassing an interstellar scale of 10^{19}m.
- **Data characteristics.** Since we can capture astrophysical data only from Earth, Earth-orbiting satellites, or spacecrafts inside our solar system, the available intrinsic data are Earth-centered (or Sun-centered for interstellar or intergalactic scales) in nature. Hence, we actually navigate in an Earth-centered (or Sun-centered) data space, which influences our choice of default rotation center in the multi-touch gesture design.
- **Adaptive travel speed.** We have to adaptively change the camera movement speed in a natural way appropriate to our current scale (e.g., the solar system or interstellar scale). We could address this issue by adopting input devices with huge dynamic range to control the traveling speed over a widely variable range, or by allowing the users to specify the desired speed themselves. These approaches are, however, not suitable for interactive applications designed for use by the general public. Hence, we adopt a method that takes the Sun as the reference (since astrophysical data are essentially Sun/Earth-centered), so that we can automatically adapt the traveling speed based on the distance between the reference and our virtual camera. Such a mechanism can, of course, be further generalized to allow users to alter the reference center, but this may complicate the navigation control for untrained users.

DESIGN ISSUES

Since we target our exploratory system for general-public users, we must address the following system design issues:

- **Intuitiveness of user interface control.** Multi-touch interaction methods are used instead of elaborate mouse-keyboard controls;
- **Easy-to-use and practical spatial navigation.** We provide automatic travel speed adaptation when exploring different spatial scales;
- **Ergonomics of human posture.** We consider the finger and hand posture (orientation, etc.) in the design of the multi-touch gestures;
- **Large display screen.** This work targets a large display screen with multi-touch support; the users should be able to perform the multi-touch gestures anywhere on the display screen.
- **Control-display rate.** Care is needed in tuning the rate of change of the display when mapping changes from the controlling device (finger movement) to the virtual camera movements. Large-scale changes must be restricted to be smooth and to lie within the range of human comfort.

MULTI-TOUCH FOR LARGE-SCALE NAVIGATION

As noted, virtual navigation in large-scale 3D astrophysical simulations is inherently complex due to the many possible view change options as well as the spatial scale range being explored. In traditional mouse-keyboard interfaces, navigation control options are typically specified with non-intuitive combination of keyboard strokes and mouse movements (with/without a button press). A pop-up menu is often called up by the user to help remember what combinations of keystrokes and mouse button controls have been preassigned to the different navigation options.

With multi-touch user interfaces and displays, new opportunities exist to design more intuitive user interaction techniques for navigation in large-scale 3D spaces. This section begins with a brief description of the multi-touch whiteboard-style display used in this work and the characteristics of different types of multi-finger gestures associated with this multi-touch interface. The interaction design and the functional mapping of various navigation operations to different finger gestures are then presented in detail.

Hardware: The multi-touch display

In this work, we built an upright whiteboard-style multi-touch display interface as illustrated on the left hand side of Figure 3 (see also Figure 2 for the real setup). It is a vision-based multi-touch system that illuminates (diffuses) the finger contact points using infrared laser light plane (LLP) emitters mounted at each of the four corners of the display. As

