EFFECTS OF SPATIO-TEMPORAL ALIASING ON OUT-THE-WINDOW VISUAL SYSTEMS

Barbara T. Sweet, Ph.D.
Aerospace Engineer
&
Leland S. Stone, Ph.D.
Research Psychologist
NASA Ames Research Center

Dorion B. Liston, Ph.D.
Research Associate
San Jose State University

Tim M. Hebert, Ph.D.
Software Engineer
VDC Display Systems

Abstract

Designers of out-the-window visual systems face a challenge when attempting to simulate the outside world as viewed from a cockpit. Many methodologies have been developed and adopted to aid in the depiction of particular scene features, or levels of static image detail. However, because aircraft move, it is necessary to also consider the quality of the motion in the simulated visual scene. When motion is introduced in the simulated visual scene, perceptual artifacts can become apparent. A particular artifact related to image motion, spatio-temporal aliasing, will be addressed. The causes of spatio-temporal aliasing will be discussed, and current knowledge regarding the impact of these artifacts on both motion perception and simulator task performance will be reviewed. Methods of reducing the impact of this artifact are also addressed.

Background

Aliasing occurs when a continuous signal is digitized using a sampling scheme that is too sparse (i.e., at an inadequately low frequency). This can be a spatially-varying signal, where sampling frequency refers to the spacing of sampling locations (as in the 2-D display), or a temporally-varying signal where sampling frequency refers to the sampling period. When the signal is periodic (repeating, either in time or spatial direction as in a pattern), and the sampling interval drops below the Nyquist frequency[1], the sampled signal will generally not faithfully reproduce the original signal, and additionally will typically exhibit frequency content that is dramatically different than the original signal. Figs. 1-3 depict the effect of sampling at rates above, at, and below the Nyquist frequency for time-varying signals.

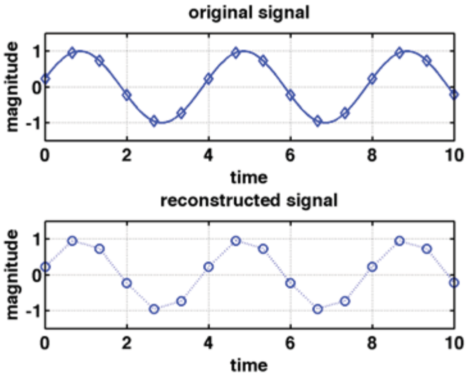

Fig. 1 Time varying continuous sinusoidal signal sampled at a rate above the Nyquist frequency (top), and sampled reconstruction (bottom). The reconstructed signal is a good representation of the original signal.

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[1] The Nyquist frequency is two-times the bandwidth of the signal being sampled. For example, the Nyquist frequency for a signal consisting of a sine wave with a 30-Hz frequency, the Nyquist frequency is 60 Hz.

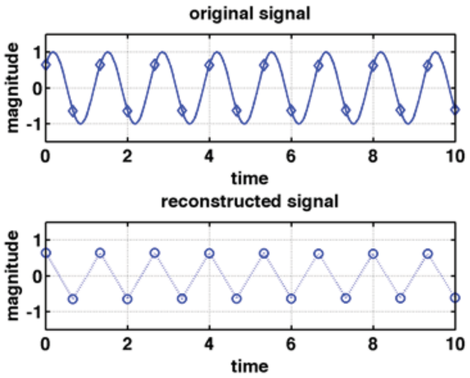

Fig. 2 Time varying continuous sinusoidal signal sampled at the Nyquist frequency (twice the signal frequency) (top), and sampled reconstruction (bottom). While the reconstructed signal is not a perfect reproduction of the original signal, it retains the essential frequency characteristic of the original signal.

