Multi-resolution Amplification Widgets

Kiril Vidimce and David C. Banks
{vkire|banks}@erc.msstate.edu
NSF Engineering Research Center
Mississippi State University

Abstract

We describe a 3D graphical interaction tool called an amplification widget that allows a user to control the position or orientation of an object at multiple scales. Fine and coarse adjustments are available within a single tool which gives visual feedback to indicate the level of resolution being applied. Amplification widgets have been included in instructional modules of The Optics Project, designed to supplement undergraduate physics courses. The user evaluation is being developed by the Institute of the Mid-South Educational Research Association under the sponsorship of a 2-year grant from the National Science Foundation.

1. Introduction

This paper describes amplification widgets that deliver to the user an amplified version of changes that occur in a 3D object. Instead of offering just one level of amplification, these 3D widgets [Conner] allow multiple scales of operation. Our reason for creating such widgets was specific and practical, but the widgets themselves can be used in more general and even fanciful settings.

During the past four years we have developed several interactive 3D graphical tools as part of The Optics Project (TOP) to teach principles of optics to undergraduate physics students. The student sometimes needs to apply very fine control to an optical element in a simulated system. For example, moving a mirror or changing the wavelength in a Michelson interferometer produces large changes in the interference patterns on an observation screen. The resolution of a mouse is insufficient for providing satisfactory control.

Fine control is important in other application areas of computer graphics. A surgeon makes precise cuts with a scalpel, and a surgical simulation should offer such precision. Tele-operation of robotic controls may require precision beyond what a typical input device can afford. For individuals with motor disabilities, it is desirable to construct a user interface that improves the resolution of a non-dextrous hand.

If you want to translate an object with precision, one standard strategy is to zoom, move, and unzoom. If you don't zoom, the resolution of the mouse maps a 1-pixel motion into a relatively large translation. But when you zoom, the 1-pixel motion of the mouse converts to a small translation. It would be nice to have fine control without demanding the zoom/unzoom sandwich around the translation.

One strategy is -- by fiat -- to decree that the 1-pixel motions of the cursor are converted to tiny translations of the object. But that sacrifices the virtuous goal of direct manipulation: the object should move together with the cursor. How can you simultaneously provide direct manipulation and fine control?

Rotation creates similar problem. To exercise fine control over the orientation of an object you might use a knob. When you rotate the knob, the object rotates too. But how do you make the object turn by a millionth of a degree? You might make the knob be *really* big; then a 1-pixel motion on the knob would only rotate by a millionth of a degree. But there is not enough screen to make the knob that big. Alternatively, you could decouple the knob's rotation from the object's, so one degree on the knob becomes a millionth of a degree for the object. But that seems to sacrifice direct manipulation of the object. A solution to one problem promises a solution to the other.

The single most influential work that inspired our efforts was the 1992 paper by the group at Brown University on 3-dimensional widgets [Conner], which demonstrated how effectively a 3D object can be manipulated through geometric elements that visually connect a representation of the input device (a cursor for a mouse, a hand for a 3D tracker) to the object being manipulated. When the object undergoes a simple 1-to-1 motion that tracks the device, such widgets may be gratuitous. But indirect control is mediated very effectively by an intervening widget.

Other researchers have addressed the general problem of how to design a "natural" 3D interaction technique that allows a user to manipulate an object without demanding a 1-to-1 correspondence to the input device. Poupyrev's "go-go interaction" applies a non-linear mapping of the user's hand position to the world, so that a reaching gesture will grab objects that are much farther than an arm's length away [Poupyrev]. Mine took the idea a step further by automatically stretching the manifestation of the user's arm as long as is required to grab the object beyond the hand [Mine].

Bier's group developed "magic lenses" to permit multiple styles of display and interaction through a see-through interface [Bier]. They designed several overlay tools for 2D displays. They describe the notion of composing a widget with a lens:

> ... consider a click-through button on top of a magnifying lens. Mouse events pass through the button, are annotated with a command, and then pass through the lens, which applies the inverse of its transformation to the mouse coordinates.

Although they did not illustrate this idea for multiple scales of translational or rotational control, the notion was certainly part of their overall view of a modular layered interface.

Mackinlay's perspective wall [Mackinlay] and Furnas's fish-eye view [Furnas] share the strategy of warping a display in order to selectively scale (zoom) a region of interest. We depart from this scheme by restricting the deformations to the widgets rather than to the entire display, and by concentrating on translation and rotation rather than scale.