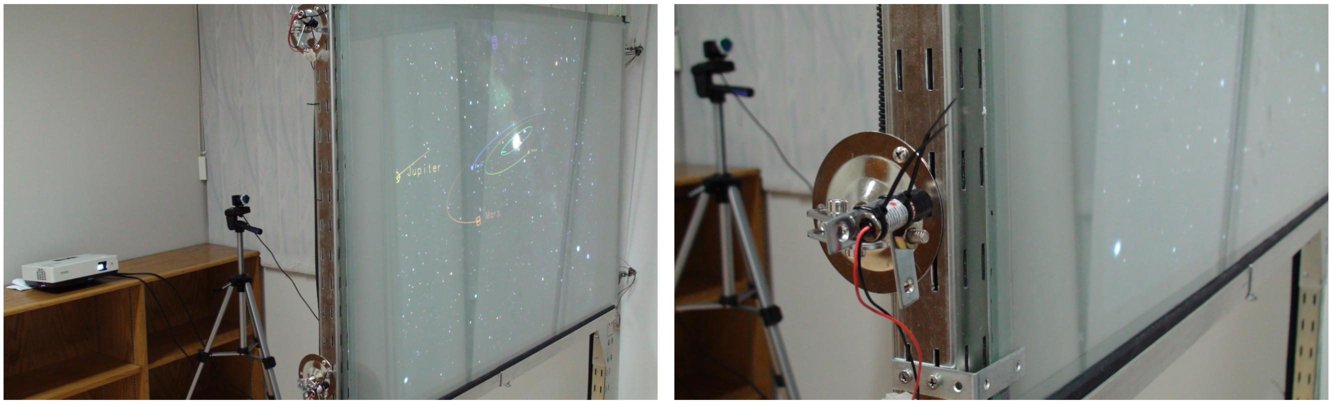

Figure 2. Left: The entire hardware setup for the multi-touch display; right: A close-up view of one of the infrared laser light plane (LLP) emitters.

shown on the right hand side of Figure 3, when a finger contacts the interaction surface, the tip of the finger intersects a sheet of infrared light presented just above the screen surface. After the finger tip(s) diffuse(s) this invisible light, one can use an infrared CCD camera behind the screen to pick up the diffused spots, which are then further processed and tracked to generate the multi-touch event signals.

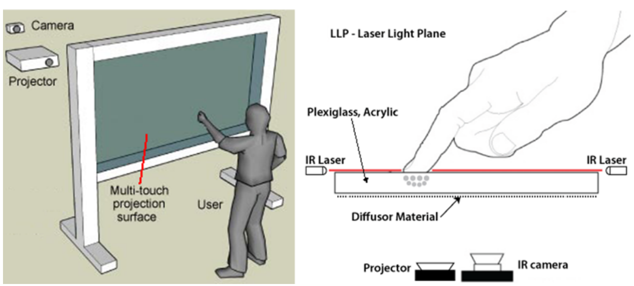

Figure 3. Left: The multi-touch display setup used in this work; Right: The laser light plane technique for detecting multiple finger contact on the interaction surface.

Software: Multi-touch tracking and rendering

We used the Community Core Vision (CCV) software [34] to calibrate the multi-touch interaction area on the physical surface and to track the finger actions over the screen surface. In addition, we employed the TUIO (Table-Top User Interfaces Objects) API to decode the TUIO (Open Sound Control (OSC)) messages sent out from the CCV software. In practice, interaction-sensing is implemented as a thread, listening to a certain UDP network port; this thread records all multi-touch events and stores them in a linked-list data structure shared with the rendering thread. The rendering thread is implemented using OpenGL to render the virtual simulations of the astrophysical Universe; details can be found in [20]. The system checks various user inputs including the multi-touch input via the linked-list data structure.

Characteristics of different finger gestures

Multi-touch gestural interaction comes in two basic flavors: *direct gestures*, which allow direct manipulation of on-screen objects, and *indirect gestures*, which can be used to represent abstract ideas. For example, bringing the five contact fingers of each hand towards each other until they meet in the middle could signify a request to close a pop-up menu or to quit the selected application. As highlighted by Yee [47], indirect gestures, which are often adopted in productivity workspaces, have many usability concerns associated with their design and applicability.

The scope of the interaction design presented here is confined to direct gestures that are based on one, two, three or more simultaneous finger interactions. Our end goal is to develop an efficient and easy-to-use multi-touch digital planetarium system for members of the general public, aiming at developing an interactive walkthrough exhibit in a science center. As such, the design of the multi-touch interaction must be highly intuitive and responsive. At best, only cursory user instructions should be needed at the display. We believe that a well-considered design using only a small subset of direct gestural interactions is sufficient to provide most of the fundamental navigation requirements needed for visual exploration of large-scale astrophysical simulations.

One-finger gestures – These are the simplest finger gestures commonly used in pop-up menu selection or in performing rotation or view panning in the direction associated with the contact finger movement dragged across the display screen.

Two-finger gestures – These are more complicated finger gestures because we may also need to consider whether the two contact points are from fingers of the same hand or not. The ability to disambiguate these cases is useful because the subsequent gestures can be mapped into different intuitive navigation commands intended by the user (see Figure 4).

