The Use of Head Tracking Technology in Armored Vehicle Simulation

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ABSTRACT

The physical, mechanical and electrical properties of armored vehicle simulator modules present a highly challenging environment for the use of head tracking technology. However, the potential of head tracking to enhance simulation fidelity and dramatically reduce cost demanded that a solution for this application be found. In 1993, General Electric (now Lockheed Martin) delivered the M1A1 Platoon Gunnery Trainer which was the first U.S. armored vehicle simulator to use head tracking technology. Subsequently, the head tracking design was refined for the M1A2 PCOFT (Saudi Foreign Military Sale) which will be delivered in 1995. Head tracking will also be integrated into the Advanced Gunnery Training System (AGTS) which was awarded to Lockheed Martin in 1994. Concurrently, Evans and Sutherland is developing a comprehensive head tracking capability for M1A1, M1A2, Bradley Fighting Vehicle, Armored Personnel Carrier (APC), and FIST-V modules in fulfillment of Close Combat Tactical Trainer (CCTT) program requirements.

The power of head tracking technology lies in its ability to provide natural (transparent to the trainee) display switching, total field of view control, high resolution area of interest control, and motion parallax for improved depth perception. Major design issues include minimizing transport delay, reducing and filtering noise created inherently by the simulator, physical integration of head tracking equipment within the limited confines of the simulator module, eliminating confusion of the device as it is controlling the imagery of multiple displays, calibration for individual trainees, and real-time calculation of viewport geometry. This paper presents the state-of-the-art in head tracking for armored vehicle simulation and the prospects for even higher fidelity head tracking in future developments.

ABOUT THE AUTHORS

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RATIONALE FOR HEAD TRACKING

Head tracking technology provides a means to increase the fidelity and reduce the cost of military simulators. Fidelity is increased by using head tracking data to control the field of view presented to the trainee such that it matches that of the operational system for the full range of possible head positions and orientations. A natural by-product of the use of head tracking is motion parallax, i.e., the relative position and orientation of close objects in the scene changes more rapidly than distant objects in response to head motion. Motion parallax enhances the sensation of depth in computer generated images and allows the trainee to look around objects that are close to the eyepoint.

Cost is reduced because the image generator capacity can be sized to support only the worst case instantaneous field of view and not the total field of view (field of regard). Head tracking further optimizes cost/performance by allowing the image generator to increase forward resolution and decrease peripheral resolution within the instantaneous field of view. This is commonly referred to as area of interest processing.

CURRENT MILITARY APPLICATIONS OF HEAD TRACKING

Head tracking is currently used in head-slaved area of interest (AOI) projection systems and in helmet mounted display (HMD) systems. Head-slaved projection systems are designed to display each frame of imagery at its correct on-screen position based on the eyepoint supplied to the image generator by the host computer. In other words, the image is always maintained at the correct angular location and in true perspective relative to the own-vehicle. The image, therefore, will "trail" the instantaneous head position in proportion to the transport delay of the system and the rapidity of head position/orientation. As long as the AOI field of view is large enough and head motion slow enough, the high resolution (foveal) region of the trainee's eye will remain within the high resolution AOI
inset. Lower resolution background projectors may remain fixed or may also slew with head motion.

In HMD systems the display device is physically coupled to the head. The image cannot "trail" the head, therefore, prediction software and/or hardware panning is required in order to display an image field of view that is highly accurate for any given instantaneous head position and orientation

In existing armored vehicle simulators, the display devices are neither HMD's nor head-slaved projectors, but fixed CRT's. The use of head tracking with fixed CRT's in armored vehicle simulators will now be discussed.