Ahlberg and Masui both addressed the problem of positioning a slider bar during a search of a large dataset [Ahlberg] [Masui]. Both coarse-scale seeking (finding the right chapter of a book) and fine-scale seeking (finding the right sentence or word) can occur within moments of each other. Masui's rubber-band slider offers two levels of resolution. Ahlberg's offers two or three levels.

Mackinlay's work on rapid controlled movement demonstrated that an exponential relation between fine control and coarse control is effective in navigating a 3D environment [Mackinlay2]. We pursue a similar approach, although for manipulation rather than navigation.

Stoakley's worlds-in-miniature addresses a complementary problem to ours [Stoakley]. Rather than apply micro-scale changes to sensitive objects, his users manipulate physical props to speed up interaction, providing a means to produce large changes in translation. We have not yet applied amplification widgets to produce gross translations (or rotations for that matter, but rotations are essentially bounded by 360 degrees which makes them uninteresting for coarse control), but we plan to do so in the future.

2. Amplification Widgets

An amplification widget is a cascade of 3D components, one controlling the next, with one component directly controlling a given object in a scene. The hierarchy of these components propagates increasingly fine control outward from the object being manipulated so that direct manipulation occurs at the object. For example, a box can be positioned at a scale of 1:1 by a widget component, but can also be translated at a scale of 2:1 by the neighboring component, which in turn is translated at a scale of 2:1 by its neighbor, and so on. In a similar fashion, an object can be rotated at a 2:1 ratio; the rotating element can be similarly rotated by another, and so forth, until the outermost component amplifies a minuscule rotation of the object into a large sweep of the mouse or tracker.

The benefit of amplification widgets is that they (1) eliminate the requirement that a user zoom, micromanipulate, then unzoom (a situation that arises when small changes are made within large environments); (2) preserve the spirit of direct manipulation by visually connecting the point of control with the point of attachment; and (3) provide multiple scales of resolution for manipulation.

2.1 Translation Amplifiers

Our strategy for giving interactive control works like this. A widget has a sequence of components to govern the movement of the object they are attached to. The position of component number u is p(u), with p(0) indicating the point of attachment that provides direct control of the object. The user grabs component number u and drags it. Direct manipulation applies to the component of the widget, not to the object itself. The sequence of widget elements ties the cursor to the object in a natural, visual way.

There are many mathematical functions that exaggerate motion away from the zero point, but the function $p(u) = sb^u - q$ is perhaps the most convenient way to capture this desired behavior. We chose this equation since it can be used to encapsulate the notions of widget scale (s), exponential base (b), and the widget's point of attachment to the object (q). The base b produces the multi-resolution effect: the k-th knuckle amplifies the object's motion by b^k. The scale term is applied to the ensemble of knuckles as a whole so that the user can dictate how large the entire collection is on the screen.

The translation amplifier (TransAmp) has n segments that stretch or squish and n+1 knuckles that can be dragged by the cursor. Since p(0) = s-q, changes in the scale s produce translation of this point of attachment. Changes to the exponential's base b have a different effect: the point of attachment p(0) is independent of b, but the relative lengths of the segments change. When b is large, the furthest knuckle considerably amplifies the object's motion when s changes.

