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# Interactive timeline for vector field visualization

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**We propose an interactive timeline method for a three-dimensional vector field. In contrast to the usual timeline method applied to experimentally obtained flows, the proposed method is intended for application to the visualization of computer-generated vector fields by various simulations. Based on a large-scale stereoscopic display technology, one can analyze the target vector field in an environment that is immersive as well as interactive. Timelines are released from a virtual "wire" held by the viewer's hand. The wire can be moved arbitrarily. A sequence of timelines is released from the wire, and their three-dimensional dynamics are observed in the stereoscopic view.**

## 1. Introduction

In scientific visualization, the word "timeline" has two different meanings. One is a type of graphical display of information in temporal order. The other is a flow visualization using successively released material lines that are conveyed by a flow. This study is related to the second one.

Timeline visualization is commonly used to visualize experimental water flows. In a classical paper[1)], Schraub et al. proposed the use of electrolysis-generated hydrogen bubbles along a wire to visualize water flows. Electrolysis pulses on a wire immersed in water produce a sequence of bubbles on the wire. A line of bubbles (bubble line), which is initially straight along the wire, is conveyed by the flow. Bubble lines sequentially ejected from the wire by electrolysis pulses visualize the time-varying flow field. This is the timeline method. Because the bubbles are conveyed by the flow as if they are massless particles, a bubble lines can be regarded as a material line.

In the experimental timeline method, the wire is usually fixed in time. It would be theoretically possible to dynamically move the wire in order to analyze the experimental water flow more interactively. If such interactive control of the seeding wire became possible, the power of the timeline visualization method would be greatly enhanced. One can, for example, place the wire around a "hot spot" where intriguing dynamics is occurring in real time. While it is practically difficult to realize such an experimental setup, it is relatively easy to implement such an interactive tool using computational visualization.

The purpose of this paper is to propose an interactive timeline method for a three-dimensional flow field (or more generally, any vector field) that is produced by computer simulations.

## 2. Method

Our interactive timeline method relies on a projector-based, immersive display technology that allows one to virtually stand in the target vector field. He/she observes the flow field with a stereoscopic view after a visualization algorithm is applied to the flow data. Head and hand tracking systems are indispensable to realize the immersive sense for the viewer. The computer system acquires the three-dimensional position and angles of the viewer's head and hand in real time. He/she can walk in the tracked space. Since the views of the three-dimensional scenes are automatically adjusted to the viewer's eye position, everything looks natural for him/her. Similarly, the hand tracking system helps the viewer to analyze the flow data interactively. He/she can, for instance, specify/create/destroy a virtual object by hand with a natural hand motion.

In the visualization method proposed in this paper, a short virtual beam, or a "virtual wire", appears from a portable controller. As the viewer moves and changes the position of his or her hand (the controller), the virtual wire follows the motion. It always appears from the tip of the controller. Pushing a button on the controller makes a "pulse" on a timeline, which is ejected from the virtual wire. In the present application, a timeline consists of tracer particles (or virtual bubbles) that are conveyed by the flow as in the standard particle tracer visualization that is popular used in scientific visualization. The viewer can observe the dynamical change of three-dimensional timelines with the help of stereoscopic viewing enhanced by the head tracking system. He/she can move his/her foot while the timelines are moving and morphing under his/her nose.

We recently developed an interactive streamline method (COMB method) for the immersive display systems[2)]. In the COMB method, we draw multiple streamlines whose release points are also placed on a virtual short beam emitted from the controller. The interactive timeline method proposed in this paper can be regarded as a variant of the COMB method.

## 3. Hardware System

In this study, we use a projector-based, room-sized, one-screen display system called pCAVE (Figure 1), on which a wireless head and hand tracking system is installed. The screen size is 3048 mm (width) × 2441 mm (height). A computer system (SGI Asterism adt08) is used for graphics rendering and number processing, with 2× AMD Opteron 2350 processors (2.0 GHz, 4-core), 64 GB of memory, and an NVIDIA Quadro FX 4600 graphics card. For tracking, Intersense IS900 is used along with the Trackd software package. The stereo projector is a Christie Mirage S+4K. For stereoscopic viewing, a liquid-crystal-based, time-multiplexed system is used. The portable controller, on which the hand tracking sensor is installed, has a joystick and five buttons.