HEAD TRACKING IN ARMORED VEHICLE SIMULATION

For armored vehicle simulators, a low cost, non-intrusive head tracker of moderate fidelity is needed. However, the physical (confined space), mechanical (cab material characteristics), and electrical (EMI producing) properties of these simulators make achievement of even modest head tracking performance very challenging. The first U.S. armored vehicle simulator using head tracking was the M1A1 Platoon Gunnery Trainer (PGT) delivered in 1993 to Ft. Knox by General Electric Corporation (now Lockheed Martin). The head tracking design has continued to evolve with subsequent developments, viz., the M1A2 Platoon Conduct of Fire Trainer (PCOFT) to be delivered in 1995 to Saudi Arabia, and the Advanced Gunnery Training System (AGTS) to be delivered in 1996.

In 1993, Evans and Sutherland began work on a head tracking design for M1A1, M1A2, M2A2/M3A2, FIST-V, and APC armored vehicle modules in fulfillment of the Close Combat Tactical Trainer (CCTT) contract requirements. Development of these modules is scheduled to be completed by June 1996.

The Ft. Knox PGT system simulates the forward three vision blocks (periscopes) of the M1A1 tank (there are a total of six vision blocks in the operational tank). The PCOFT and AGTS trainers simulate all eight

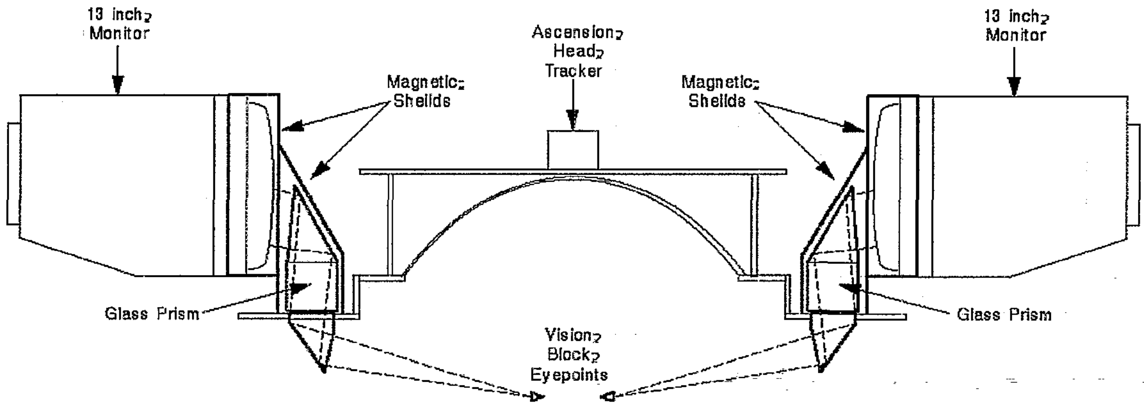

Figure 1. PGT/PCOFT/AGTS Commander's Station, Side View.

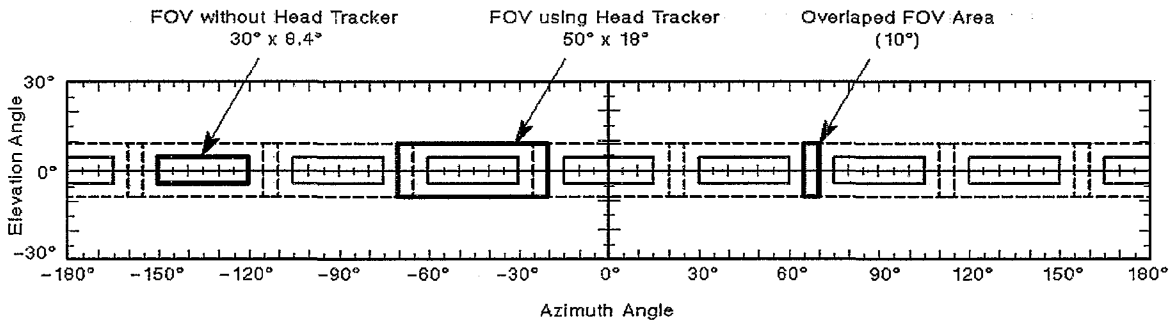

Figure 2. Field of View through M1A2 Commander's Vision Blocks.

vision blocks of the M1A2. The head tracker is used to determine if the vision blocks are being viewed, and which three of the eight vision blocks will be supplied with imagery.