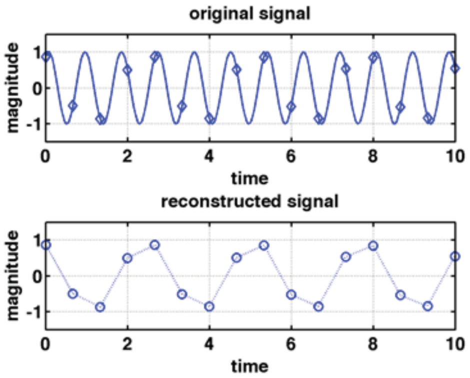

Fig. 3 Time varying continuous sinusoidal signal sampled at a rate below the Nyquist frequency (top), and sampled reconstruction (bottom). The reconstructed signal is not an accurate representation of the original signal, and in fact appears to have a different, lower fundamental frequency than the original signal.

Aliasing can also occur in a sampled two-dimensional signal, such as an image. This effect can be easily observed when viewing a texture in a 3-D scene without the appropriate level of filtering or mip-mapping; the resulting perceived texture can appear to be have a much lower spatial frequency, or the periodicity that might originally be present in a texture could appear to be highly irregular or incoherent (Fig. 4).

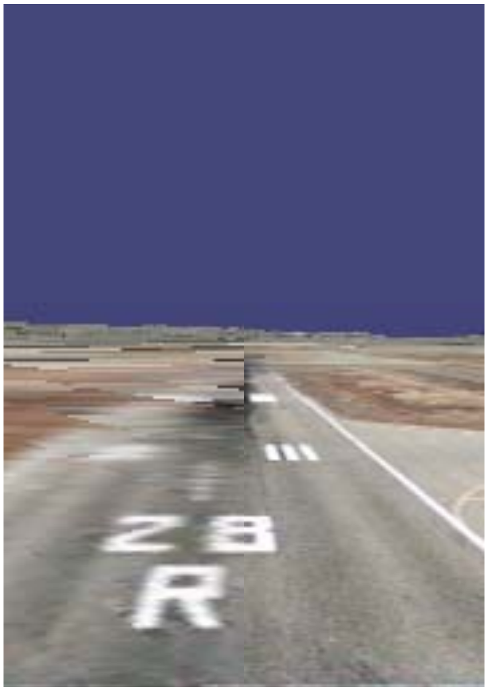

Fig. 4 Runway image applied as a texture with antialiasing off (left) and on (right). Significant spatial aliasing is evident on the left, particularly in the foreground.

Spatio-temporal aliasing is associated with the temporal sampling of a moving image. Perhaps the best known example of this is the wagon-wheel effect, observed in camera images of a spoked wheel (Fig. 5).

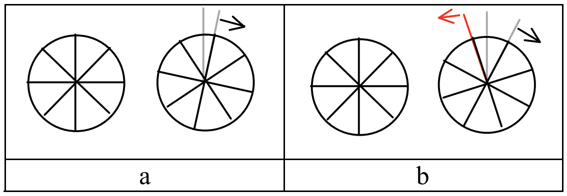
a b

Fig. 5 Example of spatio-temporal aliasing. In (a), if the spoked wheel rotates a small amount, the perceived direction of motion will be in the true direction of motion; the brain connects the motion of the spokes in the proper sequence. In (b), the wheel is rotating more than half of the angle between the spokes per frame; instead of perceiving motion in the correct direction (black arrow) motion appears to be occurring in the opposite direction (red arrow) because of the smaller angular offset to the next spoke.

Although the wagon-wheel example is a special case of a periodic or repeating visual image (from the symmetry of the wheel), spatio-temporal aliasing can occur with any image sequence depending on the sampling rate and image resolution.

Analysis of spatio-temporal aliasing, and often explanation of the phenomenon and the resulting effects, are frequently done in the frequency domain, based on periodic or repeating features in the image (as shown in the previous examples). Although these techniques can very accurately represent the effects of temporal sampling of a time-varying, two-dimensional spatial image, our perceptions occur in the time-domain. Specific cases in which we can easily observe spatio-temporal aliasing in visual simulation include sampling moderate image motions at too low a rate[2], or sampling very fast motion at a moderate rate[3].

