HARDWARE TECHNIQUES

An optical videodisk system for visual performance testing with stereoscopic TV displays

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The potential advantages of and several problems with using interactive videodisk technology for vision research are discussed. A visual performance testing system is described in which a computer-controlled, dual-channel, interactive videodisk apparatus was used to present realistic three-dimensional images with a stereoscopic TV display.

In recent years, major efforts in the experimental study of vision have been directed toward understanding visual perception under complex, dynamic stimulus conditions. Indeed, this trend toward increased stimulus complexity has been occurring in many areas of behavioral research and has been made possible by the adoption of inexpensive, powerful information processing technologies. Interactive optical videodisks provide vision researchers with opportunities to record large quantities of detailed, dynamic visual imagery onto a lightweight, compact, easily duplicated, durable storage medium and to randomly access the stored imagery in a wide variety of playback modes under programmable computer control. Thus, it would seem reasonable that vision researchers and experimental psychologists from a diversity of specialized areas of interest would adopt optical disk technology for its many desirable features.

To date, however, very few vision researchers have used optical disk equipment in the laboratory and, with the exception of Kristina Hooper's 1981 article in this journal, almost nothing has been written on the topic in the behavioral research literature. Most of the information on optical disk technology has been published in specialized communications and engineering trade journals or in the proceedings of communications or engineering conferences that few behavioral researchers attend.

In this paper, we briefly review available optical disk technology and consider its usefulness as a general research tool for the vision researcher. We also provide several of our strategies for use of optical disks in conducting visual performance experiments with stereoscopic TV displays. We hope that this information will stimulate wider consideration within the vision research community for the interesting opportunities provided by optical videodisks and similar emerging technologies.

AVAILABLE OPTICAL VIDEO DISK TECHNOLOGY

Optical disk technology is gaining wide acceptance as a medium for mass digital data storage in the form of audio compact disks (CDs), compact disk read-only memory (CD-ROM), interactive compact disk (CD-I), and write-once read-many (WORM) optical disk drives. However, for the purposes of this paper, we focus only on optical disk systems dedicated to storage and playback of video imagery that offer frame-precise random access and rapid interactive control features.

At present, five generally available optical videodisk formats provide this sort of random access and interactive control. These include the LaserDisc, OMDR, Hitachi, VHD, and LaserFilm formats, two of which are described in detail below. A recent comparison of all these formats is provided by Jarvis (1986). Unfortunately, the five formats are not compatible insofar as a disk recorded on one cannot be played back on any of the others. Lasers are used with all formats to write and read information stored on a spinning disk, and for this reason, they are frequently referred to as laser disks. Once written, the

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information is permanently embedded in the surface of the disk, and it cannot be erased and rewritten. Large-scale efforts are under way within the computer industry to provide erasable optical disks, and working prototypes of several candidate storage technologies have been demonstrated; however, reliable, low-cost products are probably at least several years away (Lieberman, 1986).

The two currently available optical disk formats with which we are most familiar are the 30.48 cm (12 in.) diameter Constant Angular Velocity (CAV) disk, and the smaller 20 cm (8 in.) diameter Optical Memory Disk Recorder (OMDR) disk. Available in prerecorded form on the home video entertainment market under the trade name LaserVision, a CAV disk holds up to 54,000 frames, or 30 min of real-time motion imagery on one side. Similar in size and appearance to the CAV format is the Constant Linear Velocity (CLV) format, but CLV is a capacitive storage medium that is read with a mechanical stylus, as is a conventional phonograph record. It does not provide random frame access capability, so we will not consider it further here. The smaller OMDR format is intended for much more specialized industrial applications and is limited to 24,000 frames, or approximately 13.3 min of continuous motion playback on a side. The main advantage of the OMDR format over the CAV format is the availability of relatively inexpensive recording devices: OMDR recorders are available at a cost under \$20,000, whereas the least expensive CAV recorder costs 10 times that amount.