In all PGT/PCOFT/AGTS systems head tracking is also used to change the instantaneous field of view(FOV) of individual vision blocks in response to head motion. By changing the FOV appropriately with head motion, the trainee is able to look around the "dog house" and other own-vehicle obstructions as he would do in an actual armored vehicle. The trainee is also able to look around trees, corners of buildings and other objects in the scene that are near the eyepoint.

In PCOFT/PGT/AGTS systems, the imagery of each vision block is provided by a dedicated CRT monitor (see Figure 1). To maximize resolution, the instantaneous FOV of each vision block fills the entire horizontal width of its corresponding monitor. When the head is moved side to side or up and down, the FOV on the monitor is "scrolled" between pre-set FOV definitions by the image generator based on the head tracker data. The position on the monitor and size of the image remains constant as does the resolution of the imagery which provides for consistent target detection.

For CCTT, a similar approach is used to simulate the vision blocks of the M981 (FIST-V) and M113 (APC). Three of seven vision blocks are simultaneously active for the FIST-V, and three of five vision blocks are simultaneously active for the APC. The head tracker is used to select which three monitors are active, and to provide access to the total field of view of each active vision block. Instead of scrolling, the image generator uses the head tracking data to continuously recompute the instantaneous FOV displayed on each active monitor.

CCTT M1A1, M1A2, and M2A2/M3A2 simulators are required to provide imagery for the commander's popped hatch (CPH) as well as all vision blocks. The

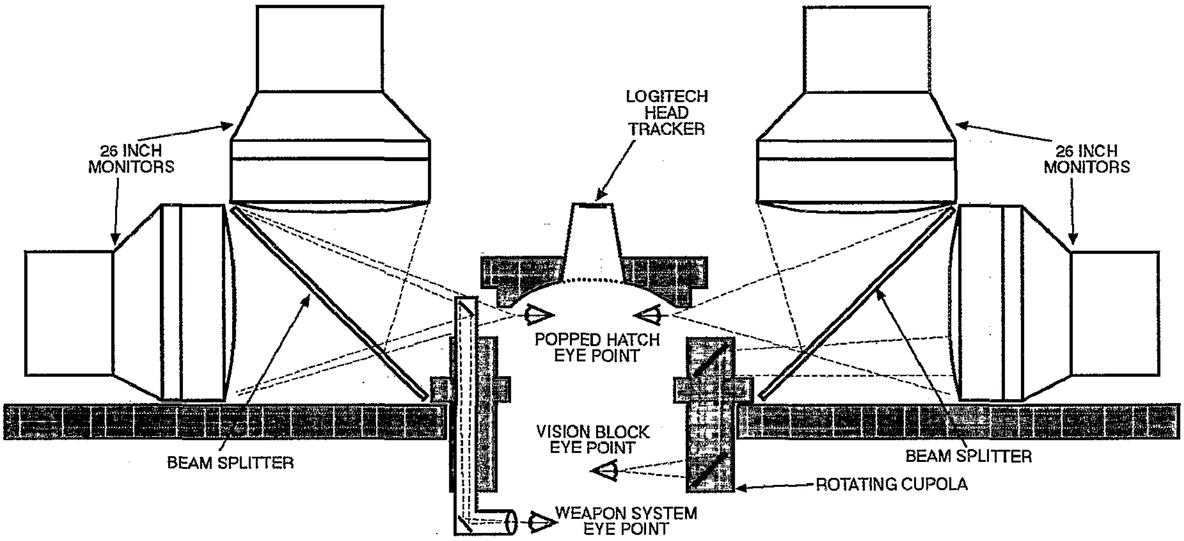

Figure 3. CCTT Commander's Popped Hatch, side view.