Perceptual Consequences

Watson, Ahumada, and Farrell (1986) proposed an analytical method to predict when a human observer would detect spatio-temporal aliasing, considering both CRT-like displays (very short duration) and LCD-like displays (sample and hold). Given the limits of human temporal sensitivity (typically 60 Hz), and limits of spatial acuity (typically 30 to 60 cycles/deg), the method can be used to predict the "critical" sampling frequency, the frequency at which sampled motion could be distinguished from continuous motion. The critical frequency can be determined with the following formula:

$$\omega_c = \omega_l + r\, u_l \qquad \text{(Eq. 1)}$$

where ω_c is the critical sampling frequency, ω_l is the temporal sensitivity (in cycles/sec or Hz), r is the speed of the image motion (in degrees/sec), u_l is the limit of spatial acuity (in cycles/deg). When the image itself is limited in spatial frequency (i.e. less than eye-limiting resolution), the critical frequency becomes

$$\omega_c = \omega_l + r\, u_b \qquad \text{(Eq. 2)}$$

where u_b represents highest spatial frequency content of the image.

In the equations above, critical sampling frequency (refresh rate at which spatio-temporal aliasing becomes noticeable) is determined as a function of human temporal sensitivity, image motion, and image spatial resolution. In practice, refresh rate is not a variable; it is a fixed feature of a display. If the sampling frequency is known, Eq. (3) predicts the level of image motion at which spatio-temporal aliasing becomes noticeable:

$$r = (\omega_c - \omega_l)/\, u_b \qquad \text{(Eq. 3)}$$

Solving for image motion (r) for a display refresh rate (ω_c) of 60 Hz, and a typical human temporal frequency limit (ω_l) of 60 Hz, we find that any image motion is expected to produce spatio-temporal aliasing ($r = 0$). This finding is not completely consistent with flight simulation experience, where refresh rates of 60 Hz are routinely used with acceptable image performance. This discrepancy can likely be explained by considering that the Watson et al. (1986) analysis is based on the discrimination between sampled and continuous motion, not on assessing when spatio-temporal artifacts become noticeable or distracting, or adversely impact functionality. Additionally, the model assumes space-time separability (i.e., ω_l is independent of u_b) and linearity (i.e., the responses to each image frequency are independent from each other). The empirical validation of the model was also accomplished using essential 'point' features (i.e., a single frequency components) rather than a full image. Thus, known non-linear interactions across frequency components, such as masking, were not taken into consideration.

This discrepancy stills allows for the examination of qualitative rather than quantitative effects of refresh rate and image resolution. Fig. 6, derived from Eq. (3), shows the relationship between this theoretical image motion threshold and spatial resolution for varying refresh rates. It is expected that at higher resolutions, the visibility of spatio-temporal artifacts will occur at lower image motions. Additionally, increasing refresh rate would likely reduce the visibility of these artifacts.

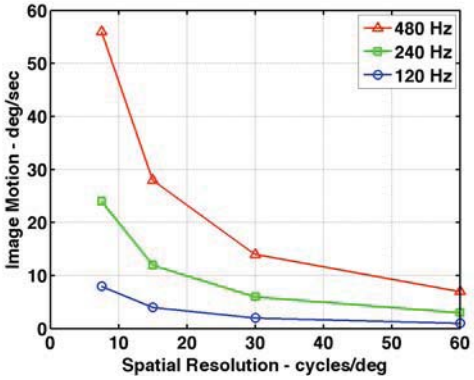

Fig. 6 Image motion at which spatio-temporal aliasing is predicted to become detectable as a function of image spatial resolution and refresh rate.

There are additional empirical results studying the effects of refresh rate on spatio-temporal artifacts using imagery rather than a 'point' feature. Kuroki, Nishi, Kobayashi, Oyaizu, and Yoshimura (2006) conducted a series of experiments examining the effect of refresh rate on moving image quality. Using a CRT display capable of achieving refresh rates of up to 450 Hz, they obtained subjective measures of

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[2] Such as is experienced when an image generator regularly runs over frames and updates every two refresh cycles.