Both formats are capable of recording a stereophonic sound track directly onto the disk or dubbing in one or both audio channels, but these features are only enabled when recording or playing back at the conventional NTSC motion frame rate of 30 interlaced frames per second.

Interactive video exists in many forms, so why choose videodisk? Most users choose the videodisk medium because of the rapid and precise access to individual video frames that it provides. Access times can be 200 to 300 times faster using a videodisk system than using the magnetic tape format. Unfortunately, the process of producing a videodisk is quite a bit more involved than using one of the conventional or alternative pictorial storage technologies that Hooper (1981) compared (i.e., drawings, photographic prints and transparencies, motion pictures, videotape recordings, and computer-generated images). Such materials serve only as the starting points for CAV disk production. CAV disks are generally produced by assembling a variety of visual materials and then submitting these to a CAV mastering facility for transfer to disk.¹ Recent developments in CAV recording technology (Magel, 1986) have greatly reduced the costs for producing small numbers of disks.

Assuming that the researcher has decided upon an appropriate set of stimulus frames or frame sequences, he/she must then select a pictorial medium on which to submit the materials to the disk mastering facility. If still-frame imagery is all that is required, the most economical visual medium is 35-mm slides. All of the CAV mastering facilities have high-quality color cameras set

up to convert the materials to video signals that can be transferred to disk. The method with the greatest resolution and quality would be to record live with broadcast-quality cameras, but this approach is expensive and time-consuming and is rarely done. An alternative method is to put together images from original camera-mastered tapes. The most popular and widely used method of doing this is with very expensive, commercial-studio quality 1-in. video recorders. The interactive images, along with a required SMPTE time code track, are pre-edited on the 1-in. tape into the sequence required by the user, and then they are directly copied to disk at the mastering facility.² Another alternative method is to submit 35-mm movie film shot at 30 frames per second (24 fps is normal). Shooting at 30 fps improves the resolution of the images by 25% and also is directly translatable at the NTSC frame rate. Both methods described above will provide the user with resolution superior to conventional home entertainment standards. If one cannot afford the 1-in. format, materials may also be submitted in the 3/4-in. videotape format, but this method will, at best, provide about 85%–90% of the available resolution that the disk is capable of providing.

Access Speed

The speed of access to imagery offered by optical disk players can substantially improve data collection rates, even when still frames are used only in a slide-projector-type display mode. For example, typical random access times for conventional 35-mm slide projectors are on the order of 3 sec for a tray of only 80 slides. Optical disk players can access and display any one of tens of thousands of individual pictures in as little as .5 sec. Their speed advantage for accessing motion sequences is even more dramatic when compared with speeds of videotape and motion picture film. Because tape and film transports and the linear arrangement of pictures provided by both media limit access speeds, it can easily take 3 min or longer to access a frame sequence; even so, there is no assurance that the precise sequence of frames sought has actually been accessed.

Obviously, use of optical disks can greatly simplify experimental setup or modification, particularly when many stimuli are required or when it is desirable that many randomized orders of stimuli be presented. As with systems in which stimulus patterns are totally computer generated, randomizing orders of presentation reduces to a trivial programming chore with computer-controlled optical disk systems.

Repeated Playback

Optical disks, in addition to providing rapid random access, support prolonged display of a single frame; a much more limited display time is possible on a videotape player. Over a period of continuous access to a single frame, the videotape will gradually deteriorate to a point at which the resolution is so poor that the frame becomes unstable and unusable. This is particularly problematic

when experimental design dictates prolonged and/or frequently repeated display of single frames or frame sequences. Image quality of single frames displayed by means of optical disks will not be affected over a long period of repeated accesses, because optical read/write heads track 1 to 2 mm above the disk surface and because optical disks store data below their surface. The disks are relatively impervious to small dust particles and minor scratches.