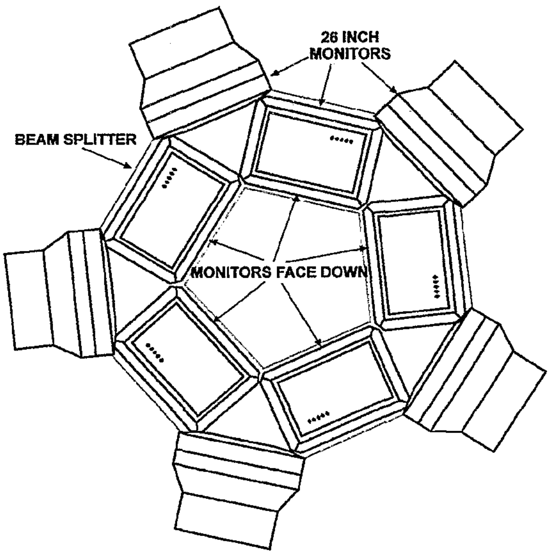

Figure 4. CCTT Commander's Popped Hatch, top view.

CPH imagery is presented on a ring of ten 26" monitors that surrounds the simulated hatch opening (see Figure 4). The head tracker is used to select five of the ten 26" monitors to be active simultaneously providing an instantaneous horizontal FOV of 180 degrees within a 360 degree total horizontal FOV. The instantaneous vertical FOV is 27 degrees at the design eyepoint. The instantaneous horizontal FOV for each of the ten monitors is 36 degrees at the design eyepoint.

During an exercise, the trainee's head position will move up and down, left and right, and in and out with respect to the design eyepoint. All head movement results in a frame by frame recalculation of each active monitor's FOV, and distortion correction (see section on Viewport Geometry) for oblique viewing of the true perspective images on the display monitors. Based on vertical head position data (up and down movement of the head) from the head tracker, an additional 28 degrees (14 degrees in each direction) of vertical FOV can be accessed resulting in a total vertical FOV of 55 degrees.

In addition to smooth and natural FOV control, continuous tracking of the trainee's head position provides motion parallax and the ability to look around own-vehicle obstructions and nearby objects when peering out of the popped hatch in CCTT simulators.

This same ring of monitors is also designed to be seen from within the M1A1, M1A2, and M2A2/M3A2 armored vehicles through the vision blocks (see Figure 3). Access to vision block total field of view is achieved automatically in these modules (without head tracking), because the vision blocks point to a larger continuous FOV being displayed by the monitor ring. However, motion parallax and the ability to look around own-vehicle obstructions is not presently provided, because the eyepoint used to compute the imagery on the CPH monitor ring is not dynamically updated from head tracker data while the vision blocks are being viewed.

