Innovative Technologies for Effective Mitigation of System Latency and Image Alignment Error in Next Generation Helmet Mounted Display Systems (NGHMDS)

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ABSTRACT

Many existing combat platforms such as the F-16 and the F/A-18 are being retrofitted with Helmet Mounted Display (HMD) systems. New advanced aircraft such as the F-35 Joint Strike Fighter (JSF) are committed to using HMDs in combat operations. System latency and image alignment error are major issues associated with their use in flight simulators and these errors must be addressed in order to ensure effective training. System latency manifests itself through the occurrence of physiological disturbances similar to symptoms of simulator sickness and includes eyestrain, headache, nausea, sweating, dizziness, and a general sensation of not feeling well. Additionally, simulator sickness can be a significant distraction during training and may result in ineffective training, negative training, reduced user acceptance, and a reduction in simulator usage. Image alignment error manifests itself by reducing the accuracy of the training environment and may result in ineffective training and negative transfer of training to the real world. Innovative solutions to address latency and alignment error problems must be developed so that training can be optimized as aircrews are afforded the capability to "train as they fight" using Next Generation HMDs in a simulation environment. The current project developed a number of innovative technologies that effectively mitigate both system latency and image alignment error. The technologies developed include: 1) a customized Kalman predictive filter, 2) a learning predictive neural network, and 3) image warping technology. These technologies operate independently yet in concert to continually sample, compare, and adjust their outputs to produce the most accurate prediction of future image placement possible using current available head movement and position data. Results indicate that effective system latency was reduced an average of 65% and image alignment error was reduced an average of 45% from the baseline condition.

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INTRODUCTION

The ability of Helmet Mounted Display (HMD) systems to increase the effectiveness of pilots in combat operations has been well documented over the last several years. Many existing combat platforms such as the F-16 and the F/A-18 are being retrofitted with HMD systems. New advanced aircraft such as the F-35 Joint Strike Fighter (JSF) are committed to using HMDs in combat operations. System latency and alignment error are major issues that currently exist in advanced flight simulators. Resolving system latency issues over the past decade has typically relied on advances in computing power and speed coupled with linear predictive solutions known as Kalman Filters. Resolving image alignment issues has typically involved "warp and blend" technology that uses estimates of error present in displays and then attempts to compensate accordingly to integrate images generated from different image generators (IGs) into one continuous visual image.

With the need for advanced simulation capabilities involving multiple displays and IGs on the rise, these solutions are beginning to reach the limits of their functional utility. Innovative solutions to address latency and alignment error problems must be developed so that training can be optimized as aircrews are afforded the capability to "train as they fight" using Next Generation HMDs in a simulation environment.

This project developed a number of innovative technologies that effectively mitigate both system latency and image alignment error. The technologies developed include: 1) a customized Kalman predictive filter, 2) a learning neural network, and 3) image warping technology. These technologies operate independently yet in concert to continually sample, compare, and adjust their outputs to produce the most accurate prediction of future image placement possible using current available head movement and position data.

HMD Simulation Systems

In an HMD simulation system, two display sub-systems exist. If either of the display systems is not functioning effectively or if the two display systems are not performing in concert, the training system will not be maximally effective. The first system provides the HMD display. This system includes the HMD itself, the head tracking device attached to the HMD, and the IG which generates the images for the HMD display. The second display system is responsible for the out-the-window (OTW) view. This system consists of a projection screen and multiple independent IGs projecting the background/OTW view on the viewing screen.

Next Generation Helmet Mounted Displays

While the current HMD systems are auxiliary in nature and are not necessary for the pilot to execute combat missions, this will soon change. That is, currently, the Heads-Up Display (HUD), which is the primary information display system for the aircraft flight and weapons systems, displays the same information as the HMDs. However, Next Generation Helmet Mounted Display (NGHMD) systems such as those proposed for the Joint Strike Fighter (JSF) F-35 HMD, along with an upgraded Joint Helmet Mounted Cueing System (JHMCS) will be integrated with the avionics and weapons systems and should provide much greater functionality and capability for the warfighter. In other words, HMDs in future aviation platforms will most likely be primary systems and may not have a HUD as a backup display system. Their use will be necessary for piloting and targeting during flight and, in turn, training. Along with the challenge of preparing these systems for use during actual flight, other challenges exist in integrating NGHMDs into flight simulators for training.