In the context of the vertically-mounted multi-touch display used in this work (see the left hand side of Figure 3), observations of the physical constraints of the human arm and wrist can be employed to help disambiguate the interpretation of how the two contact points were formed. Since a line orientation is always associated with two non-touching contact points, it was observed that when the user interacts with a vertical touch surface, a one-handed two-finger touch normally results in a vertical orientation (see the right hand side of Figure 4) as this is a more natural wrist posture compared to the horizontal touch that requires an uncomfortable twist

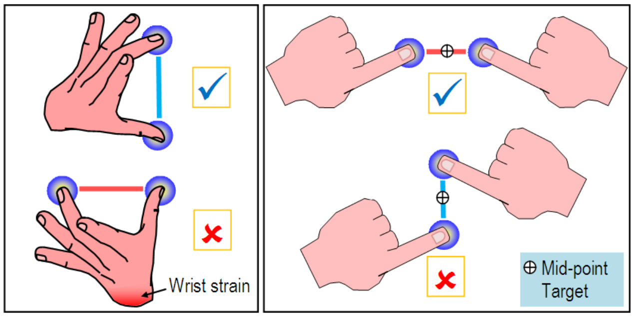

Figure 4. Left: Vertical orientation is favored for one-handed two-finger contact and the resulting vertical line is often used to specify an anchor line for subsequent operations with a third finger gesture. Right: Horizontal orientation is favored for two-handed two-finger contact and the subsequent gesture is usually an inward or outward motion (or zooming) of the two fingers. The mid-point between the two contact fingers usually suggests the center about which a visual movement or zoom is performed.

to the wrist. Conversely, the user would find it more natural to touch a vertical surface with two fingers from different hands in a horizontal orientation (see the left hand side of Figure 4), especially when the two fingers are used to frame a target object or a waypoint in the middle position between the two fingers. These observations were used to design the proposed multi-touch interactions. It is worth noting that the stated assumptions may not hold true for tabletop implementations and other multi-user interaction environments.

Three-finger gestures – As shown in Figure 4, one of the more common characteristics of a three-finger gesture used in direct manipulation is to have two fingers from the same hand form an anchor *line or plane* while a third finger from the other hand drags across the screen to perform a directional operation such as a 3-D tilt of the selected object or scene about a related *plane*. In some cases (e.g., the left hand side of Figure 8), disambiguation between a right and left-handed user becomes necessary as the former would most likely perform the third finger drag using the right hand and vice-versa.

Many-finger gestures – In our context, this is defined as a gesture involving more than three fingers. The most basic many-finger gesture for direct manipulation is to place all five fingers on the screen and drag them across the screen as in the case of a one-finger panning gesture.

Multi-touch interaction design

For typical interactions in virtual simulations of astrophysical exploration, the users would like to be able to select stars on the screen, pan around the virtual space, and move forward and backward towards a desired visible waypoint. In addition, users would also like to go across various scales to travel between the interstellar domain and the solar system scale, and rotate the universe against different points of reference, such as the Sun, a selected star or a planet. Here we identified six basic operations frequently used for exploring and navigating within our large-scale 3D astrophysical simulation environment. These include:

1. Object selection on screen, e.g., a planet or star;
2. Rotating the 3D world about a center, e.g., the Sun;
3. Camera movement to/from a desired visible waypoint;
4. Rotating the 3D world about a selected object;
5. Powers-of-ten style movement across different scales;
6. Camera panning.

The multi-touch interaction designs related to each of these operations are described in turn below, ordered by the number of fingers involved in the interaction.

One-finger interactions

Star selection and de-selection – Tapping a finger on an object on the screen is used to select a star or planet. The selected object is labeled and a few lines of descriptive text are displayed on the screen to show related information, e.g., its size, distance, visual magnitude, etc. Responsive feedback [14] to the user indicates a successful action. A finger tap on another screen object results in de-selection of the previous one.

Rotating the 3D world about a center – As discussed in the data characteristics item in the Section on “Characteristics of Large-scale Navigation,” astrophysical data are intrinsically Earth-centered or Sun-centered by nature. Since our experimental simulation covers the Earth, the solar system, and interstellar space, we assign the Sun to be the default center for 3D rotations, and apply the rolling ball mechanism [23] to incrementally update the view-world transformation upon successive multi-touch actions.

