A Personal Paradigm for Computer-Aided Visualization

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Abstract

We consider visualization to be a creative human endeavour and explore how the computer can assist this process, beyond mere image production. We propose a computer-aided visualization system which is driven by the unique abilities of each user. From an initial specification, the system provides a wide variety of visual representations by making combinations of components. From this range of choices, the user makes selections based on personal criteria for meaningfulness. These selections determine the fitness of the displayed representations and this information is used to provide new alternatives for display, consideration and selection. In this way, the space of all available visual representations can be effectively navigated under the user's control. The operation of this computerized tool complements the process of human inventive thought, as described by many scholars.

1 Introduction

The nature of scientific visualization and the role of the computer in the visualization process has been contentious: "opinions differ on whether visualization is a mental process aided by powerful computational tools, the computer processes that create the images, or the computer images themselves" [7] That visualization "offers a way to see the unseen" [9] is true whether it is done through a computer monitor or the mind's eye. Whatever the source, imagery must be interpreted by the viewer. That imagery will be much more meaningful if the viewer is actively involved in its creation. This distinction can mean the difference between "watching" and "doing" [17].

Mathematicians and visualization specialists at Simon Fraser University have created visual tools (i.e. [5]) for mathematical communication and discovery. Although these visualizations succeed with good communication amongst researchers, some translation is still required.

What might be possible if the mathematicians could produce effective visualizations working directly with a computerized tool? For their students, the authors of *Calculus and Mathematica* [2] express it in the following way: "your eyes will send ideas directly to your brain. And this will happen without the distraction of translating what your eyes see into words. Take advantage of this opportunity to learn visually with pure thought uncorrupted by strange words."

"The purpose of computing is insight, not numbers," wrote Richard Hamming as the motto of his 1962 text on numerical analysis. Visualization (with or without computers) is clearly another tool for insight [9]. Is there a methodology for visualization which promotes insight? When insight is the goal, it is more appropriate to consider a methodology for problem solving. There have been numerous accounts of a framework from which insight has been achieved [4, 14].

Promoting the viewer's direct involvement in image creation seems clearly beneficial, yet there are different ways in which a computerized tool might do this. Systems such as AVS (Application Visualization System) [15], allow the user to create complete visualizations by combining basic building blocks. These systems free the user from low-level programming but require use of a dataflow model to connect the basic blocks. More recently, the Mix & Match system [10] provided refinement to the earlier large-grain dataflow systems. The user of these systems combines the building blocks, possibly limiting the choice of representations to his or her own experience. Direct selection from the space of all available representations is an overwhelming task and artificial intelligence techniques have been employed in automated presentation systems [8] to address this difficulty.

Our approach provides an alternative paradigm for exploring visualization space. We seek to encourage invention and discovery, which "be it in mathematics or anywhere else, takes place by combining ideas" [4]. The poet Valéry [4] said that, "It takes two to invent anything. The one makes up combinations; the other one chooses, recognizes what he wishes and what is important to him in the mass of the things which the former has imparted to him." In our system, the computer presents combinations of the building blocks which determine an image and the user can engage in analogical and combinatory play [6] towards a meaningful result.

Bertin [1] described a visual expression of the discovery process by distinguishing three successive forms of graphic application in decision making: matrix analysis of the problem (questions are defined); graphics information-processing (answers are discovered); and graphic communication (answers are communicated). Our system focuses on the information-processing (discovery) stage of Bertin's model. Visualizations which enable discovery for an individual also provide an excellent basis for the communication stage.

2 Description

The system, which we have called *cogito*, aids creativity by providing alternatives to the user. The possibility that the selected alternatives will come from combinations generated outside the user's experience is a very powerful aspect of this approach. It is much more likely that fruitful combinations will be explored through this system.

The space of all available representations is determined by the data, and the functions associated with the data, as supplied to the system. Two sorts of functions can be associated with the data:

- operations on the data, including: coordinate transformations (i.e. conversion between polar and Cartesian), selection (i.e. values in data equal to some constant), and quantities derived from the data (i.e. calculation of areas in a two-dimensional grid)

- methods for construction of the visual elements, (i. e. three-dimensional surfaces, scatter plots, and colour maps). Currently, these building blocks of the visualizations are represented as Inventor [16] scene graph nodes

Functions can be more or less closely associated with the data. Particular problems may require the definition of several specific functions. All functions, especially standard ones like ‘area’, can be grouped into libraries to provide easy access.