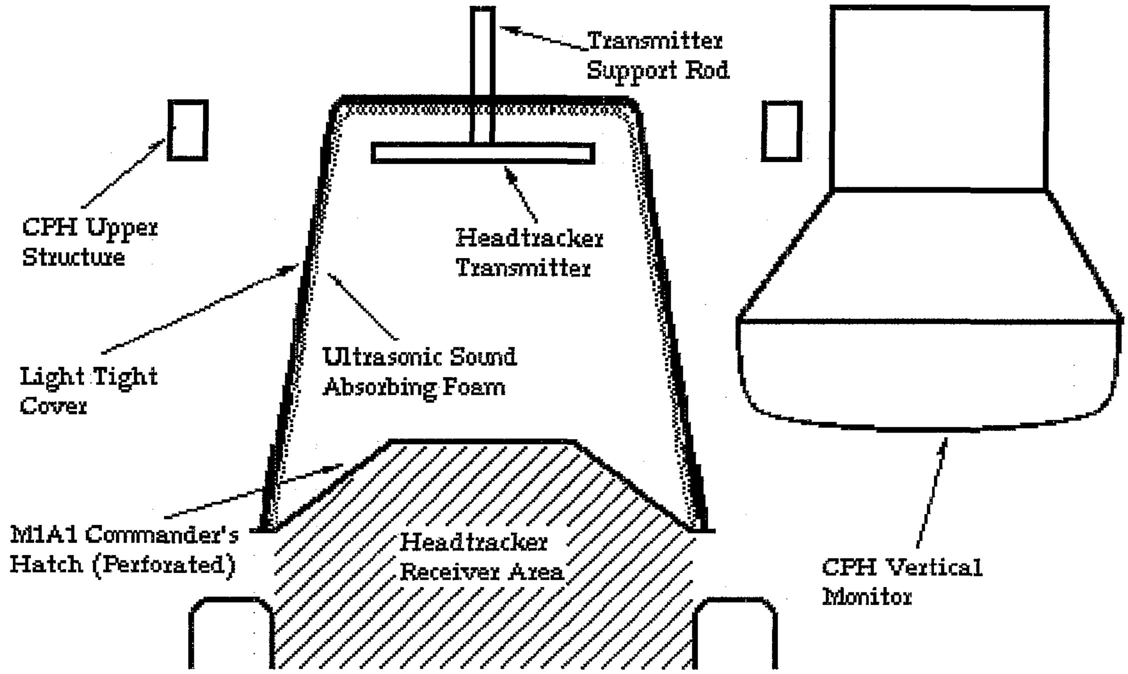

Figure 5. CCTT Head tracker

TECHNICAL DISCUSSION

Head trackers are selected based on their cost, achievable performance, range of motion, and compatibility with the environmental and safety factors inherent to the given application in which they will be used. Lists of commercially available head trackers and their manufacturers are found in the references [Lathom 1994, Hollands 1995]. Comparisons of the major types of head trackers are also found in the references [Meyer 1992, Ferrin 1991]. For CCTT trainers, the Logitech ultrasound head tracker has been selected. The Ascension "Bird" (dc electromagnetic) head tracker is used in PCOFT/PGT/AGTS simulators. The following is a discussion of technical performance issues relating to the integration of these head trackers into armored vehicle simulations.

Linearity.

Linearity is the measure of how consistent the head tracker's performance is over the device's entire range of motion or viewing volume of the application. The performance of all commercially available head trackers is degraded by noise inherent to the environment in which they are used. Noise typically varies as a function of spatial position within the environment resulting in not only degraded performance, but non-uniform performance of the device. Non-linearity can often be greatly reduced by mapping head tracker error as a function of spatial position. This is accomplished by taking a large sample set of measurements at registered positions within the viewing volume and comparing the head tracker readings with the known values.

The electromagnetic field produced by the Ascension Bird head tracker can be spatially warped by electromagnetic interference (EMI) emanating from CRT displays, and by any metal components which are associated with the simulator, resulting in non-linear performance. A calibrated jig is used to compare actual head tracker output readings with the true values for approximately 500 points within the viewing volume of PCOFT/PGT simulators. The set of error values are transformed into coefficients (by a software utility provided by Ascension). These coefficients are in turn used by a software program which corrects the non-linear output readings of the head tracker in real-time. A high degree of linearity is achieved using this technique.

The performance of the Logitech head tracker used in CCTT modules can potentially be degraded by any physical object in or near the viewing volume. The Logitech head tracker makes use of three ultrasound waves which are transmitted by three miniature speakers and detected by a receiver unit comprised of a set of three miniature microphones. By triangulation, the outputs of the three microphones are used to determine the position and attitude of the surface on which the receiver unit is mounted (in this case the top of a soldier's helmet). If any object comes between the transmitter and receiver, the direct wave will be blocked resulting in degradation or even non-performance of the head tracker.

In the CCTT armored vehicle modules, it was desired to include a physical hatch (in the popped position) as part of the mock-up of the simulated vehicle's physical structure. However, the only feasible mounting configuration for the head tracker causes the simulated hatch to block the direct path between the transmitter and receiver units (see Figure 5). For this reason the solid hatch structure was replaced by a metal mesh. The mesh was designed to be sturdy, yet transparent enough to allow ultrasound waves to pass through it.