[3] Such as is experienced in depicting high rotational rates, as in fighter aircraft, or when moving rapidly in close proximity to a planar surface such as a runway.

motion quality as a function of refresh rate, for rates of 62, 125, 250, 333, and 450 frames/sec. The image sequences studied contained motions in the range of 7 to 78 deg/sec.

Subjective motion quality measures, related to the absence of blur and 'jerkiness', improved with increasing frame rates up to 250 fps; rates above this did not produce significant improvements in the subjective measures. Although 125 fps refresh rate was associated with some degradation relative to higher refresh rates, it was significantly better than the lowest refresh rate of 62 fps.

Although this study provides some insight regarding the point of diminishing returns regarding refresh rate, the results are not directly applicable to real-time visual simulation image generation. The image sequences used in this study were captured using a high-speed camera (at 1000 Hz), then for each refresh rate, frames were generated through a frame-averaging process. Thus a 500 fps image sequence was generated by averaging two frames, 333 fps by averaging 3 frames, etc. This effectively reduced the resolution or spatial frequency of the image sequences as a function of displayed refresh rate, rather than examining refresh or frame rate independent of the spatial resolution of the image. This technique introduced image blur typical of fixed frame rate camera images.

Winterbottom. Gaska, Geri, and Sweet (2008) conducted an assessment of a laser projector capable of update rates up to 240 Hz (Kikuchi et al., 2008). Interestingly, this assessment yielded similar results to those reported by Kuroki et al. (2006). Image sequences of an F-16 aircraft moving perpendicular to the line-of-sight of the observers were generated (without simulated motion blur or frame averaging) to correspond to 10, 20 and 40 deg/sec aircraft motion (see Fig. 7). The projector was configured to be at a spatial resolution of 11.5 cycles/deg. Observers were asked to report the presence of motion artifacts at update rates of 60, 120, and 240 Hz. At 60 Hz, subjects reported motion artifacts at all conditions. For the 120 Hz condition, motion artifacts were apparent only at the highest motion (40 deg/sec). No motion artifacts were reported at the 240 Hz update rate.

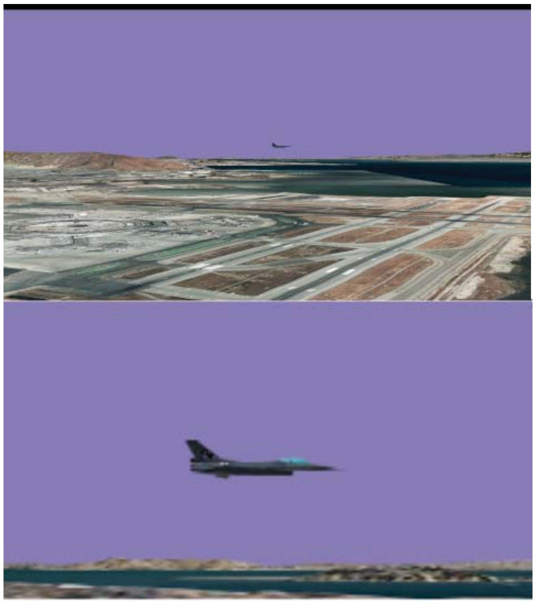

Fig. 7 Single frame of image sequence used to assess spatio-temporal aliasing with high frame rate laser projector (top), and cropped image showing level of detail of F16 (uncompressed) shown below.

These empirical results are somewhat more promising than the theoretical analysis presented in Fig. 6. It should be noted that the Watson method is related directly to differentiating smooth from temporally-sampled motion, whereas the Kuroki and Winterbottom empirical studies were related to the quality of the motion depiction. Additionally, the Watson analysis did not consider the eye movements of the observer. As will be shown, some perceptual artifacts of spatio-temporal aliasing are likely related to the eye movements of the observer.

Eye Movements

Humans have two distinct types of voluntary eye movements that they use to follow moving objects of interest: pursuit which smoothly moves the eyes to match the eye velocity to target velocity and saccades which ballistically correct for position offsets in order to keep the image of the target close to the fovea (the retinal locus of highest acuity).