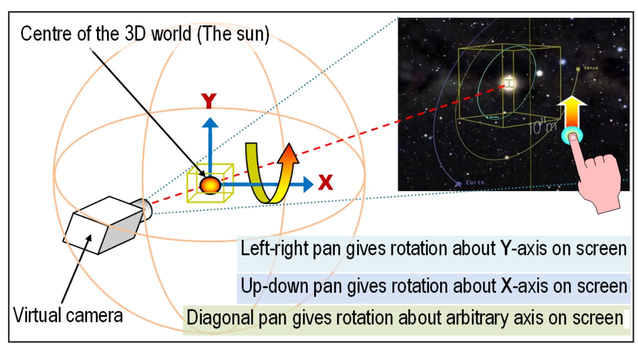

Figure 5. Rotating the 3D world about its center, i.e., the Sun.

Note that such a 3D rotation can be easily done with a one-finger gesture. The motion of the contact finger defines the rotational direction on the touch-sensitive display (see Figure 5), and the amount of rotation is directly proportional to the screen distance covered by the finger movement. This gesture is intuitive and responsive since immediate visual feedback can be given to the user via changes in the virtual world observable on the screen. Furthermore, a fast finger movement can produce a sustained rotation (auto-rotation) so that an animated visualization can be created. Such an auto-rotation stops whenever the screen is touched again.

Two-finger interactions

Camera movement – Camera movement can be performed by moving two fingers towards or away from each other. This is most comfortably done with one finger from each hand rather than with a one-handed gesture (both fingers from the same hand). In this gesture (see Figure 6), the line orientation subtended by the two contact points should remain within $\pm 60^o$ of the horizontal position. As explained in Figure 4, an active angular zone is necessary to disambiguate two-finger operations from the three-finger scale-change operation to be described later.

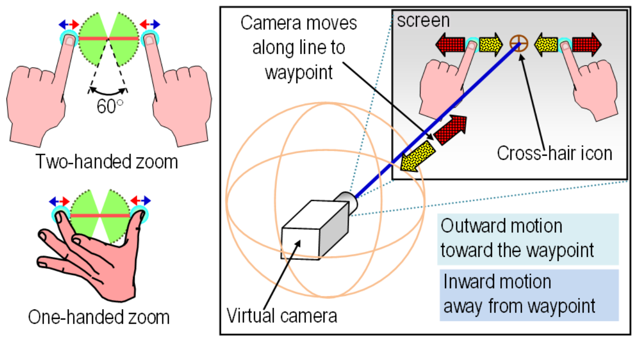

Figure 6. Left: Camera movement with two hands or one hand. The active angular zone (shaded in green) allows for variation in the two-finger line orientation in which the gesture is still interpreted as a movement operation. Right: Relationship between the virtual camera motion towards (like zooming in) and away (like zooming out) from a user specified waypoint and the motion direction of the two moving fingers.

The advantage of the proposed multi-touch camera movement control, compared to a traditional mouse-keyboard method, is the intuitive way that a waypoint in space can be directly specified by the user as a point about which the operation is to be performed. The user simply uses the mid-point between the initial two-finger contacts on the screen to specify the waypoint. Similar to the work of Benko et. al. [4], we provide a mid-point cross-hair icon on the screen to improve the precision of the waypoint specification (see the right hand side of Figure 6); such a target could be a star or planet at a certain distance away.

The other parameter that we need to consider is the magnitude of movement or the control-display rate. Since we travel in a virtual space with a wide range of spatial scales, we have to adaptively adjust the amount of movement according to the spatial scale. Early in this investigation, we considered using finger movement rate to control the travel speed. However, at 60 frames-per-second (fps), the camera used to track the finger movement cannot provide sufficient temporal resolution for fine grain control. In addition, prolonged and frantic finger actions are needed to move quickly from Earth to star viewing scale. Even at 200 fps, it could still be difficult to implement flexible zoom speed control over such a large variation in viewing scale using only finger movement rate. Since the interactive visualization system is targeted for general users, we decided to keep the movement operation simple, and to employ the distance of the virtual camera to the Sun as the factor to scale the movement rate. Therefore, when we are inside the solar system, we can move at a speed that is proportional to the scale of the solar system, i.e., 10^{11} to 10^{13}m; when we move to a larger spatial scale, say interstellar space, we can still achieve a proper amount of movement that is commensurate to the current viewing scale. As a result of this automatic adjustment, the user can seamlessly achieve responsive and adaptable navigation for different spatial scales in the virtual simulation.

Rotating the 3D world about a selected star – In exploring astrophysical data, it is often desirable to rotate the entire virtual space about a reference object other than the default center so that we can examine the surroundings about the selected reference. Rotation about a selected star allows the user to visually inspect the neighborhood environment, say a star cluster at the interstellar scale surrounding the selected star (or other object).