The user’s first decision involves which functions to include: more functions mean a richer set of available alternatives since the system will use all possible (compatible) combinations of visual elements and data. When the user restricts the functions associated with the data, many alternative representations are dismissed without consideration.

Once the space of available alternatives is constructed, the user may further configure it in two ways:

- impose a particular requirement on the combinations created by the system (i.e. all images must depict a certain combination of variables). Such an imposition will reduce the number of alternatives available for consideration.
- organize the combinations in the search space according to a particular property of the elements (i.e. dimension of the visual representation), so that the displayed alternatives present samples

In choosing to limit the search space before any images are created, the user performs an operation which corresponds to Bertin’s notion of matrix processing. Researchers[6, 3] have found that constraint of the search space can be important to creativity. Left without user guidance, the system will present images taken from the entire search space. In this case, however, a higher proportion of the alternatives presented may be deemed unusable. And since only a relatively small number of alternatives will be displayed, it is more likely that useful ones will be missed. All representations available to the system form a possibility space [11]. Perkins suggests that these spaces may be either clue-rich (homing space) or without a clear path of clues (Klondike space). In a homing space, the *cogito* approach allows a visualization to be found in an intuitive way. A Klondike space can be explored effectively by pursuing a particular direction with each search and performing many searches.

The selection of alternatives is facilitated through a flexible visual interface, the core of which is reminiscent of Sims’ system for artificial evolution in computer graphics [13]. The interface (see Figure 1) displays a subset of available representations (sampled according to the selected organization of the search space), generated from the current data, with which the user can interact. The dynamic nature of this tool differs from other systems, such as SageTools [12], which seeks to provide advice to designers by example of previously successful data-graphics and some facility for reuse of these graphics.

In our system, the search of the whole space of alternatives is driven by a genetic algorithm, with the user providing the fitness function through his or her selections. At each step the user may choose one or several promising representations, to define the search space for the next iteration. New alternatives are presented by performing crossover operations to recombine the visual elements of previous selections. Individual elements may also be mutated through parameter modification. The end result of the iterative search process will be one or more distinct representations which may be linked and used in concert.

In order to provide context and improve navigation, the user is always able to access the generation history of a visualization and modify the associated parameter values. Successful representations can be saved and used as “genetic material” for other visualizations.

We contend that the user will not be overwhelmed with the choices implied by this model. Rather, we feel that the system will

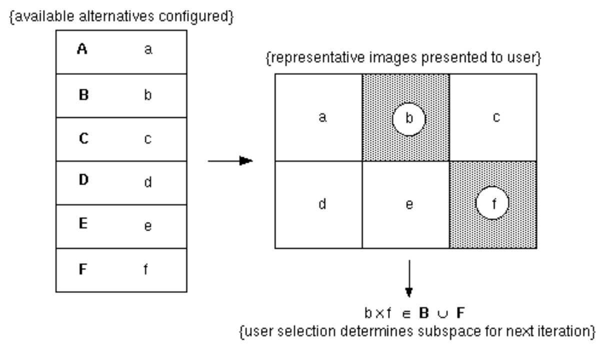

Figure 1: Schematic look at the interface: the space of available alternatives is grouped according to user-specified criteria. Each group (A – F) has a representative element (a – f) which is displayed to the user. The subspace for the next search iteration is based on the user selection (b and f).

allow the user to quickly dismiss useless representations and focus on those possibilities which are meaningful, some of which might not have even been otherwise considered.

3 Example

As an example of how this system can be applied to a real problem, we consider the study of invariant tori in a dynamical system [5]. Although the system has arisen from work on mathematical problems, the ideas which it embodies are widely applicable.

In that paper, we studied the dynamics of two linearly coupled oscillators. An invariant torus is present when there is little or no coupling, but breaks down for strong coupling. Visualization was used to gain a qualitative understanding of the breakdown process, by examining tori computed for a range of coupling strengths. We now put this earlier work into the framework of *cogito*.

3.1 Data and Functions

Each oscillator (i.e. pendulum) can be described by an angle, θ, and a radius, r. The torus that arises through the coupling process is itself a two-dimensional object (described by the angles θ_1 and θ_2), and it is embedded in the four-dimensional space of the radii and the angles $(r_1, r_2, \theta_1, \theta_2)$. The data for visualization includes the strength of coupling, δ, used in the computation and a list of four-tuples which give the pair radii and the angles at which they were computed.