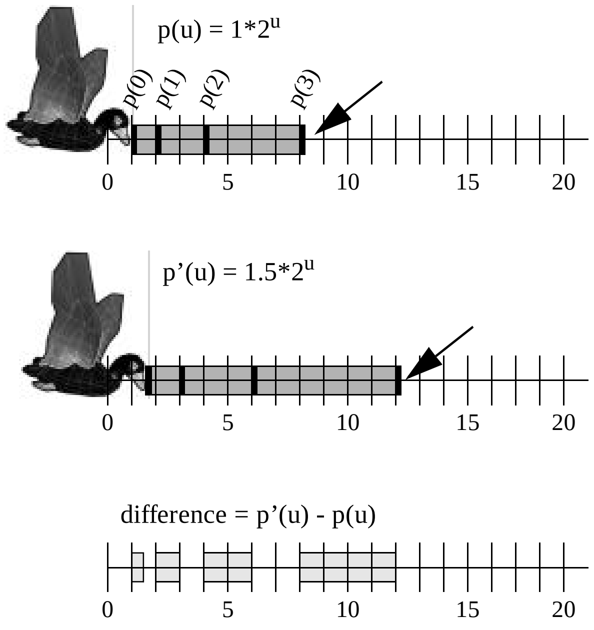
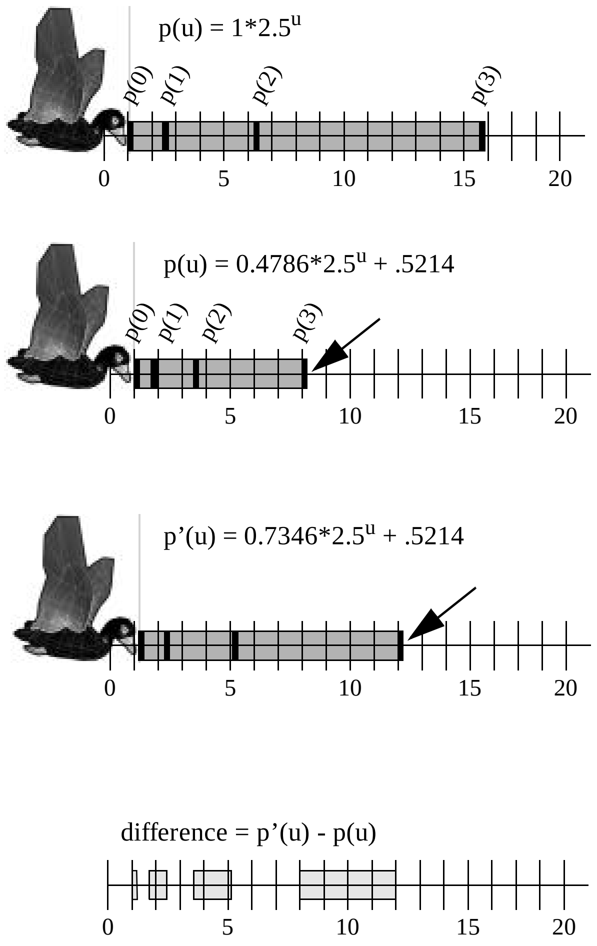


Figure 1. (Top) The mouse (indicated by the arrow) drags knuckle number 3, beginning at position8. Other knuckles in the widget move according to he equation shown. (Middle) When the mouse reaches position 12, an appropriate scale factor is computed to maintain the form of the equation. As a consequence, the other knuckles move. (Bottom) The grey regions show how much each knuckle moved.

Figures 1 and 2 illustrate a TransAmp with three segments. The left end, p(0), attaches to an object at position p(0)=1. With the scale s=1 and the base b=2, the other knuckles lie at p(1)=2, p(2)=4, and p(3)=8.

When the rightmost knuckle p(3) is dragged to a new position p'p'(3)=12, the scale s is recalculated as s=1.5 and the other knuckles are updated accordingly. Thus p'(0) becomes 1.5; the point of attachment moved 0.5 units while the rightmost knuckle moved 4 units, thereby amplifying the object's motion by a factor of 8. This is equivalent to saying that the motion of the TransAmp is amplified with respect to the one of the object. Point p(2) only moved 2 units, so if it had been selected and dragged the cursor's motion would amplify the object's motion by a factor of 4. Similarly, point p(1) amplifies by a factor of 2.

We can easily calculate this factor by noting that $p_u = (p_0\text{-}q)b^u$, where p_u denotes p(u). When p_0 changes, so does p_u. The amplification is the rate of change of one with respect to the other and is given by the derivative



$p(u) = 1*2.5^u$
p(0)
p(1)
p(2)
p(3)
0
5
10
15
20
$p(u) = 0.4786*2.5^u + .5214$
$p'(u) = 0.7346*2.5^u + .5214$
difference = p'(u) - p(u)

Figure 2. (Top) The base of the exponent is increased, making the widget longer and more sensitive at the rightmost end. (Middle) The widget is scaled and offset to look like the one in figure 1. The right end is again moved to position 12, but the object moved less than in figure 1. (Bottom) The grey regions show how much each knuckle moved.

$$\frac{dp_u}{dp_0} = b^u$$

A TransAmp with n knuckles and length *l*, with a maximum amplification of B, therefore satisfies $b^n = B$, so $b = B^{1/n}$. Furthermore, we note that $s = l/(B\text{-}1)$ and $q = p_0\text{-}s$. Thus the scale, the base, and the offset can be easily calculated to satisfy a desired configuration for the widget.