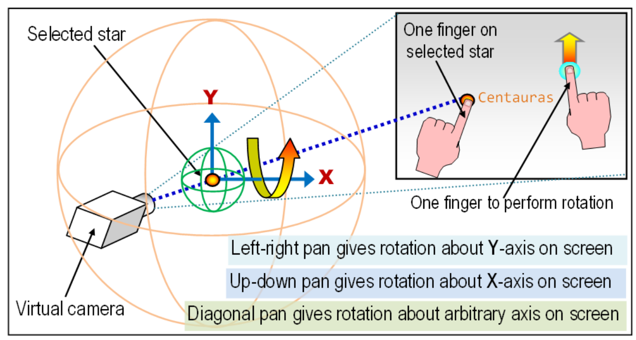

Figure 7. Rotating the 3D world about a selected star.

In order to perform this operation, the user can first tap on a desired star to select it. A stationary finger is then placed over the selected star and a finger from the other free hand is dragged across the screen to produce a rolling ball rotation with the selected star as the center, see Figure 7. Again, the rolling ball mechanism is used to produce such a rotation in exactly the same manner as rotation about the Sun.

Three-finger interactions

Powers-of-ten movement across different scales – The astrophysical world modeled in our simulation spans several orders of spatial magnitude, from 10^7 to 10^{19}m. Navigation in such a virtual simulation is inherently complicated since linearly-scaled movements, e.g., with the two-finger gesture above, are insufficient to provide the necessary controls to travel across different scales in the virtual simulation.

We propose novel interaction technique, the *powers-of-ten ladder*, to provide the user with an intuitive and easy way to traverse various scales in the large-scale 3D world. Whenever a near-vertical two-finger contact is made with the touch screen, two graphical powers-of-ten ladders are extended from the anchor line formed by the two fingers (see the left hand side of Figure 8). The two ladders (one extending to the right and the other to the left) are necessary to accommodate both left and right-handed users. Once the third finger contacts the internal area of any of the two ladders, the ladder on the other side will automatically disappear from the view to avoid scene clutter (see the left hand side of Figure 8).

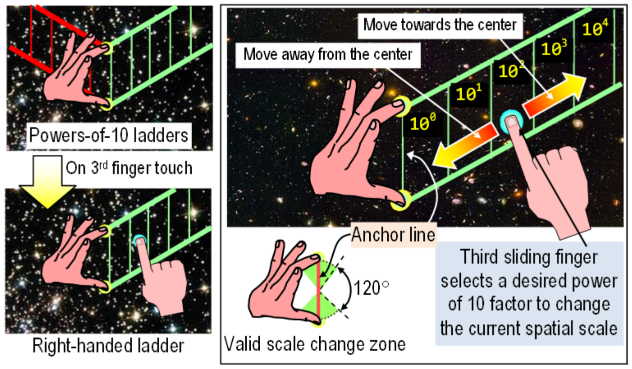

Figure 8. Left: The two left and right-handed powers-of-10 ladders. On first selection of an appropriate ladder, the other will disappear. Right: The user selects the factor for changing the spatial distance (in logarithmic scale) from the world's center, i.e., the Sun, by touching the appropriate scale factor selection zone. Subsequently sliding the finger towards the anchor line moves the camera away from the Sun while the opposite motion takes the camera towards the sun. Movement is at an exponential scale relative to the Sun. Slight angular variation (shaded in green) in the vertical anchor line still produces the powers-of-10 ladders.

As shown on the right hand side of Figure 8, the user can move away from or towards the 3D world center (i.e., the Sun) with an exponential movement scale. The current distance from the center can be changed quickly or slowly by selecting the appropriate segment on different zones of the ladder. The larger the power, the faster is the scale change, and subsequent movement of the third finger towards (or away from) the anchor line causes the camera to move away (or towards) the Sun at the selected rate. In order to accommodate variations from the expected vertically-oriented anchor line, a valid angular zone of $\pm 30^o$ about the vertical is offered.