Recently, interactive visualization using touch screen systems attracts the attention (see, for example[3]). In contrast to the touch screen system, our interactive visualization environment based on a wireless tracking system enables us to perform a fully three-dimensional analysis. We can intuitively specify, in three-dimensional space, a seed line for timelines by hand.

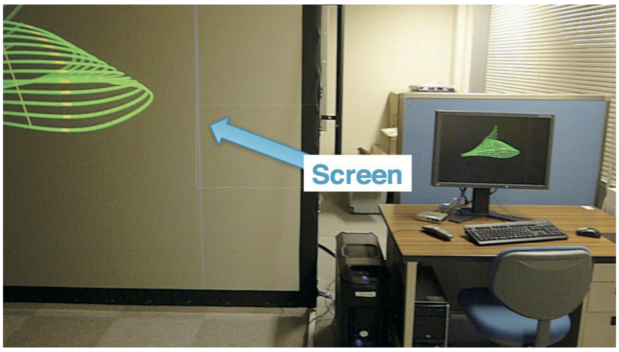


**Fig. 1.** Projector-based virtual reality system, pCAVE, used in this study.

## 4. Developed Software

In the interactive timeline method proposed in this paper, the seeding line for the timeline, which is usually a wire with hydrogen bubbles in water experiments, appears from the tip of the portable controller in the viewer's hand. When a button on the controller is pressed, a timeline is immediately released from the virtual wire. While the button is being pressed, a sequence of timelines is released one after the other with a very short time interval. Therefore, in the default setting, the consecutive timelines constitute a surface-like structure (time surface). See Figure 2.

Each timeline is made of 50 virtual bubbles (tracer particles). The motion of each particle is integrated in the positive directions of the target vector field. The standard fourth-order Runge-Kutta method is used for numerical integration. A third-order interpolation is applied for the spatial interpolation of the vector field for each particle.

As mentioned above, when the time interval between subsequent releases of the timelines are short, the sequence of timelines becomes a time surface in effect. When the user moves his/her hand while the timelines are released, the time surface shows a wrinkled structure as shown in Figure 3. By observing the wrinkles and the deformation process of the whole surface, the analyzer can intuitively grasp the three-dimensional structure of the target vector field. This kind of fully interactive timeline analysis is difficult to realize in experimental timeline visualizations.

The interactive timeline method in this paper is implemented as a component of a general-purpose visualization program, VFIVE[4), 5)], for CAVE-type virtual reality (VR) systems. VFIVE is written in C++ language with standard APIs (OpenGL and CAVELib). It has a menu-based user interface to select the input data, applied visualization method, and various parameters. Standard visualization methods are implemented in VFIVE, including particle tracers, streamlines, stream tubes, stream ribbons, arrow glyphs, isosurface, slicers, volume rendering, and line integral convolutions. VFIVE also holds originally developed visualization methods, such as "snow-flakes"[4)], "frozen-in-line advector"[6)], and "COMB" method[2)].

The interactive timeline method proposed in this paper is the latest visualization method integrated into VFIVE. As in other visualization method, subsidiary procedures for the visualization itself, such as the loading of the target vector field, spatial interpolation, and integration, are all automatically performed by VFIVE in the interactive timeline method.

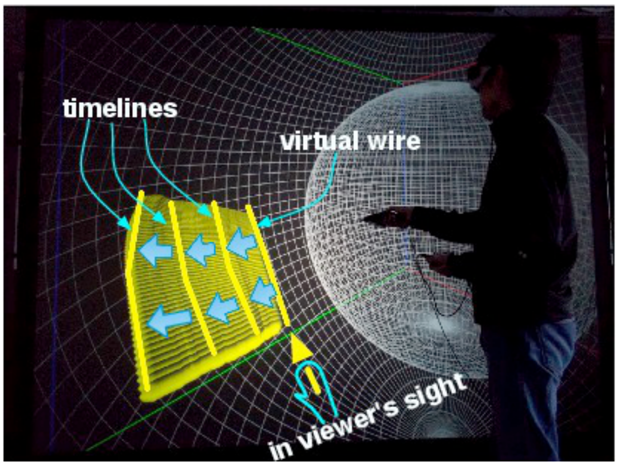


**Fig. 2.** Interactive timeline method proposed in this paper. In the viewer's sight, a short beam (i.e., a virtual wire) for the seeding points for the timeline method appears from the portable controller in his hand. The position and direction of the virtual wire are controllable in real time while the timelines are released. He can swiftly move the virtual wire like waving a flag.