When a knuckle is dragged, the new value of s is computed as $s = p_u/b^u$. We also allow the user to drag a knuckle for the purpose of changing the base b, rather than for producing a translation via a a change of the

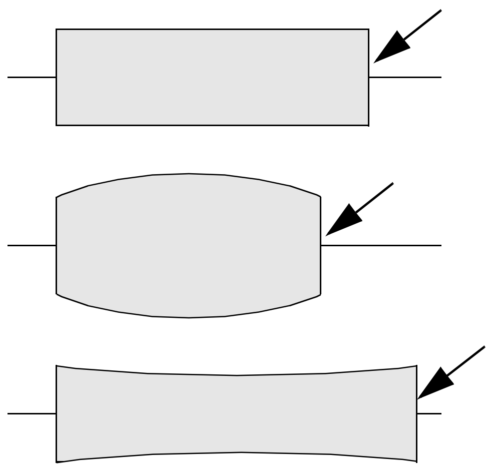


Figure 3. (Top) A cylindrical component of the translation amplifier in its rest state is grabbed (arrow). (Middle) The cylinder bulges when it is compressed. (Bottom) The cylinder squeezes in when it is extended.

scale s. In that case, the new value of b is given by $b = (p^u/s)^{1/u}$.

2.2 Look and Feel

As the components move, the widget's shape distorts. The *object* moves rigidly, the *cursor* moves rigidly, the *knuckles* move rigidly, but not the widget as a whole. When the user releases the widget, how should it return to its rest state? One choice is to simply switch from the stretched state to the rest state discontinuously. But a smoother transition is produced by briefly animating the widget's return (as a visual inverse operation of the dynamic stretching the widget undergoes when it is in use). This strategy give the widget a more physical-look and feel than a discontinuous pop. The only issue is how to provide a reasonable animation. To restore the widget to its original shape, we animate the transition from distorted to undistorted when the user completes the drag (by releasing the mouse). We experimented with a damped spring and various other oscillating behaviors, but we were eventually the most satisfied with the cubic return function

$$c(t) = 2t^3 - 3t^2 + 1$$

which has velocity zero at the endpoints of the interval [0,1]. This cubic is the lowest-degree polynomial that has zero-derivatives at both ends of the interval, which makes it the simplest choice for animating the widget's return to its rest state. The point of attachment remains fixed at p'_0 during the animation, while the other knuckles return to their original rest positions, translated by

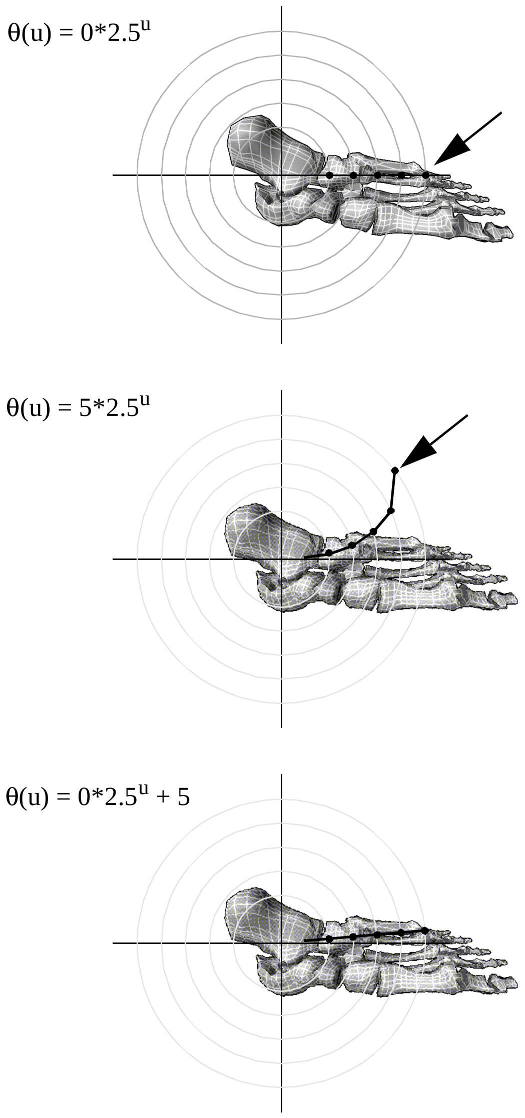


Figure 4. (Top) The outermost knuckle of the rotation amplifier is selected and dragged (arrow). The outer knuckle is rotated, changing the scale of the governing equation and producing a 5 degree rotation of the object. (Bottom) The knuckle is released and the widget returns to its rest state, but rotated now by 5 degrees.

p'_0. The behavior is given by $p_u = c(t)\, p'_u + (1-c(t))\, (p'_0 + p_u)$.