Latency

A variety of types of latency, or system "lag," exist (e.g., communication, operational, simulation, mechanical, and biomedical fiber stimulation latencies). The current paper is concerned with latency as the time delay from the user's input action until the response becomes available for display (Wu and Ouhyoung, 2000). During the period of latency, the effects of the user's action are not yet observed and, thus "latent." Several factors contribute to the overall latency. These include the time necessary for: the head tracker to sense and process head movement, the image generator to compute the appropriate image (for the user looking in the new direction), the electronic processing between the image generator output and the HMD display, and the time necessary for the HMD to "draw" the image in the HMD.

In simulation applications, latency is measured in milliseconds (ms) or frames (one frame = 16.67 ms). Research indicates that latency should be no more than 16-80 ms (Patterson, Winterbottom, and Pierce, 2006). The degree of latency desired for future Joint Strike Fighter (JSF) F-35 simulators is a maximum of 60 ms (Personal Communication: JSF visual engineers, 2008).

Image Alignment

Another challenge of interest in the current project is that of image alignment. When symbology overlays match up appropriately with the visual display, they are in proper alignment. Unfortunately, alignment errors or "misalignment" also occur. One cause of image misalignment is helmet slippage during rapid head movements. Although in the operational world pilots have personalized helmets which fit comfortably and snugly on the individual pilot's head, slippage can occur with the HMDs used in simulators.

In addition, system inaccuracies (such as head tracker processing delays) can also generate misalignment. A primary issue with alignment and misalignment is measurement. It is essential to systematically test, measure, and document the actual degree of alignment error in training systems that will be using HMD technology. Only when the magnitude of alignment error is known, can implementation of countermeasures to mitigate the error occur.

Effects of Latency and Alignment Errors

Unfortunately, latency and alignment errors may manifest themselves in a variety of ways in the human user (the trainee) from eye strain to simulator sickness and may also lead to negative transfer of training. First, consider alignment. Alignment is a more difficult issue in simulation than in an aircraft because non-collimated OTW displays must line up in three-dimensional space with both left and right eye images of the HMD. In addition, eye strain inducing misalignments can also occur due to less than optimum HMD optics configurations, form/fit design, and fabrication issues. Misalignment problems are exacerbated by pilot head motion in the OTW display, creating variations in image directions and variations in distance that do not occur in the aircraft.

A slow update rate and the associated long lag time is also troublesome. First, it may contribute to simulator sickness (Biocca, 1992; Kalawsky, 1993; Pausch, Crea, and Conway, 1992). Patterson et al., 2006, explained that HMDs create significant perceptual problems for the user which, in turn, can lead to simulator sickness. One reason for the perceptual problems is that the images on the display (symbology, video, imagery, etc.) are linked to the user's head movement. Normally, the object a person views does not move with the person's head movement; head movements automatically alter the pattern of retinal stimulation. As the user scans the environment for objects or targets, the head moves or the eyes rotate, but the environment essentially remains still, thus creating a change in the pattern of stimulation on the retinas of the user.

With an HMD, however, the image on the visor moves with the head. The resulting *unnatural* pattern of retinal stimulation, coupled with the *natural* pattern of vestibular stimulation experienced when the head moves or rotates, produce conflicting cues that, in turn, may contribute to symptoms of simulator sickness. These may include eyestrain, headache, nausea, sweating, dizziness, and a general sensation of not feeling well. Systems with slow display update rates will exhibit greater latency, and greater latency increases the potential for perceptual cue conflict.

Finally, the time delays in latency errors can result in users adopting a different behavior than they would use in the actual task. Consider the “move-and-wait” strategy. When system lag is evident, the user may adapt to the lag by moving his/her head toward a prospective target and then waiting for the computer generated graphics and imagery to catch up before executing any further action. This strategy, while helpful in the simulation, can result in negative transfer of training once the user is performing the actual task (Kaber, Draper, and Usher, 2002; Liu, Macchiarella, and Vincenzi, 2008). Negative transfer occurs when the trainee reacts to a transfer stimulus correctly as they have practiced and as they were trained, but incorrectly in relation to the real world (Kaber, et al., 2002; Liu, Blickensderfer, Macchiarella, and Vincenzi, 2008; Liu, et al., 2008).

Thus, latency and alignment errors can generate a variety of unwanted effects. Unfortunately, the inherent time needed for computation, sensor, and display processing, make it difficult--if not impossible--to reduce latency to zero (Jung, Adelstein, and Ellis, 2000).