Pursuit is a highly evolved motor capability that taps into an elaborate primate brain pathway dedicated to motion processing (Maunsell & Newsome, 1987). Under a broad range of conditions, it is capable of generating very precise ocular control limited by visual speed and direction signals shared with perception (Kowler & McKee, 1987; Stone, Beutter, Eckstein, & Liston, 2008; Stone & Krauzlis, 2003). Furthermore, the accuracy of pursuit is directly linked to perceptual accuracy (Beutter & Stone, 1998, 2000; Krukowski & Stone, 2005; Stone, Beutter, & Lorenceau, 2000). Typically, humans can generate eye speeds that nearly match target speeds (i.e., gains in excess of 90%) with few catch-up saccades necessary for target speeds up to about 30 or 40 deg/sec and can perform effectively up to about 60 deg/sec where saccadic tracking then begins to dominate (e.g., Lisberger & Westbrook, 1985; see also Fig. 8).

As stated above, human motion perception has a spatio-temporal sensitivity that makes it vulnerable to perceiving spatio-temporal aliasing when the displayed moving image is under-sampled either spatially or temporally (or both). When target motion is under-sampled, humans perceive artifacts that disrupt acuity and distort spatial features of the target (e.g. doubling, blurring), and ability of smooth pursuit to continuously track moving objects is degraded.

Fig. 8 demonstrates the effect of refresh rate on eye movements. Eye movements are shown for target velocities of 10 to 60 deg/sec at two refresh rates, 60 Hz and 120 Hz. The eye movements are color coded to differentiate smooth pursuit eye movements (blue) from saccadic eye movements (red). The dashed line indicates what 'perfect' eye movements would be, i.e. the fovea is maintained on target. As can be seen, at the 60 Hz refresh rate catch-up saccades typically begin to occur frequently at 30 deg/sec target motion. For 120 Hz refresh rate, catch-up saccades become more prevalent at 40 or 50 deg/sec target motion, close to the limit of effective pursuit tracking.

This increase in catch-up saccades is not only caused by the impoverished visual signal but also may contribute to perceptual artifacts commonly seen with spatio-temporal aliasing. At some conditions, a smoothly-moving image will suddenly seem to double or jump. Catch-up saccades produce sudden displacements of image features to different locations on the retina, which could lead to perceptual doubling. This effect is similar to a 'double exposure' caused by a jarred camera as, for an instant in time, a feature is perceived to be in two places at once.

Lastly it should be noted that the sensitivity to spatio-temporal aliasing it dependent on whether the image motion is actually tracked with pursuit eye movements, or whether the eyes are fixated on a fixed point within or over the moving image. More specifically, although spatio-temporal aliasing may compromise pursuit, the pursuit response will tend to decrease the motion of the attended feature on the retina and thus act to reduce aliasing of the tracked feature or at least to change its qualitative properties. (Conversely, pursuit may actually increase the aliasing of peripherally viewed features which could adversely impact or delay responses to secondary tasks). Thus, the overall perceptual impact of display sampling will depend on whether a moving display feature is tracked or if eyes remain fixated on a stationary feature. Spatio-temporal aliasing artifacts were examined by Kuroki et al. (2006) in both fixation and pursuit. They found that spatio-temporal aliasing was much more evident in fixation than pursuit. In visual simulation, fixation is certainly the exception to the rule; operators are most likely engaged in pursuit eye movements when viewing a simulated out-the-window display. This provides an additional explanation for the apparent disconnect between the predictions of Watson et al. (1986) and common simulator applications for 60 Hz update rates.