THREE SPECIFIC APPROACHES USING STEREOSCOPIC TV DISPLAYS

A Static Stereoscopic TV Application

In this section, we do not intend to provide an exhaustive treatment of all possible uses of optical disk technology for studies of visual performance using stereoscopic TV displays. Rather, our modest goal is to present a few examples from our own recent experiences with optical disk technology. We have been working to implement as versatile a system as possible to support visual performance testing with various stereoscopic TV display strategies for teleoperator systems (i.e., remotely operated manipulators and vehicles). For our work, the interactive disk system must be configured in two distinct ways; the first supports field image acquisition, and the second supports visual performance testing in the laboratory. We discuss each configuration in turn.

Experiments conducted thus far with the optical disk system have dictated the collection of stereoscopic video images of outdoor scenes from a variety of camera interaxial separations, each taken at multiple levels of image magnification (Spain & Pepper, 1986). Video recording, as opposed to photographic recording with subsequent transfer to video storage, was desirable for several reasons. Recording was required in order to ensure identical images for presentation to multiple experimental observers both within and across testing sessions. Direct recording to optical disk, as opposed to recording on videotape with subsequent transfer to CAV optical disk, was considered critical to ensure efficient in-house production of stimulus materials. We also sought to minimize stimulus production time and costs by ensuring adequate image quality by carefully inspecting the recorded images immediately after recording during field image-collection sessions. Repeated playback of the same sets of video frames used as stimulus materials required that the recorded medium not be degraded by subjecting single frames to thousands of repeated accesses of several seconds' duration each. Random access was desirable to efficiently present frames to observers in pseudorandom orders to control for various order effects that generally have not been adequately controlled in many past experimental designs using stereoscopic TV displays (see Smith, Cole, Merritt, & Pepper, 1979, for more detailed criticism). Precise synchronization of frames, during both image recording and playback, was required to eliminate

spurious stereoscopic effects that would have resulted had the left and right channels not been synchronized. All of these requirements were met by a pair of Panasonic TQ-2023F Optical Memory Disk Recorders (OMDRs). The OMDRs support real-time color video recording at image-resolution levels superior to those attainable with conventional, portable video tape recorders. OMDRs are remotely controllable through a standard RS-232 interface operating at 19,200 baud. A command protocol consisting of simple ASCII strings is provided for the OMDR, which supports 20 commands, including SEARCH FOR FRAME, STILL/STEP FRAME, VIDEO ON/OFF, and PLAYBACK (at normal frame rate as well as a variety of fast and slow rates). Average access time between any two frames on the disk is fast, approximately .5 sec. A special command is provided to allow frame jumps of ± 5 frames during the video vertical-blanking interval. This feature supports limited interactive motion simulation, free from annoying video flutter and drop-out effects that occur between frame accesses. Simultaneous control of both OMDRs from a single serial port was accomplished by splitting the outgoing signal lines of an RS-232 cable to the serial ports of both OMDRs. The OMDRs were synchronized frame-for-frame with each other and with the array of video cameras by means of a video sync generator.

Since, in general, outdoor lighting and scene conditions are in a constant state of flux due to factors beyond experimental control, it was necessary to record a series of video frame-pairs from varying interaxial separations in rapid succession, before the scene changed substantially. An array of four unequally spaced cameras was electronically balanced, optically adjusted, and aimed along paralleled optical axes. By time-multiplexing the video signal outputs from the five unique left-right camera pair combinations that were possible given this arrangement, five separate stereoscopic views of the same scene could be recorded by our dual-channel recording system within a period of six video frames, or approximately 200 msec. For each of the frame pairs recorded to the disks, left and right frames were recorded simultaneously, eliminating spurious depth effects produced by motion of objects in the scene. The equipment configuration used for stereoscopic image collection is diagrammed in Figure 1. It should be noted that field operation of the OMDRs required special provisions to be made for voltage regulation and for temperature and humidity control. It was our

Figure 1. Apparatus for stereo image collection.

experience that the OMDRs only worked reliably in the 70% humidity that is typical in Hawaii at temperatures lower than 21°C (70°F).