Technologies to Reduce Latency

First, improved technology continues to reduce latency via faster information transmission between the various components of the HMD and the simulator, a more efficient arrangement of hardware and software, and faster computer processing speeds. However, despite the continued potential for faster information transmission and processing, latency will remain a problem in the foreseeable future as the rapid movement of the user’s head will simply be too great for technology alone to mitigate completely. Thus, researchers are pursuing new and innovative technologies or combinations of technologies to mitigate latency much more efficiently and accurately than traditional solutions such as linear Kalman predictive filters.

The new technologies developed in this project include: 1) a “Warper Board” (for image warping and latency reduction) developed through a Small Business Innovative Research (SBIR) effort, and 2) a learning predictive neural network. The typical linear Kalman predictive solution is also used in this effort, but it is not the main predictive strategy. Rather, it is used as a reality check to ensure predictions generated by the learning predictive neural network remain within realistic boundaries. Each of these technologies is discussed in detail later in this paper.

HOW THESE TECHNOLOGIES WORK

Warper Board (Geometric Correction Extrapolator or GCE)

Latency reduction techniques are applied using a combination of mathematical motion prediction and real-time image processing. Prediction is applied based upon a head tracking device data stream that provides 240 Hz samples of trainee head position and attitude. Head motion attitude prediction was applied on the three axes of pitch, roll, and yaw.

For each axis of motion, two separate predictions are performed. The first prediction is generally set to compensate for the total system latency, from time of actual motion until associated changes in generated imagery are displayed, typically expected to be on the order of 3 – 4 video frames. The second prediction is set to a single video frame forward. A longer prediction period will generally result in a less accurate result when compared to a very short interval. Comparisons have been run on varying prediction states of forward prediction which confirm this assumption.

The system uses both predictions in parallel (in all axes) to present a perspective to the trainee that is adjusted for the difference between the two predictions, long and short. A two-dimensional (2-D) adjustment is made as shown in Figure 1.

In cases of typical motion, it has been determined that the difference between the two predictions is small, much less than a single degree. Additionally, only a small attitude adjustment is required to move the scene. With a typical HMD field of view on the order of 40 x 30 degrees (H x V), an attitude correction of 0.5 degrees would mean a shift of imagery on the order of 1.67% of the total field of view. Since this is a 2-D, and not a 3-D correction, it is not a perfect correction, However, at such a small range of adjustment, the improvements outweigh this small perspective distortion.

Correction is limited to a programmable value, based upon a reasonable correction limit for typical head motion. A limit of 1 to 1.5 degrees in any dimension has seemed a reasonable limit in current testing, but could be expanded easily. This limit has an effect on the image source requirements. If using a typical IG scene to be presented in the HMD, the IG must render enough overscan of scenery to allow the set limits to be achieved in all axes without introducing regions into the corrected display that have no valid scene input. A series of limits for varying allowable speeds can be found in Pray and Hyttinen, 2004.

When head motion greatly exceeds the range where the programmed limit can adjust the scene, it is highly likely that discrete frame intervals (such as typical 60 Hz video refresh rate) will appear such that discontinuity is apparent between successive images displayed. Extrapolated Frame Correction (EFC) produced by the Warper Board is not expected to add to or help this problem if the difference between predictions is larger than the threshold.