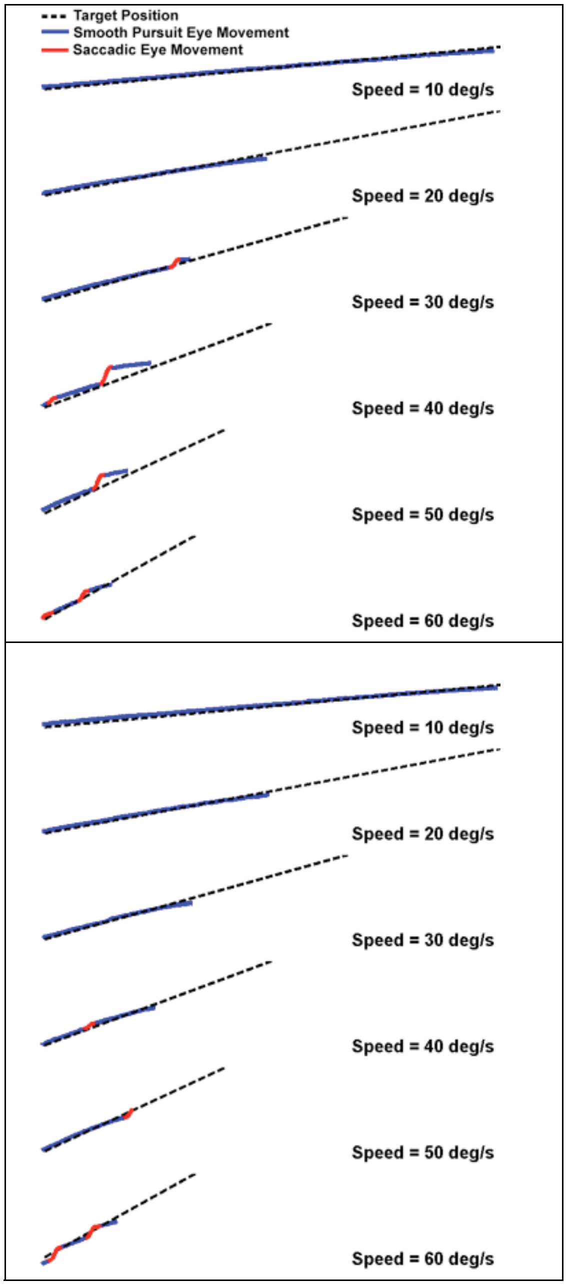

Fig. 8 Eye movement velocity for 60 Hz (top) and 120 Hz (bottom) refresh rates, at varying target speeds. When the blue line is directly over the dashed line, pursuit eye movements are tracking the target accurately. When pursuit starts to fall behind (blue line dips below dashed line), the eye does a "catchup saccade" (red) to realign the eye with the target.

The theoretical and experimental results described in this section all indicate frame rates on the order of 240 Hz are necessary to minimize perceptual artifacts resulting from spatio-temporal aliasing. This represents a daunting technical challenge. For visual simulation, perhaps the more important question is when does spatio-temporal aliasing create an erroneous perception of motion, and how does that affect task performance? Oculometric analysis (as illustrated in Fig. 8) may provide a useful objective tool for establishing the functionally relevant trade-offs between sampling rate and visuomotor performance (as opposed to subjective judgments of perceptual esthetics) in the important 90 to 240 Hz range.

Simulator Performance Implications

As was the case regarding the effects of spatio-temporal aliasing on perception, relatively little research has been done quantifying the effects of this artifact on task performance in simulators. However, there are several research topics that are directly relevant to this issue. First, many factors influencing vehicular control tasks are well understood, including the impact of velocity information on task performance. Secondly, research has demonstrated the effect of impaired velocity information on active control tasks which require velocity information. Lastly, some research has addressed the issue of spatio-temporal aliasing on specific simulated flight tasks.

Motion Perception Requirements for Vehicular Control

Tasks typically performed in a simulator span a continuum from very tight, continuous, closed-loop control, to monitoring and the execution of discrete actions. The first end of this continuum is commonly called manual control. Dating from the 1940's, researchers in this engineering field have sought to determine what type of compensation, or control activity, a human operator will provide to accomplish a vehicular control task (comprehensive overviews of manual control are available in Wickens, 1987, and Hess, 1997).

