Abstract -This article discusses the current use of virtual reality tools and their potential in science and engineering education. One programming tool in particular, the Virtual Reality Modeling Language (VRML) is presented in light of its applications and possibilities in the development of computer visualization tools for education. VRML can be combined with other software development tools to create interactive dynamic computer graphics to assist in the teaching and understanding of scientific and technological principles. One contribution of this article is to present software tools and provide examples that may encourage educators to develop virtual reality models to enhance teaching in their own discipline.

Index Terms - Virtual Reality, Visualization, Educational tools.

INTRODUCTION

Virtual Reality offers new possibilities for science and engineering education. The recent progress in personal computing and the internet has generated many software tools for easy and practical development of web pages including graphics and visualization tools. Virtual reality and computer graphics components consist of methods and tools for the generation of virtual objects and scenes that simulate real systems and landscapes. One aspect of virtual reality programming languages is their ability to create virtual representation of physical systems on a computer display. It is now possible to illustrate complex, expensive, or dangerous systems safely and economically on a computer screen. The potential of virtual reality in education is just beginning to be exploited by a few educators and institutions. For a long time, science and engineering education has relied on drawings and pictures to describe a variety of systems and objects sometimes accompanied by laboratory experiments with real systems for hands-on practice. It is now possible and easy to generate virtual models of systems. Coupled with the widespread use of personal computers and recent progress in information technology, a multitude of software tools have been developed that make the development of virtual reality and visualization aids for education not only affordable but easy and accessible to all. Many of these tools are being used very effectively in the development of web documents of increasing scope and quality. The graphics capabilities of these tools, particularly in the development of virtual reality displays can be of great assistance in teaching, learning, and experimenting. Recent research by the author has led to the development of several software visualization and animation tools that have proven effective in the teaching of robotics and the description of mechanical systems to undergraduate engineering students [1] [2]. The author has produced several computer graphics programs that allow students to visualize three-dimensional systems in support of a robotics course. An introductory robotics textbook with accompanying computer visualization programs is currently under development as well [3]. This article presents some of the results of this research as they apply to science and engineering education.

New software tools for easy development of virtual reality models can now be integrated with common graphical programming languages such as Visual Basic, Visual C++, Labview, Java or others. High quality Graphical User Interfaces (GUIs) allow users to interact with Virtual Reality models, integrate user-supplied parameters into those models, and trigger animations. These new technologies have the potential to bring science and engineering education to a higher level of sophistication and efficiency.

This article discusses some of these new computer tools and offers several examples of how they can be integrated to generate virtual reality models for science and engineering, particularly in mechanical and robotic systems. One new programming tool, the VRML (Virtual Reality Modeling Language) [4] [5], has evolved in recent years into a computer tool for easy generation of three-dimensional objects, scenes, and models that can effectively illustrate and help explain various science and engineering systems. VRML-generated graphics can be embedded in web pages to produce high quality visualization in web-based education. From planetary systems to atomic and molecular structures, several concepts can be easily and effectively represented using virtual reality scenes and simple computer-animated models.

THE VIRTUAL REALITY MODELING LANGUAGE

VRML is a text based programming language for the description of 3-dimensional objects on a computer display. The text source file is interpreted by an internet browser equipped with a VRML-viewer plug-in. Since its appearance in the mid 1990s, several viewers have been developed and most of them, if not all, are available for free download from their makers’ web sites. The Cortona Viewer [6], available from the Parallel Graphics™ web site, is one of several that can be found easily by conducting an internet search for “VRML Viewers”.

The main advantages of VRML as a graphics development language for education are listed here:
a. No costly software is needed to view and interact with VRML files.
b. Easy text-based programming for simple systems.
c. Several VRML development software tools are currently available.
d. VRML files can be integrated into web pages or transferred over the internet easily.
e. VRML objects can be viewed from any direction, angle, or proximity at the click of a mouse button.
f. VRML displays can be animated in response to viewer actions.