The functions associated with data could include the following:

- a specification of the two special periodic solutions on the torus, $\theta_1 = \theta_2$ and $\theta_1 = \theta_2 + \pi$
- a transformation for a change of coordinates $\theta_1 = \theta_2 - \pi/2$, to permit clearer viewing of the special periodic solutions
- routines to draw tori, cylinders, surfaces, and curves, and to create and use different colour maps. When the dimension of the data is greater than that of the representation, multiple representations will be used and shown together. For example, two tori in three dimensions $((r_1, \theta_1, \theta_2)$ and $(r_2, \theta_1, \theta_2))$ will be shown

3.2 Configuration

There are many ways in which the space can be configured, depending on what is important to the individual user. In this example, we choose to limit the alternatives to those with three dimensions and to organize the search space by shape (i.e. torus, cylinder (which is a torus cut once), etc.).

3.3 Interaction

From this configuration of the search space, a set of nine representative images is displayed. These images are static, but it is possible to interactively examine the combination from which the image was created before deciding whether or not to select it. If no combinations are selected, the user may either

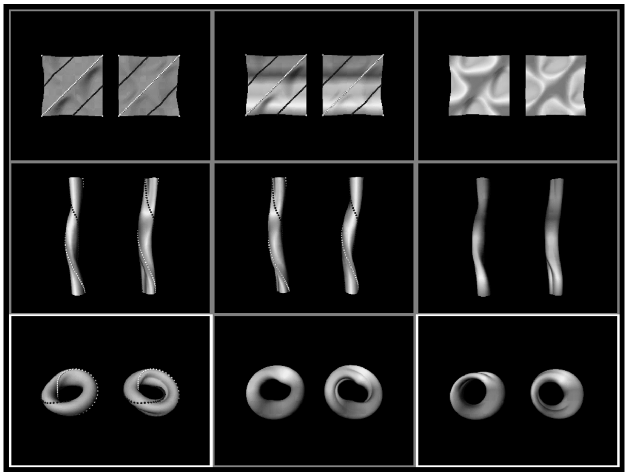

Figure 2: A display of representative images for the torus study, based on earlier choices for configuration of the search space. From this screen, two images are selected from the bottom row (as indicated by the highlighted borders on those images). This input is used to determine the next set of choices available to the user.

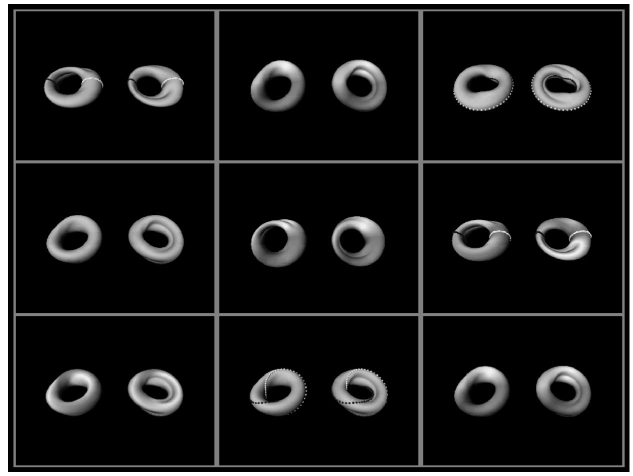

Figure 3: This display presents a new set of alternatives for consideration, based on the user's selection. Both selected images (see Figure 2) were tori, so this next set of alternatives provides choices within that range. Further iterations will continue this process of refinement.

continue to browse more alternatives on subsequent screens or return to reconfigure the search space. The number of alternatives seen at once can also be defined by the user.

In Figure 2, we see a collection of images based on our configuration of the system. We see the three available three-dimensional shapes (torus, cylinder and surface) with variations in other properties of the images. In this simple example, these other properties are colour; data transformation (whether or not the change of coordinates is applied and the order of the angles in forming the shapes); and display of the special periodic solutions.

Based on the selections made from the choices in Figure 2, a new set of alternatives is displayed in Figure 3. The two selections at the first stage both contained tori, so no other shape is shown here. The properties of colour, data transformation and display of special solutions are all varied again in this set of alternatives, influenced by their selection in the previous stage.

4 Conclusions

We claim that this exploratory approach to visualization is effective in fostering discovery. It allows each user the freedom to create meaningful visual representations, in a way which does not require programming of the system. It can also provide the foundation for communicating those representations and insights to a broader community by allowing a particular representation to be modified easily or assembled quickly from components; and by permitting the inclusion of other computerized tools as additional layers in the system.

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