Once an appropriate set of stereoscopic images was recorded in the field, the recordings were transported back to the laboratory where the same machines used to record the images were used to play them back under computer control. Figure 2 is a diagram of the system used to display stereoscopic images in the laboratory. Both monoscopic and stereoscopic images were shown by means of a bench-mounted polarizer stereoscopic TV display of the type frequently used in stereo TV experiments (see Cole, Pepper, & Pinz, 1981, for a detailed description). Stereoscopic images were provided by playing back the right-channel OMDR's signal to the right-channel monitor and left-channel signal to the left-channel monitor. Monoscopic images were presented by splitting either a left- or right-channel signal to both the left and right monitors. This arrangement provided a more appropriate control condition for comparisons between stereoscopic and monoscopic display techniques than did simply turning off or blanking one of the video displays or using a single monitor as a display.

With the OMDRs, literally thousands of stereoscopic still frames were available for testing within a single experimental session. Randomizing orders of presentation was simply a matter of selecting from a number of frame sequences that were predefined and stored by the controlling computer as testing protocols. Response time measures were taken by synchronizing the start-up of the computer clock with the video and measuring elapsed time between onset of frame display and the observer's responses. Comparisons between various candidate video system parameters were made in the laboratory that would not have been practicable under field testing conditions. Stereoscopic images required for experimental instructions and initial screening/training sessions for new observers were also facilitated by use of the OMDRs.

Interactive Motion Parallax Simulation

Results of a preliminary study undertaken several years ago (Spain & Cole, 1982) suggested that depth relationships among objects in a stereoscopically televised scene were perceived with increased accuracy when movements

of a remote pair of video cameras were linked to the natural head and torso movements of a human operator. In addition to providing retinal disparity cues, these stereoscopic TV viewing systems allowed the operator to observe the layout of the televised scene from a variety of viewpoints and to use body movements to produce motion parallax cues to the relative depths of objects in the scene. A controlled simulation of the remote presence system utilizing the interactive capabilities of the videodisks is currently under way.

Given sufficient access speed, storage capacity, and an appropriately constructed and indexed image database, a single optical disk player could provide a convincing simulation of what would occur visually as a result of an operator's complex body movements relative to a depicted scene. Practical constraints on speed of frame access (i.e., the number of frames that the playback head can move reliably within the period of the video vertical blanking interval) limit what a single disk player can be used to simulate. With only modest computing power, however, it is possible to coordinate frame access and to selectively switch video output from a bank of multiple disk players to overcome the frame access speed limitations of a single player. Successful implementations of the strategy exist for surrogate travel systems (e.g., Lippman, 1980) and for advanced flight-simulation systems that allow up to six degrees of freedom for motion (e.g., see Tucker, 1984). But, for our somewhat more limited experimental interests, we decided to forgo most of the complexity of natural body movement, to constrain observers to a single axis of linear movement, and to note the effects of simulating this simple linear movement on performance with a stereoscopic TV viewing system. Given such constraints on the axis of motion as well as the acceleration and velocity of observer head movements, a pair of OMDR players operating in parallel with their +5 frame jump capability were judged to be adequate to simulate head motion in preliminary demonstrations.

Given these constraints, the simulation methodology reduces to a matter of establishing a common time base between the control computer and the OMDRs, and then determining the amount of time required to sense and output a jump-to-frame command over the serial interface in sufficient time for the command to have effect during the next frame interval. Care must be taken during image collection to provide finely enough sampled viewpoints to overcome artifacts induced by the discrete nature of video image sampling. Sampling should ensure a smooth, apparently continuous transition between various frames within the constraints dictated by experimental design.

A memory buffer in the controlling computer can also be used to store a large number of sampled head positions and to execute them in a delayed fashion in order to introduce time delays between head motion and apparent viewpoint in the display to determine any effects that such delays might have on perceptual performance. Additionally, the portion of the simulation control program

Figure 2. Visual performance testing apparatus.