In the design process supporting multi-touch interaction for huge scale changes, the design issues were considered important for our digital planetarium application:

- **Maximizing data visibility.** First, we need to provide maximum visibility of the astrophysical data during the exploratory navigation. Originally, we consider using a more traditional GUI such as a pop-up slider bar instead of the proposed power-of-ten ladder. We found that the ladder design with its minimal graphical overlay provides maximum data visibility while giving the user sufficient positional feedback (e.g., the spacing between ladder rungs) for selecting the desired zooming scale. In addition, the two slanted parallel sides bounding the ladder rungs provide a strong visual boundary to guide the directions in which the user's finger should slide to perform the zooming operations (i.e., in or out) at the selected power-of-ten scale (see right side of Figure 8).
- **Human ergonomics.** Second, notice also that an upward slanting ladder was implemented instead of a horizontal version. The slanted orientation considers the ergonomics of human posture, especially the hands and shoulders, when touching the vertical screen surface. Sliding one's hand horizontally results in greater shoulder movement than sliding one's hand diagonally-upward.
- **Interaction locality.** Third, we also considered an alternative design that provides a visually unobtrusively-placed fixed slider bar at the bottom of the multi-touch screen so that the user can easily choose the power-of-ten scale at anytime instead of initiating a three-finger gesture to bring up a ladder. This idea was quickly abandoned because of the interaction locality problem. When scaling this digital planetarium application to a large multi-projector display, keeping the scale selection in a predefined screen location becomes very inconvenient to the users. The pop-up nature of the powers-of-ten ladder allows the interaction to take place at any screen location. The users can just initiate it at their current location. The proposed ladder concept, in our view, is an ideal solution for quick and high-visibility "on-the-spot" scale selection.

Many-finger interaction

Panning the virtual camera view – The last operation in our application is camera panning. Again, we apply the rolling ball method to manipulate the rotation on the screen, so that the users can naturally change their views toward their desired directions. Since the one-finger dragging action has already been assigned to a more useful operation, i.e., rotation around the center of the 3D world (typically useful for data/object inspection), the four or five-finger drag across the screen pans the virtual camera as shown on the left of Figure 9. In our design, the many-finger movement mimics the dragging of a very large piece of paper mounted on the screen. When our fingers drag downward, all objects on the screen (like dragging a large piece of paper) move downward accordingly. Such view panning is highly intuitive with immediate corresponding visual feedback, and, like other rotations, the amount of panning is directly proportional to the screen distance covered by the finger movement.

Besides camera panning, such an interaction also allows us to rotate the camera about its viewing direction. The right hand side of Figure 9 demonstrates this interesting hand maneuver. By performing a circular many-finger movement (like rowing) on the XY screen plane, the accumulated rotations produce a camera roll about the viewing direction (perpendicular to the screen XY plane). Continuous rolling can bring the view back to the original camera orientation.

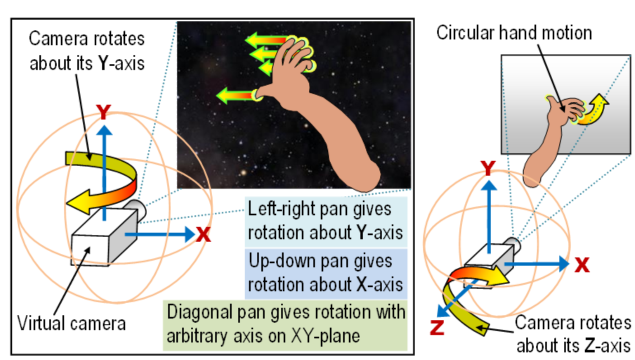

Figure 9. Left: Relationship between the virtual camera rotation and the panning motion of the five (or four) fingers. Right: The rolling ball can produce Z-axis rotation by continuous circular hand movement.

This is a non-intuitive gesture, which is made possible due to our use of the rolling ball mechanism [23], and it is available for more advanced users as the need to execute such view rotation is not often required for general exploratory navigation in a 3D astrophysical simulation.