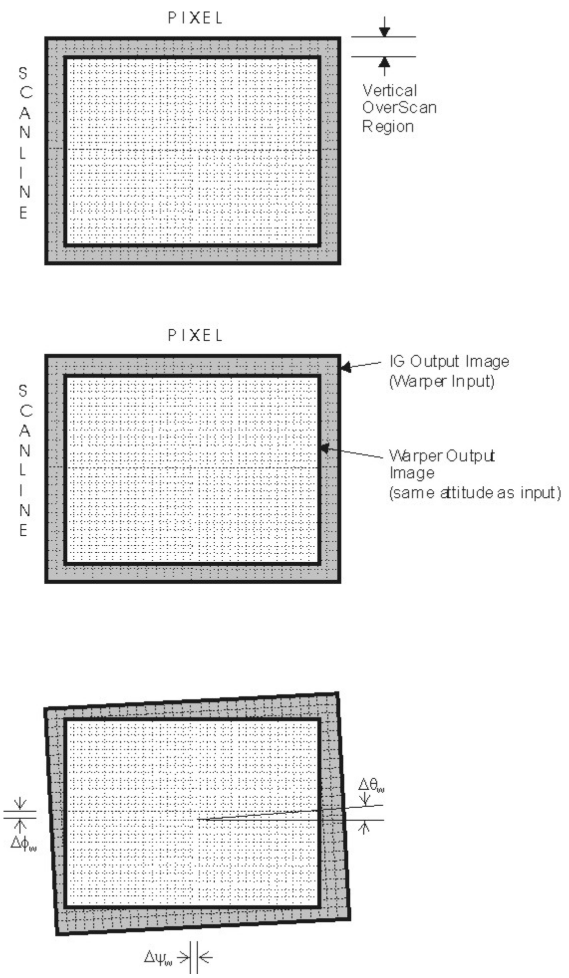

Figure 1. An example of 2-D Attitude Adjustment – Extrapolated Frame Correction (EFC).

At abrupt changes of direction, the EFC function can help to reduce or eliminate the image effect of scene overshoot or undershoot to the 'stop' attitude. EFC will make such a correction rapidly and in the correct direction of change between the previously commanded IG perspective and the actual viewer perspective.

If the input scene is not a typical OTW or sensor video scene, but more like symbology, it may often not cover the entire range of the display field of view. This allows the EFC range to be set larger than the overscan range which is an advantage for the solution.

The EFC corrected input is then applied to a geometric alignment warp grid following the attitude adjustment to allow it to map correctly to a complex surface, or to maintain alignment between an aligned HMD image and the background display. This grid can be altered on a frame-by-frame basis to provide dynamic geometric alignment of HMD imagery to a background display, which can be essential in a display system where the perceived distance from the trainee to the screen surface is small. Short distance screen viewer perspective can change dramatically with typical allowable range of head motion.

The motion of a viewer that is close to a display surface can create wide variations in perceived field of view, for example. Figure 2 depicts such an example of various trainee positions with respect to the display surface. A 'slice' is presented in a single axis for clarity.

Given a static background alignment, with marks representing fixed angular displacement from the display system 'design eyepoint', a viewer from that eyepoint would see a matching field of view as shown in the top example of Figure 2.

As the trainee moves within the viewing volume of allowable range of motion, the apparent field of view between the viewer and the background changes as shown in the lower depictions. If the viewer moves closer to the screen, their 'personal' field of view subtends smaller regions of the screen due to its close proximity. As the viewer moves further away from the screen surface, the personal field of view subtends larger angular displacements of the background.

In a traditional system with only the trainee's eyes perceiving the background, it is common to ignore this effect and keep the background alignment static. It can be beneficial, however, to have the support for dynamic alignment to constantly adjust the background alignment of angular displacements to create a virtual collimation effect. This, in conjunction with an image generator redrawing to the new trainee eye position can create the effect of the screen distance appearing much further from the viewer.

In the case where a transparent, or 'see through', helmet mounted display is involved, a similar issue arises. The HMD will generally have a fixed optical field of view. If we align that field of view to match the background from the design eyepoint and constantly display imagery to that alignment, HMD imagery will become misaligned with the background as the viewer moves around in the display system. Having the ability to dynamically adjust the displayed imagery within the HMD is critical to ensuring proper alignment of HMD imagery to the simulated background world for tasks such as target recognition / tracking, etc.

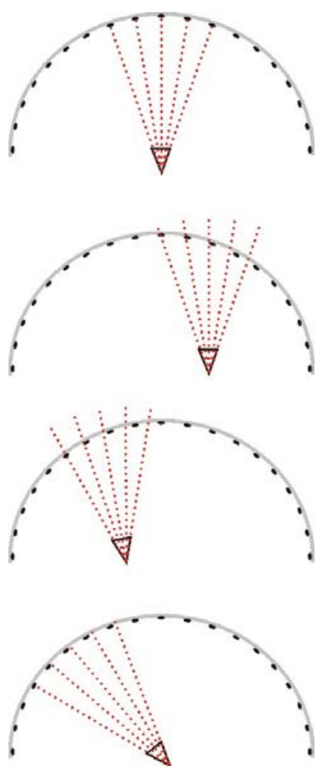

Figure 2. An illustration of Short Distance Screen Perspective Changes.

As described in Nanda and Pray (2009), the combined HMD simulation system must generate the out-the-window view in high fidelity and real-time for the pilot to view through the transparent helmet display. Additionally, the system must generate imagery for the HMD and, in turn, correlate that imagery in space and time with the OTW view.