To give additional visual feedback during dragging, we make them bulge outward when compressed and squeeze inward when stretched (figure 3). This is the appropriate behavior for a cylinder of constant volume as its length changes. We give the cylinder a parabolic profile to preserve the original volume. In normalized units, the axis of a cylinder runs from -1 to 1 in the x-direction, its radius is r, and its volume v is $2\pi r^2$. When the length of the axis is changed to some other value l, the radius is found by the quadratic expression $r = au^2+b$, where where a and b are chosen to preserve the volume of the cylinder as it bulges or contracts. This quadratic is chosen so that the radius at the endpoints of the cylinder remains fixed.

We apply texture mapping to the cylinders forming the TransAmp segments. We created periodic texture maps so that there would be no visible seam where they wrap, and constructed the textures from multi-frequency noise so their appearance would remain acceptable throughout varying degrees of expansion or compression.

We experimented with segments whose lengths formed a geometric progression so that segment k has length $l_k = b\ l_{k-1}$. The visual effect is not appreciably different from the exponential function already described, but the math is considerably more tedious.

Three improvements to the TransAmps became immediately evident. First, there is no need to scale the knuckles beyond the one being dragged. This is especially obvious when the knuckle at the point of attachment is moved. All the other knuckles spread out exponentially, which really isn't their purpose. We therefore restrict the scaling to the knuckles between the one that's dragged and the one at the point of attachment. The others simply translate by the same amount as the dragged knuckle.

The second improvement is an implementation detail. Rather than calculate the absolute position of each knuckle, it is more convenient to calculate the relative position of one knuckle with respect to its neighbor. Since the scale s and the base b are actually variables, the change of position p is given by the total derivative

$$dp = \frac{\partial}{\partial u} sb^u du + \frac{\partial}{\partial s} sb^u ds + \frac{\partial}{\partial b} sb^u db$$

$$= s \ln b b^u du + b^u ds + sub^{u-1} db$$

Therefore

$$dp(u-1) = \frac{1}{b}(dp(u) - sb^{u-1} db)$$

Thus we have an expression for the change in position of component u-1 (which is closer to the object) as a function of the change of its neighboring component u. In this way, the motion of the mouse is propagated from knuckle to knuckle, all the way back to the point of attachment to the object.

When the user is not adjusting the value of the base b, then db=0 and the right hand side is simply dp(u)/b. This means that the knuckles can be recalculated progressively toward the object by moving each one by a fraction 1/d of the distance its neighbor moves. The knuckles can be recalculated progressively outward from the dragged knuckle by moving each one the same distance dp(u) that the point p_u moved.

The third improvement exploits the relative calculation of distance from knuckle to knuckle. The calculations were designed to agree with the exponential function for the positions p_u. But we can continue to blithely use these relative calculations even if the initial positions of the knuckles result from a completely different distribution. At first blush this may seem jarring: why should we be justified in applying phoney derivatives that don't match a set of positions? But the idea is actually quite familiar in a different guise. Bump mapping assigns "fake" tangents to a polygon in order to produce more complicated reflectance effects than a flat surface can afford.

Two 1-dimensional TransAmps can be attached to an object to permit fine control in two dimensions. Likewise, three TransAmps can be fitted to it to permit three degrees freedom for precise translation.

2.3 Rotation Amplifiers

If you can amplify translation, you can amplify rotation. This is useful in cases when small rotations produce large results, because unlike translation (where zooming provides a simple scheme for converting mouse motion into small absolute motion in world space), rotation angles do not change when a scene is zoomed. Let θ(u) represent the angle as a function of the distance u from the point of attachment connecting a rotation amplifier (RotAmp) to an object. Initially we set θ(u) = θ(0) for each knuckle u, which means that the scale s is zero. When one knuckle is rotated by some amount dθ(u), the neighboring knuckles (working inward toward the object) are updated in the same manner as the TransAmp:

$$d\theta(u-1) = \frac{1}{d}(d\theta(u) - sb^{u-1} db)$$

Just as for TransAmps, knuckles on a RotAmp may be placed according to an arbitrary initial distribution θ(u); the values of u need not even be uniformly spaced. For knuckles outside the one being dragged, we apply the same incremental rotation as that of the dragged point. The inner ones are adjusted according to the iterative equation above.