VRML IN EDUCATION

The Internet is showing evidence of several attempts by educators in a variety of areas to use virtual reality development tools in science and engineering education already. For people interested in astronomy, the national geographic society’s virtual solar system [7] is an excellent example of the practical value of virtual reality in science education. Planet locations, relative orbits, relative sizes, colors, natural satellites, rings and orientation, and many other features of the solar system can readily be illustrated and visualized. With this virtual reality model, every student can experience the view of Saturn from the opposite side of its largest moon Titan as shown on Figure 1, or navigate through the solar system from one planet to the next. The virtual solar system is also supported by windows that provide valuable information on the celestial body under focus. The virtual solar system referenced here uses the Viscape SVR viewer which can be downloaded from the National Geographic Virtual Solar System web site [7] free of charge. Chemistry is another field that can greatly benefit from virtual reality imaging as stated by James Krieger [8], “VRML (pronounced vermal) holds the promise for chemistry of literally ratcheting up the Internet information revolution to another dimension. VRML is the three-dimensional analog of HTML. And chemistry is inherently three dimensional.” This assertion is equally true for many other fields that are concerned with three-dimensional objects including vector analysis, space geometry, biological system, nanosystems, electromagnetism, semiconductor design, mechanical systems, aeronautics, and robotics to name just a few.

Figure 2 shows a virtual representation of a Complex Ion geometry taken from reference [9] which, according to its authors, illustrates “the relationship between the metal D-orbitals and ligands in the octahedral geometry.” In this example, some useful features of VRML models are illustrated. The writings on the model serve as triggers that, when clicked, cause some action or animation to take place. The cone-shaped orbitals have been adjusted to be somewhat transparent so that they still allow viewing of objects located behind them.

In biology, VRML can be used to represent various systems from cells to organs with animations that model biological functions. Several examples VRML models of biological systems are available in [10].

In mathematics, integration over a surface area or over a volume can be daunting in the case of certain shapes. If one tried to visualize the volume of integration in 3D space, computer graphics can be used to easily generate a 3D rendering of a regular volume allowing easy visualization and evaluation of integration limits and other problem parameters. Suppose that, in a given situation, an integral is to be evaluated over the volume of intersection of two cylinders. While this volume can be drawn on a piece of paper, it can be far more effectively shown using a 3D rendering of the volume of interest on a computer screen. To illustrate this point, Figure 3 shows views of a VRML description for a volume obtained by intersecting two cylinders of equal radii centered at the origin of a 3D coordinate system. Students can, at the click of a computer mouse, view the volume from any angle, evaluate its dimensions from known cylinder characteristics, and estimate the limits of integrations as needed.
With the help of the VRML model pictured on Figure 3, it becomes easy to show that the volume of interest has a projection on one of the coordinate planes that is square while having a circular projection on an orthogonal plane.

An area of engineering where 3D visualization can greatly enhance teaching is Robotics where virtual reality provides an excellent modeling and simulation method. Robotics is typically concerned with the simultaneous motion of several solids in space. Robot links and components move with respect to one another while the robot is carrying a load in an environment that may include other moving objects. The operation of a robot is difficult to visualize unless a robot in motion is actually demonstrated. Real robots are expensive, bulky, and require some safety considerations before they can be operated by students. A virtual robot on the other hand is inexpensive, safe, and available for interactive experimentation to several students simultaneously. Virtual reality simulations can be used to illustrate many concepts in robotics and mechanical systems for students.

**DEVELOPMENT OF VIRTUAL MODELS**

One major purpose of this article is to encourage educators of all fields to start developing their own virtual reality models to support education in their respective areas of expertise wherever such tools can be useful. There are several computer-based 3D graphics authoring tools that are easy to use and effective in the description of 3D objects. Spazz3D [11] is one such programming software package that has been effectively utilized by the author.

**DESCRIBING OBJECT LOCATION IN SPACE**

In areas like space geometry, vector analysis, electromagnetism, molecular chemistry, aeronautics, and many others, it is important to mathematically represent the location in space of some object or system components with respect to others. An object in space has 6-degrees of freedom and therefore requires a minimum of six parameters to be fully determined. Three positional components (x, y, z) and three rotation angles (α, β, γ) representing, for example the roll, pitch, and yaw of the object are typically used.