For example, consider an HMD providing supplemental target information to a pilot. The system detects a target on the ground (e.g., vehicle). Since the target may be barely perceptible to the pilot, the HMD generates an icon that directly overlaps the target in the background view and enables the pilot to detect the target. The icon must align accurately with the target regardless of pilot head movement. Integrating the images from these two separate display systems is an extremely complex problem and has yet to be done to a satisfactory level.

The combination of the two interdependent display systems to comprise an effective training system has been a major component of this research effort. All previous combinations of these two visual systems (i.e., the HMD and the OTW virtual environment display system) have consistently shown unsatisfactory performance due to issues with misalignments and latency.

Learning Predictive Neural Network

Neural prediction is performed using a "neural mesh" with full interconnectivity between all nodes in the network. The predictor can be sized by parameters to define the number of nodes in any level of the mesh and the number of levels of nodes within the entire mesh (Figure 3).

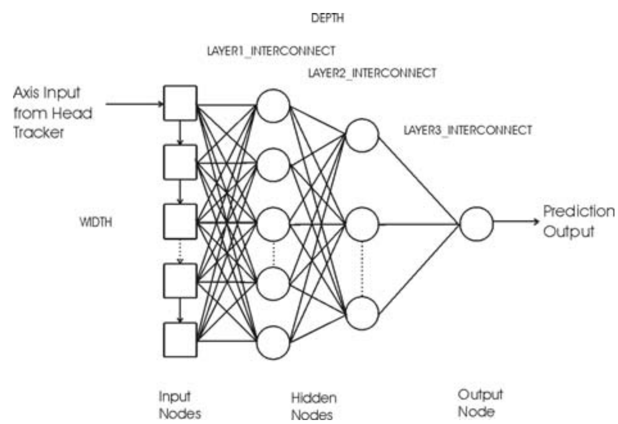

Figure 3. Neural Mesh Example.

Each neural mesh takes as input a streaming attitude of one axis from the head tracking device. The input width defines a state of pipeline delay registers that pass successive input samples from one to another at the input data rate, creating a history of input samples. This history is then passed to the first hidden layer of neural processing nodes.

Each node contains a weighting factor (Wn) for each node input that is multiplied by the corresponding node input. The result of each multiplication is then summed to form the node's output (Figure 4).

Each mesh also makes only one prediction at a programmed set of forward states. As such, there are six operating neural networks all computing in parallel.

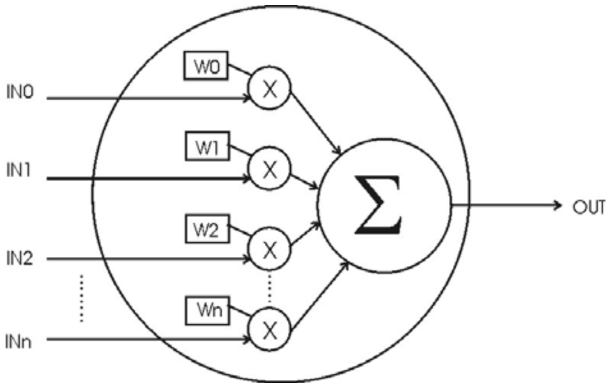

Figure 4. Illustration of each individual processing node.

For each network and forward prediction state, the network is trained using recorded actual head motion data. A typical trainee wearing the HMD and associated head tracker performs a series of motions that represent a wide range of user head motion. In early experiments, our results yielded less than expected accuracy for vertical (pitch) motion. By looking back at our training data, we discovered that our recording had very little change in the pitch axis at any time, and as such, the neural network was trained to expect little change in motion. This will be corrected in subsequent efforts.

Training is performed by using a least error approach. All weighting factors at all nodes are initialized with random values. The recorded data is then fed to the network sample by sample. From the programmed forward prediction state value (number of states or frames ahead), the network output is compared to the recorded value at the chosen number of forward states ahead in the data file that corresponds to the prediction time. Each weighting parameter in the network is then varied until it creates a state of minimal error with respect to the recorded forward value. One at a time, each parameter is altered for each recorded sample until we achieve a convergence to minimal overall error for a given set of weighting factors at each node. Once converged, the set of weighting factors represents the operating set to be used for that given programmed value of forward states of prediction. Separate neural networks are run for each axis and each forward prediction state. As such, we have six separate neural networks running at a time in the system.