3. Implementation and Evaluation

The original motivation for the amplification widgets was very practical -- we wanted students to exert extremely fine control over sensitive element in a 3D simulation of optical experiments. Sometimes the user wants to quickly move from a blue wavelength (400 nm) to a red wavelength (700 nm); however, the user also needs to be able to commit minute changes (on the order of one or less than one nanometer) in the wavelength in order to observe the rapid changes in the interference patterns. For this reason we have inserted amplification widgets into components of The Optics Project where they are most needed.

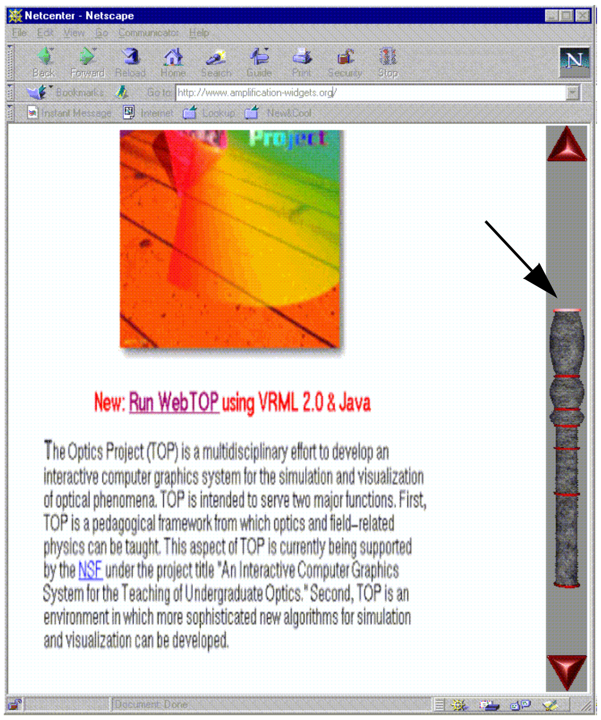
The Optics Project now contains more than 10 modules and is being field-tested in physics courses at several universities. Our analysis of the students' performance using the amplification widgets will not be available until after the spring semester of 2000; we plan to include the results on the Optics Project home page. The user evaluation is being developed by the Institute the Mid-South Educational Research Association under the sponsorship of a 2-year grant from the National Science Foundation.

We developed these amplification draggers on top of the Open Inventor framework from SGI. Open Inventor provides a convenient environment for designing new widgets. It already has translation widgets (called draggers) and rotation widgets that can control 3D objects in a scene. We have also implemented the widgets using VRML and Java as part of our Web-based deployment of The Optics Project (see color plate 3).

We have applied the widgets in several test domains. These are summarized briefly below and illustrated in color plates 1 and 1 and figure 5. (1) The Optics Project (color plate 2): Amplification widgets allow the user to control the wavelength of light at very fine resolution in the Michelson Interferometer module, but also permit gross changes in wavelength from blue to red; the widgets allow the user to make micro-adjustments to the optical elements along the workbench in the Geometrical Optics module, but also allow elements to be moved large distances out of the way, (2) Scrollbar (figure 5): The translation amplifier has been converted into a variable-resolution scrollbar to allow fast sweeps through a document or line-by-line scrolling, (3) Multiple translation amplifiers and multiple rotation amplifiers (color plate 1) have been combined to provide multi-resolution 3-dimensional control.

4. Conclusions

Multiple joined nodes create a versatile widget when one node influences the behavior of the next. We implemented a combination of components to construct translation amplifiers and rotation amplifiers for manipulating objects in a 3D environment. The widgets permit a user to translate or rotate an object at fine, coarse, and in-between levels of resolution.


Netcenter - Netscape
File Edit View Go Communicator Help
Back Forward Reload Home Search Guide Print Security Stop
Bookmarks Go to: http://www.amplification-widgets.org/
Instant Message Internet Lookup New&Cool
Project
Document: Done

New: Run WebTOP using VRML 2.0 & Java

The Optics Project (TOP) is a multidisciplinary effort to develop an interactive computer graphics system for the simulation and visualization of optical phenomena. TOP is intended to serve two major functions. First, TOP is a pedagogical framework from which optics and field–related physics can be taught. This aspect of TOP is currently being supported by the NSF under the project title "An Interactive Computer Graphics System for the Teaching of Undergraduate Optics." Second, TOP is an environment in which more sophisticated new algorithms for simulation and visualization can be developed.

Figure 5. Translation amplifier serving as a scrollbar (indicated by arrow on right). We have implemented the scrollbar as a stand-alone application and are developing a VRML+Javascript version, illustrated above.

Acknowledgments

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