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**FIGURE 3**

**VOLUME OBTAINED BY INTERSECTING TWO CYLINDERS**

**FIGURE 4**

**USER / SOFTWARE INTERACTION DIAGRAM**

Efficient visualization tools can be created by combining graphical user interfaces (GUIs) developed using any suitable graphical programming language and a VRML writer. The user interface is used to seek input data from a user and integrate that data into a VRML file that is then sent to the browser for viewing and interaction. Figure 4 shows a block diagram of the user interaction with the software in a general VRML-based educational tool. The programming language can also be used to perform useful computations and present numerical results to accompany the virtual model in a given application.

The procedure followed by the author in the development of efficient visualization tools has two major steps:

1. The creation of a virtual model using direct VRML, a VRML writer software such as Spazz3D discussed above, or more likely a combination of the two where a general model is created with a VRML writer and refined by direct VRML coding.

2. The creation of a user interface using a graphical programming language for the collection of user data and its insertion into the VRML file created in step 1.

A few examples of visualization tools developed by the author follow to illustrate the procedure above. The first concerns the creation of a tool that allows visualization and user interaction in the mathematical description of an object’s position in 3D space by use of space coordinates and its orientation as described by Roll-Pitch-Yaw angles. The second is about the development of a virtual robotic arm that can be animated by users at the click of a mouse button.
VRML allows an accurate description of an object’s location in space. To assist students in the understanding of the six degrees of freedom of 3D space and the mathematical representation of a solid’s position and orientation, a small program is created that allows students to enter position and orientation values of their choice and have a virtual display of an object moving into its corresponding location. This allows efficient visualization and understanding of the effect of every parameter in the location of an object ($x$, $y$, $z$, $\alpha$, $\beta$, $\gamma$). Figure 5 shows a Graphical User Interface developed with Visual Basic™ that computes and displays the object location in the form of a pose matrix. A pose matrix is a $4 \times 4$ matrix that is comprised of a rotation matrix in its upper right $3 \times 3$ sub-matrix and a position vector in the first three elements of its 4th column.

The GUI command button labeled “Generate Animation”, when clicked, generates the virtual model of an object at the desired location as shown on Figure 6 (some descriptive text has been added to the virtual model image for better reference).

The airplane looking object of Figure 6 was first created in VRML along with the two reference frames. The user interface of Figure 5 was then written in visual basic and programmed to insert the user-supplied values into the VRML program as well as compute the pose matrix displayed on the user interface.

The red frame is a fixed reference frame while the green frame is attached to the object and follows its motions. Using this simple tool, students can experiment at will and examine the effect of each parameter in the object’s pose matrix description and immediately assess its effect on the position or orientation of the object. Figure 5 shows the output matrix obtained with the values $x=1$, $y=-1.5$, and $z=3$ for the object position and $\alpha=30^\circ$, $\beta=45^\circ$, and $\gamma=60^\circ$ for the orientation. These numbers correspond to the location of the object-attached coordinate system with respect to the fixed coordinate system as shown on Figure 6.

MODELING MECHANICAL STRUCTURES

The structure of a robotic mechanism is typically modeled by assigning a reference frame to every moving part and using a set of parameters that describes the precise location of every frame with respect to a preceding frame. In robotics, a technique based on the Denavit-Hartenberg (DH) method [12], [13], is commonly used. In teaching robotics, it is essential that students understand how link-frames are assigned on a robot arm and how the DH-parameters are then determined from the location of each frame with respect to the preceding frame. A visualization tool that allows students to enter a DH-parameter representation of a robotic structure and produce a VRML file that represents a virtual model of the robotic structure for examination is of great assistance in the teaching of this modeling technique. In fact, RobotDraw [13] [14] is an internet-based software, created by the author and his students, that generates a virtual robot model for any robot with 3 to 6 joints. In robotics education, students using RobotDraw can visualize the effect on the structure of the robot of every single parameter in the mathematical description of the robot. They can modify a parameter value and immediately view the consequence of that modification on the structure of the robot.