USER EXPERIENCE

A study to gauge users' experiences with the proposed multi-touch system was conducted in an enclosed room in our research laboratory. The room is about 3 meters by 4 meters in size, and it houses all the necessary equipment, including the multi-touch hardware setup and two desktop personal computers (see Figure 2). A total of 16 participants were involved in this study: 14 males and 2 females, aged between 21 and 27. There were 7 research staff and 9 undergraduate students. All participants had considerable familiarity with personal computers, while only two of them had experience in using multi-touch user interfaces. Prior to this experimental study, none of them had used the multi-touch system we developed in this work. Before performing the required tasks, all of them were given a brief demonstration of how the tasks could be done using various finger gestures:

- First, we used a standardized script and read a script to the participants while demonstrating the finger gestures on the multi-touch screen;
- Second, the study was conducted with one participant at a time and the room included only the participant and the person (one of the authors) who conducted the study.
- A picture of the center of the Milky Way was first shown to the participants and all planets in the solar system had their names marked next to them in the virtual simulation, so that the participants could recognize these objects regardless of their domain knowledge in astronomy;
- In addition, we showed the planets and the Milky Way to the participants in the virtual simulation, so that they could form a clear picture of these landmarks to be used in the tasks;
- After the demonstrations, we reset the virtual simulation to the original starting view. The initial view displays the orbits of the inner planets in the solar system with the Sun at the center of the screen;

The participants were asked to perform the following five tasks common to explorations of large-scale 3D astrophysical simulations:

1. Select and de-select any two stars;
2. Rotate about the sun so that the solar system plane becomes horizontal (within $\pm 15^o$ error) (the plane was initially vertical);
3. Pan up/down/left/right to find the Milky Way center;
4. Move forward towards the Earth and then move outward to see Pluto;
5. Change the current spatial scale to 10^{18}m.

After the study, most participants found that the multi-touch system allowed them to use their hands to interactively perform the necessary navigation operations. Among the five listed operations, the majority found the first task to be the easiest to perform as it only required them to tap on an object on the screen. Task 2 was also found to be intuitive because the 3D world rotation naturally follows the movement of the finger. All participants found task 3, the five-finger panning to search for the Milky Way center, to be highly intuitive and easy to comprehend as it mapped well with the idea of dragging a piece of paper across the screen. Task 5 was found to be the most difficult, with several participants having problems creating the anchor line using two fingers of the same hand. In several instances, the folded fingers made an unintentional third contact with the screen. However, with additional practice, most were able to accomplish the task without further difficulty. They were able to correct their hand posture after becoming aware of the positions of their other folded fingers. As for task 4, most were able to move forward towards the Earth but four participants performed exaggerated two-finger movements and overshot the target waypoint. In spite of this, they were later able to move back to the target with some additional gestures to reverse the camera motion.

Our general observation was that novice users had a positive experience using the multi-touch system for exploring large scale 3D astrophysical simulations. It was observed that users who had never used any multi-touch system before were sometimes unsure about how they could use their fingers to perform more complex multi-finger gestures that involved both hands. However, with a little bit of practice, the participants were soon able to learn the required finger gestures. Another observation we had was that first-time users tended to touch the multi-touch surface very lightly or with only their finger tips. Such contact was sometimes insufficient to generate blob sizes suitable for reliable tracking by the vision system. After some advice and additional practice, these participants were able to correct their finger posture and were able to carry out the multi-touch gesture tasks without further problems.

CONCLUSION

In this research work, we designed and implemented a collection of multi-touch gestures applicable to the manipulation of and navigation through large-scale virtual simulations of the astrophysical Universe. Various multi-touch techniques involving different numbers of fingers were explored, and we also proposed a novel technique, the powers-of-ten ladder, that provides efficient scale selection over huge spatial scale ranges. Our interaction designs considered issues such as data visibility, posture ergonomics, and interaction locality, and they are potentially applicable not only to astrophysical simulations, but also to simulations at microscopic and atomic spatial scales.

In addition, we investigated the user experiences of 16 participants performing navigation tasks with our multi-touch interaction techniques. All participants reported positive experiences using the multi-touch system, commenting that they liked the physical and intuitive nature of interacting with a large display screen using just their hands. This suggests that such forms of interaction suit our goal of supporting an interactive digital planetarium for use by the general public in places like planetariums, science centres, or schools. More complex direct gestures involving multiple fingers from both hands were not immediately intuitive but could be understood and used correctly after a little practice. This suggests that simple pictorial instructions accompanying such exhibits could make this class of techniques helpful to general users as well.

Future work As a further extension of this work, we would like to explore the possibility of including pressure sensitivity on the multi-touch screen so that we could introduce additional flexibility and intuitive controls in the navigation interface. We would also like to study the learning curves of users applying multi-touch methods to large-scale navigation, and to extend our virtual simulation to include also data from very small spatial scales, such as data from bioinformatics and molecular sciences.

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