Ideal performance of the Logitech head tracker is achieved when only the direct waves from the transmitter reach the receiver unit. If any portion of an ultrasound wave impinges upon a peripheral surface and reflects back into the viewing volume it can be picked up by the receiver unit as ultrasonic noise. In CCTT simulator modules the direct path between the transmitter and receiver is surrounded by sound absorbing foam in order to attenuate reflections. Spatial mapping of head tracker error in CCTT modules is currently not planned, however this could be performed if non-linearity caused by peripheral reflections or interference from the hatch mesh structure proves to be excessive.

Resolution.

Resolution is the measure of the head tracker's ability to discriminate between relative positions and orientations within the viewing volume. The advertised ("spec. sheet") resolution of a head tracker is based on the principles of physics governing the device (e.g., electromagnetism, acoustics, etc.), the precision of the electronics (e.g., position and orientation data word length in bits), and the extent to which noise produced internally by the device itself is prevented or filtered out (e.g., noise introduced by analog to digital conversion circuitry).

The achievable resolution of the head tracker depends not only on its ideal "spec. sheet" resolution, but the extent to which environmental noise can be controlled. Correction of spatial non-linearity (as discussed above) does not eliminate all noise - it only removes most of the "dc bias" level of the noise. There are also temporal forms of noise to deal with, especially electromagnetic noise produced by CRT monitors. The burst of EMI generated during the CRT vertical retrace only exists for several microseconds, however if the electromagnetic head tracker is in the process of making a measurement when the retrace occurs (every 16.7 ms./60 Hz for the non-interlaced monitors used in PGT/PCOFT modules), the noise will introduce error in the result.

EMI is also generated during the CRT horizontal retrace, however, electromagnetic head trackers are not capable of beginning and ending a sample fast enough to avoid these noise bursts. Temporal noise that cannot be avoided can be reduced by the use of real-time post-processing software algorithms which remove noise through low-pass or notch filtering of multiple head tracker data samples. CCTT systems are presently disabling the standard Logitech software filtering and are processing the raw head tracking data with custom software to optimize performance. PGT/PCOFT systems use the standard filtering software supplied with the Ascension head tracker.

The Logitech head tracker is being operated at 50 Hz., which is its maximum sampling rate. Experimentation with the Ascension head tracker within the simulator environment revealed that the best performance (least amount of noise) is achieved when sampling at a rate of 45 times per second.

Truly random noise (with no dominant spatial or temporal frequency components) can only be reduced by eliminating its source, i.e., metal and EMI generators in the case of the Ascension head tracker, and spurious reflections and obstructions in the case of the Logitech head tracker. In PCOFT/PGT modules, supplemental EM shielding material is wrapped around monitors, and some metal structures have been replaced with fiberglass. In CCTT modules, unwanted reflections are dampened by sound absorbing foam, and a specially designed hatch is used to minimize wave obstruction as mentioned previously.

Accuracy.

Accuracy is the measure of the head tracker's ability to correlate with an absolute reference frame for position and orientation. It is also a measure of how consistent or repeatable the head tracker measurements are when the head returns to an identical state at a later time. The ideal accuracy achievable by a head tracker is degraded by noise in the same manner as resolution. Accuracy can also be degraded if the head tracking device exhibits drift over time. Drift is a problem for some inertial head trackers which are discussed in the New Technology section below. The same compensation techniques used to prevent loss of resolution (as discussed above) also serve to preserve maximum head tracking accuracy for both the Logitech and Ascension head trackers. Drift is not a concern for either of these devices.

Absolute accuracy is not required for the head tracker controlled out-the-hatch and vision block imagery. These viewports are used to provide vehicle commanders with greater situational awareness and to relay approximate bearing of targets to the vehicle gunner. This is in contrast to the precise reticle aiming of simulated weapons sights which are not head tracked.