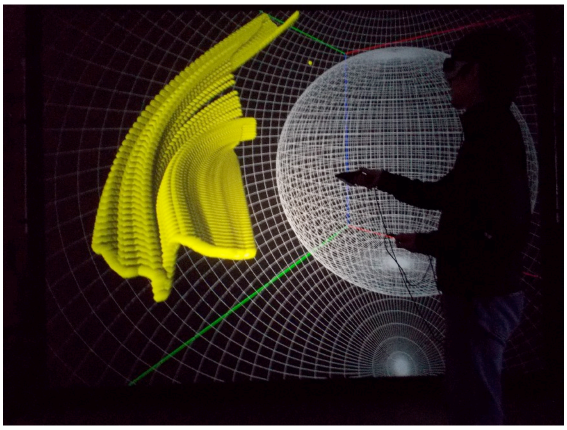

**Fig. 3.** A fluttering time-surface produced by continuous releases of timelines. He moved the wand up and down while the timelines were released.

## 5. Application

### 5.1 Geodynamo simulation

One of the purposes of the development of the interactive timeline method proposed in this paper is to understand the flow field of our geodynamo simulation[7), 8)]. Here we briefly describe the geodynamo simulation before we go into details of its data visualization.

The Earth's magnetic field, or geomagnetic field, is generated in the deep interior of the planet, called core. The core is made of iron and it is divided into two spherical regions. The inner core (radius about 1200 km) is in the solid state and the outer core (radius about 3500 km) is in the liquid (molten) state. The outer core is the place where the geomagnetic field is generated.

The physical mechanism of the geomagnetic field generation is essentially the same as that operating in the current dynamo apparatus used in bicycles, cars and power plants. Electric current is generated via the electromagnetic induction when an electrically conducting metal is forced to move in an externally applied magnetic field. In the Earth's outer core, the liquid state iron is forced to move by buoyancy in a self-generated magnetic field due to the same electromagnetic induction effect. When the induced current leads to the magnetic field that is the same configuration of the initial magnetic field, it forms a positive feedback system. The generated electric current and the magnetic field are amplified up to a saturation level in which the nonlinear effect of the Lorentz force alters the flow of the liquid iron.

To understand the dynamo process in the liquid metal of the Earth's outer core, one has to solve a set of nonlinear equations called MHD (magnetohydrodynamics) equations[9]. To simulate the geodynamo process in the outer core, we have developed a simulation code[10] by which the MHD equations in a spherical shell geometry, or the outer core region, are solved with a finite difference method. We use the Yin-Yang grid system[11] to discretize the spherical shell region between the inner sphere (interface between the inner core and the outer core) and the outer sphere (interface between the outer core and the mantle). Refer to our paper[10] for details of the physical model and the numerical scheme used in this simulation.

**5.2 Application of interactive timeline method**

One of the goals of the geodynamo research is to understand the physical mechanism of the process of magnetic field generation. Magnetic field is, in general, well described by the concept of the magnetic field lines. In the wording of visualization, a magnetic field line is a streamline of the magnetic field. An important nature of a magnetic field line is that it has no end-point. This is due to the divergence-free nature of the magnetic field (Gauss's theorem). Therefore, no magnetic field (or no magnetic field line) is created from nothing. A seed field or a seed field line is always necessary to get a strong magnetic field. The process of the magnetic field generation is, therefore, described as an amplification process of the seed field line. Suppose a seed field line of any configuration. If this line is stretched first, and then folded (by flow) to exactly the same shape as the initial configuration, then it means the initial magnetic field is doubly amplified because the number density of the magnetic field lines going through a region is proportional to the intensity of the magnetic field there. One of the purposes of the data visualization of an MHD dynamo data is find a flow that causes an effective stretch-and-fold process of field lines.

We developed a special-purpose visualization tool[6] to visualize the stretch-and-fold process of magnetic field lines. This tool, frozen-in-line advector, is also an integrated component of the VFIVE framework. We have applied this tool to the present data to identify a region where the magnetic field is the most vigorously generated.

Figure 4 shows a sample sequence of snapshots of the interactive timeline method applied to the hot spot where the vigorous dynamo is taking place. In this figure, the analyzer places the releasing line of the timeline at the hot spot. While he is pressing the wand button, a sequence of the “pulses” for the timelines is continuously released. The interval between the “pulses” is so short that the timelines constitute a surface-like object.