Figure 7 shows a virtual model, as displayed on a computer screen using a browser with the Cortona VRML Viewer, corresponding to the robot with DH-parameters given in Table 1. The controls on the left and bottom allow interactive viewing of the Virtual model from any desirable point of view.

As stated above, VRML is designed to integrate easily into web pages. Robotdraw an illustration of usage of VRML tools on the internet.
TABLE 1
DENAVIT-HARTENBERG PARAMETERS MODEL
FOR ROBOTIC ARM OF FIGURE 3

<table>
<thead>
<tr>
<th>Joint</th>
<th>d</th>
<th>a</th>
<th>α</th>
<th>θ</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.2</td>
<td>0</td>
<td>90°</td>
<td>0°</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>0.2</td>
<td>90°</td>
<td>120°</td>
</tr>
<tr>
<td>3</td>
<td>0.15</td>
<td>0.25</td>
<td>90°</td>
<td>0°</td>
</tr>
<tr>
<td>4</td>
<td>0.1</td>
<td>0.1</td>
<td>0</td>
<td>-90°</td>
</tr>
</tbody>
</table>

The RobotDraw web site offers some details on using the program as well as instructions on how to interpret the virtual model. In this instance, students can easily modify any of the parameters of Table 1 and visualize the effect on the virtual model thereby achieving a better understanding of the DH robot modeling technique that is essential to the study of robotic arms.

ANIMATION AND OBJECT MOTION IN 3D SPACE

VRML allows 3D object animation either in an automatic fashion or in response to user action. This feature is very useful in the visualization of moving systems. It is possible to create a virtual model of a real robot and have the virtual model move much like its original to illustrate the functionality of the system. Figure 8 shows a picture of a PUMA 560 Robot Manipulator, a very popular robotic arm used in industry as well as many robotics research centers and institutions. This robot arm is often used as a standard to demonstrate the effectiveness of robotics methods for analysis and control or to show the effectiveness of some computational algorithm related to robot arms. Typically, in a real robot, an operator can move each robot joint separately using a teach pendant or an interface computer or move all joints in coordinated motion.

Figure 9 is a virtual model of the PUMA 560 generated with a VRML file. Students using the virtual model can manipulate the robot in many different ways. The browser controls allow them to rotate, translate, zoom-in, or zoom out at will. Programmed VRML animations allow the robot to move its joints either separately or in a combined motion to visualize the trajectory of the robot in 3D space.

The real robot costs over $40,000, requires calibration, maintenance, an elaborate set-up and programming, and can be used by one single user at a time. It also consumes a fair amount of electrical energy, takes space in a laboratory and can cause damage or injury if not used properly.

The virtual robot is accessible by as many users as needed, does not cost anything once it has been developed, is safe, and, for educational purposes, is suitable for illustrating many robotics concepts. In VRML, it is an easy matter to embed animation programming that cause the virtual model to move its joints, follow a trajectory, and even move virtual objects much like a real robot would. It should be noted however, that a virtual robot still cannot perform any real work. That remains the main advantage of real robots!
CONCLUSION

Science and Engineering Education can be greatly enhanced and facilitated by the use of virtual reality. This article presented examples of visualization tools, developed using virtual reality programming languages that illustrate a variety of systems in astronomy, chemistry, biology, and robotics. Virtual Reality programming tools created in recent years have now progressed to the point of being readily available, easy to use, and affordable by everyone. VRML is one such tool that allows the creation of three-dimensional objects that can interact with user commands and input to produce efficient models and simulations of real systems. Integrating VRML with other graphical programming languages is an effective way to produce computer tools for students that can integrate student-supplied parameters into virtual reality scenes and systems for experimentation, simulation, and modeling of science and engineering concepts and systems.

REFERENCES

[4]. The VRML 2.0 handbook, Addison-Wesley, 1996.

FIGURE 9
VIRTUAL REALITY MODEL OF THE PUMA 560 ROBOTIC ARM