In the current implementation, each neural network is programmed with an input width of 64, two hidden layers each 64 nodes wide, and a single output node. Full interconnectivity is programmed between all internal nodes in the network.

Kalman Prediction

Given the nature of neural networks, the number of inputs, historical values, and coefficients can become quite large and may require a tradeoff to be made between the amount of history and depth of the network to maintain real-time performance. Such tradeoffs can lead to possible spurious predictions on occasion where the 'training' data did not include cases encountered during actual operation. One method to mitigate this problem is to use a Kalman prediction in conjunction with a neural network.

A corresponding Kalman filter operates in parallel to each of the neural networks for the six required axis / prediction states. The Kalman filer approach has only recently been used for simulations involving see-through HMDs. In this application, the Kalman filter is used as a "reality check" to ensure that the predictions generated by the neural network remain within realistic boundaries within the limitations of human head and neck movement. This double check ensures that the neural network will always provide realistic and usable predictions. The Kalman predictive filter is used to detect and limit cases to ensure the predictions stay within realistic boundary limits of possible motion, and in turn, to minimize error in these situations.

RESULTS

The focus of this paper is a discussion of the technologies developed as a result of the Next Generation Helmet Mounted Displays for Navy and Marine Corps Training Systems, a project funded by the Office of Naval Research, Code 34, Capable Manpower - Future Naval Capability. The results below are only a high level summary of results obtained through experimentation performed throughout the duration of the NGHMDS project to provide an indication of the functionality and effectiveness of the technologies developed. For complete results, please contact any of the authors.

The implementation of these latency and image alignment reduction technologies in an experimental test bed resulted in an average reduction in system latency from a baseline condition of 2.61 frames (43.5 msec) to 0.92 frames (15.3 msec) latency, a 65% reduction in system latency on average.

With respect to vertical alignment error, the degree of vertical alignment error was dramatically reduced. At the initial point of alignment, the vertical alignment error was zero (0) indicating that the degree of misalignment at the point of bore sighting did not change. As the HMD Test Suite moved away from the center point of alignment, the degree of vertical alignment error increased. In the baseline condition, the degree of vertical alignment error was measured at 1.77 degrees at the – 90 degree mark (turning the head 90 degrees to the right of center). The degree of vertical alignment error was measured at 1.75 degrees at the + 90 degree mark (turning the head 90 degrees to the left of center). When the EFC correction was turned on, the vertical alignment error decreased to a maximum of 0.95 degrees at the – 90 degree mark (all the way to the right of the visual screen center), resulting in a 46% reduction, and a maximum of 0.98 degrees of vertical alignment error at the + 90 degree mark (all the way to the left of the visual screen center), resulting in a 43% reduction in vertical alignment error. This amounts to an overall average reduction of vertical alignment error of 45% across the entire visual scene.

DISCUSSION

It is generally accepted that display latency and alignment errors can generate a number of unwanted effects. This includes reduced training effectiveness, simulator sickness symptoms, and even negative transfer of training when the trainee returns to the actual flight environment. If maximization of simulator use and optimization of training are goals of the training community, reduction or elimination of latency should be a primary goal in efforts to create as realistic a simulation and training environment as possible with the final objective being to maximize training effectiveness and transfer of training to the operational environment.

Current training systems exhibit system latency ranging from 4 frames (66.68 ms) and 8 frames (133.36 ms). As more complex graphics and visuals are required to provide acceptable levels of fidelity and realism during simulation events, image generators will continue to struggle to generate and redraw system visuals quickly enough so as not be noticed by the trainee. A general recommendation that is often quoted in HMD literature is that effective latency for the aircraft operational system should be a maximum of 30 – 60 milliseconds. Some current research seems to indicate that for system latency to be virtually imperceptible by the human user (and therefore have no adverse effect on the user), system latency should be less than 80 ms. How this figure was arrived at is unclear, and further research is needed in order to obtain an accurate quantitative determination of human performance visual latency thresholds.

Future combat fighters that will depend upon Next Generation HMD technology for operational aspects of combat missions will also require their effective integration and implementation in simulation and training systems. JSF F-35 combat fighters have a program goal of reducing effective system latency to 30 ms or less. This is an aggressive goal, but not one that is out of reach if creative and effective solutions such as those being developed in this project are further refined and employed in future systems.

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DISCLAIMER

The views stated in this paper are those of the authors and do not represent official views of the organizations with which they are affiliated.

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