Stability.

Stability is the measure of how much the head tracker's output varies for a stationary head position and orientation. If the output variation is large the image will appear to jump or oscillate even when the head is intentionally kept still. Stability is a function of both the average noise level and how widely the noise values fluctuate. Thresholding is used in both Ascension and Logitech head trackers in order to improve stability, i.e., the image is prevented from changing until the head position changes by a prescribed amount. This technique effectively limits the achievable resolution to the threshold value.

Transport Delay.

Head tracker transport delay is the measure of the lag between the time a new sample of head position and orientation is initiated and the time when the new values are actually available for computing an image. The Logitech transport delay varies between 25 ms. and 45 ms. (20 ms. for the 50 Hz sampling rate + 3 ms. for head tracker to host RS-232 communications + 2 ms. for host processing + 0 to 20 ms. for synchronization with the fixed update rate of the image generator). The host in this case is a Motorola 162 single board computer resident in the ESIG image generator front end. Therefore, a second host to image generator communication is not required.

The total system transport delay includes not only the head tracker delay, but also the transport delay of the image generator and display refresh. For all CCTT configurations, this amounts to an additional 184 ms. delay (the 2 1/2 frame ESIG pipe operating at a 15 Hz update rate takes 167.7 ms. and the 60 Hz non-interlaced display refresh takes 16.7 ms.). The worst case total system transport delay is then: 45 + 184 = 229 ms. This would ordinarily be too large a delay for continuous head tracking to be effective. However, the hardware panning capability of the ESIG image generator makes it possible to approximate rotation of the CCTT CPH images (in heading and pitch) by controlling the pixel location in the frame buffer at which the raster scan begins outputting the image to the display based on the current head position values derived from head tracker data. Using this technique, the effective image generator/display refresh transport delay is reduced from 184 ms. to 100 ms. and the worst case total system transport delay becomes: 45 ms. + 100 ms. = 145 ms., which is within acceptable limits for continuous head tracking for the intended application.

Hardware panning of computer generated images has been demonstrated to be a very effective form of compensation in head tracked systems, and especially in those that involve target tracking tasks [So 1991]. Head prediction algorithms are also effective for improving performance in head tracked systems, but may not be needed unless the image generator cannot perform hardware panning or if the system transport delay exceeds 380 ms. Uncompensated total system transport delays of as little as 60 ms. can increase the difficulty of task performance in some applications. Lags of greater than 120-140 ms. require far greater effort by the trainee, may preclude optimal performance, and are usually perceived as uncomfortable and objectionable.

The total system transport delay for PCOFT/PGT/AGTS systems is 277 ms. (110 ms. for sampling and software noise filtering + 33.3 ms. for synchronization with the 30 Hz. update rate of the host computer + 33.3 ms. for one frame of host processing + 100 ms. for image generation and display refresh). This amount of transport delay is also too great to allow continuous head tracking. Instead of continuous head tracking, up to ten viewport FOV definitions are predefined for each vision block. When the vision block is viewed from the center of the cupola, one viewport definition is used. When the head is moved in for close viewing of the vision block, a second viewport definition is activated, because a larger FOV can be seen with the head closer to the vision block. With the head held close to the vision block, the remaining eight viewport definitions can be accessed by moving the head up, down, left, right, or toward each of the four corners of the vision block. Each of the predefined FOV settings corresponds to the head being within a specific volume of space. The image generator scrolls between FOV definitions only after the head moves from one region of space to another as indicated by the head tracker. There is a "dead band" around the thresholds which define the boundaries between regions. This results in a "hysteresis" effect and prevents oscillation when the head stops at or near the threshold.

Viewport Geometry.