As the surface is advected by the flow, it curls up before the analyzer's eyes. The stereoscopic viewing with the help of the quick head tracking, the analyzer can arbitrarily scrutinize the three-dimensional structure of the background field by observing the moving timelines. In this case, the simulated flow in the outer core is found to have a strong negative helicity $h$ ($= v \cdot \omega$) at the hot spot. The helicity is a scalar quantity defined by the inner product of flow velocity $\boldsymbol{v}$ and the vorticity $\omega = \nabla \times v$. As Figure 4 shows, the released timelines moves upward (with the vector $\boldsymbol{v}$ upward), forming a curtain of surface that wind itself around an axis in the counterclockwise direction (with the vector $\omega$ downward). The left-handed helical winding of the curtain clearly indicates the negative helicity of the flow in this region. It is known that the helicity is the key quantity for the magnetic field generation process in the MHD physics[9]. We have thus succeeded to identify an important feature of the flow for the geodynamo process by the interactive timeline method proposed in this paper.

## 6. Summary

In this study, we proposed an interactive timeline visualization method for three-dimensional vector fields in an immersive display system. In contrast to experimental timeline methods, this method can place a wire acting as a seeding point for a timeline around a hot spot interactively.

In this method, the wire appears from the portable controller in the viewer's hand, and its position and direction are controllable in real time while the timelines are released. The viewer can specify the wire in a three-dimensional space in a very intuitive way using the hands. He/she can observe the dynamical change in the three-dimensional timelines with the help of stereoscopic viewing enhanced by the head tracking system.

Applying this method to a geodynamo simulation data, we have found that it greatly enhances the efficiency of data analysis.

As in our method, multiple timelines are used to construct a surface-like object in experimental flow visualizations[12]. On the other hand, in computational flow visualizations, a mathematically constructed surface is generally rendered to enhance the visualization quality (see, for example[13, 14]). We will employ a surface construction algorithm such as that proposed by, for example[15, 16], to improve our timeline method in the future.

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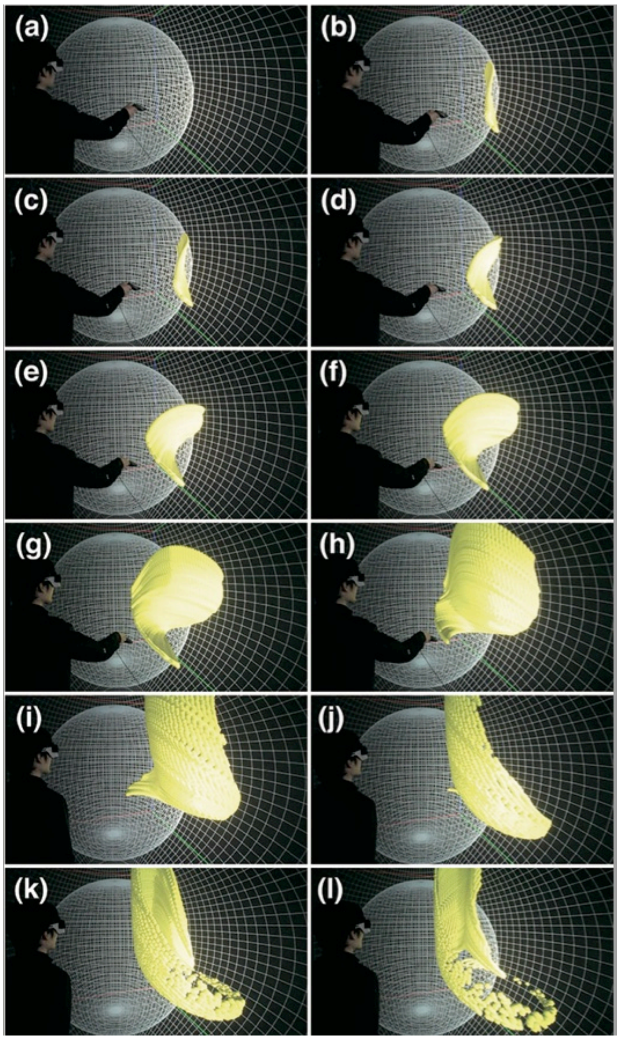


**Fig. 4.** Snapshot sequence of interactive timeline visualization method applied to geodynamo MHD simulation.