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DEVELOPMENT OF A LOW-COST VIRTUAL REALITY WORKSTATION FOR TRAINING AND EDUCATION

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1. INTRODUCTION

Virtual Reality (VR) is a set of breakthrough technologies that allow a human being to enter and fully experience a 3-dimensional, computer simulated environment. A true virtual reality experience meets three criteria:

1. It involves 3-dimensional computer graphics.
2. It includes real-time feedback and response to user actions.
3. It must provide a sense of immersion.

Good examples of a virtual reality simulator are the flight simulators used by all branches of the military to train pilots for combat in high performance jet fighters. The fidelity of such simulators is extremely high -- but so is the price tag, typically millions of dollars.

Virtual reality teaching and training methods are manifestly effective, but the high cost of VR technology has limited its practical application to fields with big budgets, such as military combat simulation, commercial pilot training, and certain projects within the space program. However, in the last year there has been a revolution in the cost of VR technology. The speed of inexpensive personal computers has increased dramatically, especially with the introduction of the Pentium processor and the PCI bus for IBM-compatibles, and the cost of high-quality virtual reality peripherals has plummeted. The result is that many public schools, colleges, and universities can afford a PC-based workstation capable of running immersive virtual reality applications. My goal this summer was to assemble and evaluate such a system.

2. THE PC VIRTUAL REALITY STATION

The first point in the 3-point definition of Virtual Reality, above, involves 3D computer graphics. The rule of thumb in digital video is that an animation must run at least 15 frames/sec to appear smooth to the human eye, so I adopted 15 frames/sec as a benchmark for evaluating PC performance. I benchmarked four different PC systems using the Sense8 WorldToolKit software to render a virtual reality scene consisting of approximately 750 polygons. The results for shaded and shaded+textured polygons are tabulated below. Only the Pentium systems gave frame rates for complicated simulations that were above 15 frames/s. A comparison of the two 486-based systems shows similar frame rates despite the factor of two difference in system RAM. In fact, the 80 MHz system with only 8MB of RAM outperformed the 66 MHz system with 16 MB RAM by a factor of 1.21, almost exactly the ratio of the clock speeds. The relative frame rates of the two Pentium systems also scaled with clock speed, the 120 MHz system being about 25% faster than the 90 MHz system. (Note, however, that the 120 MHz Pentium had a 4 MB graphics board while the 90 MHz system had a 2 MB board.)

TABLE 1: PC Performance comparisons

Processor	Clock	RAM	Graphics Accelerator	Shaded frames/s	Textured frames/s
486DX	66 MHz	16 MB	Cirrus Logic w/1 MB ram	7.5	4.0
486DX	80 MHz	8 MB	Trident 9440CX w/1 MB ram	9.1	3.6
Pentium	90 MHz	32 MB	ATI Mach 64 w/2 MB ram	16.7	7.5
Pentium	120 MHz	32 MB	ATI Mach 64 w/4 MB ram	21.0	9.0

From Table 1 we see that a 90 MHz Pentium system, or better, will give adequate 3D graphics rendering performance.

The second point in the 3-point definition of Virtual Reality was real-time interaction to user input. The participant in a VR simulation must be able to navigate through the virtual world, select objects, and move them. I tested three devices for user interaction with WorldToolKit applications: a mouse, a Logitech Cyberman (6 degree-of-freedom mouse with limited tactile feedback), and a ThrustMaster joystick. I also tested the VPL DataGlove and a Spatial Systems Spaceball (6 degree-of-freedom controller) using VPL VR simulation software. For picking and moving objects, the DataGlove was by far the best. For navigation the ThrustMaster joystick was best. The mouse was unintuitive and difficult to learn as a navigation device, as was the Spaceball. The LogiTech Cyberman was awful. I tested two Cybermen and both were poorly constructed, overly sensitive, and nearly impossible to control. The simple tactile feedback feature (a pulse modulation of the controller stem triggered by hitting virtual walls or other objects) was satisfying but did not compensate for the other shortcomings of the device. In Table 2 I rate the peripherals on a scale of 1 to 10 (10 is best, 1 is worst) in two categories: "Picking" refers to the ease with which objects could be selected or grabbed with the device, and "Flying" refers to navigation through the virtual environment. The ratings are subjective, and are based on my own experience with the devices, and the experience of students aged 5 to 12 years who have tested the PC with a VR Human Cadaver application developed at the MSFC virtual reality lab.

TABLE 2: EVALUATION OF VR PERIPHERALS

Device:	Picking	Flying
Microsoft Mouse	8	3
Logitech Cyberman	5	1
VPL DataGlove	9	7
SpaceBall	6	6
ThrustMaster Joystick	N/A	9

Finally, the third point in my definition of Virtual Reality is that the experience must be immersive. Immersion means that you forget about all outside stimuli and become a thinking, feeling part of the computer's virtual world. In theory, total immersion would include touch, smell, temperature, visual input, and sounds. In practice, it is difficult, expensive, and, fortunately, unnecessary to attack all 5 senses to produce a sense of immersion. I find that the visual cues provided by a wide-field-of-view head-mounted display in combination with 3-dimensional sound effects are sufficient to create a powerful immersive effect. The mind fills in the gaps not covered by the HMD and the 3D sound hardware.

2.1 3D SOUND FOR THE PC

3D sound technology operates on the principle that all the spatial information about a sound source is contained in its spectrum. At its source the complex Fourier spectrum of a sound is $S(f)$, where f is the frequency. The acoustic wave propagates to both ears and is filtered by reflections off the human body, primarily the head and shoulders, and the inner ear. When the sound reaches the inner ear, its complex spectrum is $T_L(\mathbf{n},f)S(f)$ in the left ear and $T_R(\mathbf{n},f)S(f)$ in the right ear; **n** is the unit direction vector toward the sound source and T is the "transfer function." The product $T(\mathbf{n},f)S(f)$ in the frequency domain can be expressed as a convolution in the time domain $T(\mathbf{n},t)*S(t)$, and this is the basis of

practical 3D sound devices.

The Alphatron is an expansion card for the PC, sold by Crystal River Engineering, that performs the 3D sound convolution. The head-related transfer function, $T(\mathbf{n},t)$, is loaded into a digital signal processor on a Tahiti MultiSound card, and up to 16 user-defined sounds, $S(t)$, can be spatialized in real time. The cost of the system is $750 retail, and I have successfully incorporated 3D sound effects in WorldToolKit applications using the Alphatron.

2.2 HEAD-MOUNTED DISPLAYS

3. CONCLUSIONS

I have assembled a low-cost virtual reality workstation for education applications using off-the-shelf technology. The least expensive system which meets all the criteria for an acceptable VR platform consists of the following:

- a 90 MHz Pentium CPU with 32 MB system RAM
- video graphics accelerator with at least 2 MB on-board RAM
- a Thrustmaster joystick for navigation
- a Microsoft mouse for object-picking
- a Virtual I/O *iglasses!* HMD with 25x9 deg field of view and 640x480 pixel resolution
- a Crystal River Engineering Alphatron for 3D sound spatialization

The total retail cost of the system, including a 15" VGA monitor and a WorldToolKit run-time license is about $6000. The ideal PC-based system would include a DataGlove for object-picking, but the cost would increase by 30%. A mouse, for only $29, is a reasonable trade-off. Three years ago a system with the same capabilities would have cost at least an order of magnitude more. With prices still dropping and capabilities increasing I predict that the next year will see increasing numbers of classrooms equipped with VR workstations.