When displaying a true perspective two dimensional image of a three dimensional virtual world on a CRT surface, the image generator assumes that the eyepoint faces the display and that the view vector passes through the center of the CRT surface and is perpendicular to it. However, through use of the head tracker, we wish to gain access to more of the virtual world by moving our eyepoint up and down and side to side while rotating our head slightly as we would do from behind an actual window. If the image generator is instructed to generate a new image based on a view vector that is not perpendicular to the CRT surface, then distortion of the virtual world will occur. This happens because the three dimensional virtual world has been projected onto an imaginary two dimensional plane that is perpendicular to the new view vector, but is being displayed on the CRT surface which is not.

In an HMD, the display is rigidly attached to the head at all times, and so distortion characteristics do not typically change on a frame-by-frame basis. (Sophisticated distortion correction can be required for some HMD's, especially when off-axis optical designs are used.) In order to maintain a true perspective image on a CRT that is fixed in space rather than coupled to the head, keystone distortion correction must be performed in real-time on every video frame. This is accomplished for the CCTT commander's popped hatch (CPH) imagery through use of the dynamic linear image mapping (DLIM) feature of the image generator. In PGT/PCOFT/AGTS systems, keystone distortion correction is performed for each of the ten predefined viewport configurations of each vision block.

Head tracker initialization.

Initialization or "boresighting" of the head tracker can either be preset or be performed for each new trainee before the beginning of a training exercise. For both CCTT and PCOFT/PGT systems, a single preset position is used. The convenience of not having to re-initialize the head tracker is currently seen as outweighing any distortion caused by differences in trainee head dimensions. When using a preset initialization care must also be taken not to skew or tilt the helmet when it is secured to the head.

Human Factors Issues.

The receiver units of both the Ascension and Logitech head trackers are mounted at the top of a standard Army helmet. These helmets are not metallic other than the snaps. This allows the Ascension receiver unit to be mounted on the inside of the helmet to prevent it from being bumped or snagged. The Logitech receiver is mounted on the outside of the helmet to maintain an unobstructed line-of-sight with the transmitter. The cords of both receivers are run down the back of the helmet and are tied with the intercom headset cord in order to minimize entanglement.

NEW TECHNOLOGY

Head tracking has become an essential component for low-cost HMD's [Bevan 1995] used in location-based and consumer entertainment products and also in advanced workstation applications, e.g., for viewing stereoscopic images, and for "hands free" control of three dimensional cursors. These and other new applications are leading to both improved performance and lower costs of existing head trackers, and to more flexible head tracking devices based on alternative technologies.

High performance, high noise immunity optical head tracking technology has until recently been too expensive to be feasible except for custom high performance applications. At least two manufacturers now offer cost-competitive commercial optical head trackers [Lathom 1994].

Manufacturer's are also offering wireless receivers as a standard option for existing head trackers. Replacing the receiver wire (used for RS-232 communication to a host computer) with "wireless" communications allows the head to rotate more freely without concern for cord entanglement.

One of the biggest limitations of traditional head trackers has been their dependence on transmitters [Hollands 1995]. The commercial virtual reality market is currently driving the development of "sourceless" head trackers. These devices depend on measuring the earth's gravitational and magnetic fields, and therefore do not require a transmitter. In essence, *the earth itself is the transmitter.* These low-cost inertial head trackers, referred to as "gravimetric" devices, presently offer only crude performance and measure only head orientation (not position).

Attempts to develop and commercialize higher performance inertial head trackers are being made by at least two companies. Angularis Inertial Technologies of Cambridge, Mass. is adapting solid state rate gyroscope technology used in inertial navigation systems for high performance head orientation tracking and accelerometer technology developed by the automotive industry for head position tracking [Hollands 1995, Foxlin 1994]. Another inertial head tracking initiative has been undertaken by the Computer Graphics System Development Corporation of Mountain View, California. This effort has been expedited by a Small Business Innovative Research (SBIR) contract with STRICOM.

The ability to integrate precision head tracking equipment into any simulator environment, including appended training systems and combined live/virtual training systems, will shortly be both technologically and economically feasible.

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