Figure 3. Apparatus for motion parallax simulation.

that maps momentary head sensor measures into outputs to the OMDRs to access specific frames for display can be modified to adjust relative gain in motion between observer head motion and apparent sensor motion. Such adjustments in the scale of motion can also be provided to the system operator for interactive optimization of performance.

In current investigations, we are interested in addressing the design question of whether the extra complexity, expense, and effort involved in coupling camera movements to operator head movements is justified by any reliable performance advantages that might be demonstrated by using it. The investigation shall employ a yoked control (i.e., a second individual who is viewing an identical display and who is required to make the same perceptual judgments as the first individual whose movements determine which frames will be accessed for the display). The equipment configuration used for this experimentation is diagrammed in Figure 3. Given synchronized, dual-channel display capability, these demonstration and control conditions can be conducted with stereoscopic TV displays.

Simulation of Variable Interaxial Separations

Another opportunity to study perception with stereoscopic TV imagery is possible with the OMDRs but is impossible to properly implement on a video system that cannot provide precise, frame-accurate access. The technique, depicted in Figure 4, involves recording imagery from a single sensor that is moved at a constant, or known, rate relative to a scene. A further assumption in using this technique is that objects in the scene remain stationary during the course of recording; otherwise, disparities that arise from the movements of objects are perceptually confusable with the disparities produced by "true" parallax between the camera and the scene. Note that the interlacing used in conventional video systems produces blurred or jittery-looking areas in the individual frames where motion of the camera relative to the scene is substantial across the $\frac{1}{60}$ of a second between the odd and even video field scans. Ordinarily, the effect is not

noticeable with motion playback, but when the still-frame mode is used, the effect is readily apparent. There are several available means of eliminating this spurious motion during still playback. The recording camera could be held stationary during picture taking and moved in incremental fashion through the scene. Alternatively, one could record the images initially with a motion picture camera and subsequently transfer the images from film to disk. A third alternative is that one could use a specially shuttered high-speed video camera that outputs a standard NTSC signal to record directly onto videodisk.

By using a pair of synchronized optical disk players, each provided with an identical copy of the videodisk, it is possible to effectively vary effective interaxial separation by offsetting the frames that are displayed simultaneously in the left and right channels of the display. For example, were the camera moved relative to the scene in a left-to-right direction (i.e., the objects depicted by the display moved from right to left across the screen on playback), delaying a frame's presentation to the right eye would effectively move that eye to a vantage point to the right, relative to the left eye's vantage point, thus providing retinal disparities that code veridical information regarding the relative depths of objects in the scene. The greater the frame offset during display between left and right

Figure 4. Apparatus for simulation of variable interaxial separations.

channels, the greater the effective interaxial separation of the viewing system tested. This is true not only for still frames, but also for motion sequences, and holds when either the scene or the recording camera or both are moved. Computer control of frame access also makes it possible, even trivial, to provide the observer a means of adjusting the effective interaxial separation by allowing him/her to set the left-right channel offset. By providing this capability, the operator can adjust the effective interaxial on the basis of immediate experience and individually optimize his/her view for a particular task.

CONCLUSIONS

In conclusion, optical videodisks and other emerging video image storage technologies offer an economical means for vision researchers to capture a considerable amount of the detail and interactive possibilities of the real world and bring them back into the laboratory. Then, through careful experimental design and implementation, researchers can provide a close surrogate to three-dimensional visual and auditory experiences in complex, real-world situations. But, unlike the situation encountered in most in-field testing conditions, the laboratory-created sensory "environment" is precisely controlled, measurable, and replicable. Thus, optical disk technology opens the way to conveniently studying complex interactions between the active perceiver and his/her environment that have not been adequately quantified and characterized in detail to date.

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NOTES

1. For a listing of the eight CAV mastering facilities currently operational in the United States, see Ochiva (1986).
2. See Mannes (1986) for details about the procedures required for transferring materials to disk.