One finding from the field of manual control is that the type of compensation an operator adopts, and the information needed to perform that compensation, is a function of the vehicle being controlled, and the task. An extensive body of work exists which confirms that in some manual control tasks, the operator needs to detect and respond to *velocity* information to effectively accomplish the task. Thus, in some vehicular control situations, perception of visual motion is potentially critical. Particular vehicle control tasks that fall into this category are helicopter position control, spacecraft attitude and position control, roll control in some aircraft types, and lateral path control in a car when forward visibility is limited.

Li, Sweet, and Stone (2005, 2006) conducted several experiments that demonstrated the effect of visual motion perception on manual control tasks dependent on velocity perception. Performance was degraded when visual motion perception was compromised, both through contrast and color variations.

Spatio-temporal Aliasing Effects on Simulator Tasks

Dearing, Schroeder, Sweet, and Kaiser (2001) conducted a study examining the effects of platform motion and visual scene content on performance of autorotative descents and landings in a Blackhawk helicopter. One of the hypotheses prior to the study was that if the ground texture resolution was *too* high, that spatio-temporal aliasing would result in impaired motion perception and reduced performance. Three texture levels were chosen, the highest-resolution being chosen (subjectively) based on the level of aliasing observed during the final portion of the approach. The highest resolution texture was associated with *worse* performance, in sink rate, than the other textures which did not create significant spatio-temporal aliasing. At the highest rate, the combination of vehicle motion, proximity to the textured ground plane, and texture resolution combined to create a perception of flashing or incoherent motion. The two lower texture resolutions appeared to move relatively smoothly and consistently.

Lindholm, Sharine, and Pierce (2003) examined issues associated spatio-temporal aliasing in flight simulation applications. The authors analyzed the degree to which spatio-temporal aliasing would occur in realistic flight simulation applications, with both high-resolution (0.15 m/pixel) and low-resolution (0.56 m/pixel) textures, at simulated altitudes of 500 and 50 m, as a function of ground speed (100 to 800 knots). They demonstrated that at a majority of these conditions, a large proportion of a simulated ground plane would exhibit spatio-temporal aliasing, on the order of 80 to 90% of the ground plane for the lowest altitude and highest resolution texture. They report that studies on perceived speed during low-level flight had produced inconsistent results. They point out that proposed ultra-high resolution systems (Kraemer, Ashby, & Chambers, 2006) will experience spatio-temporal aliasing at higher altitudes and lower airspeeds than contemporary systems.

Potential Solutions

There are two potential solutions for reducing the saliency of spatio-temporal aliasing; 1) increasing refresh rate, and/or 2) decreasing the spatial resolution (or low-pass filtering) of the image.

Refresh Rate

As determined by Watson et. al. (1986), perceptible spatio-temporal aliasing is likely to occur, with *any* image motion, for frame rates of 60 Hz or less. Increases in frame rates above 60 Hz will increase the image velocities that can be displayed without perceptible spatio-temporal aliasing. Previous empirical studies have shown that while refresh rates of 240 Hz or higher will virtually eliminate perceptible spatio-temporal aliasing, refresh rates of 90 or 120 Hz significantly improve performance over the current industry standard of 60 Hz.

Beyond the technical complexity of driving a display device to refresh at higher rates there is the challenge of supplying image content at that rate. One method that will enable higher refresh rates is reducing scene complexity to allow rendering at the desired rate. Another potential approach to supplying image content at high frame rates is to multiplex additional synchronized IG channels.

Image Resolution

High-quality rendered images, not generated in real-time, typically prevent spatio-temporal aliasing by averaging multiple image sequences rendered at a series of times within the frame duration; this has the effect of blurring the portions of the image with significant motion. Real-time rendering techniques currently lack the capability of introducing motion blur to reduce or remove spatio-temporal aliasing. One potential solution could be the reduction of spatial resolution in portions of the image with a high image velocity. Current mip-mapping techniques could possibly be modified to include image velocity in selecting the spatial resolution of textures, although there are no applications of this technique to-date. Additionally, current multi-sample techniques to enable full-screen antialiasing could be utilized to provide real-time motion blur by computing samples at different time points within the frame interval.

Conclusions

Although very little research has demonstrated a direct correlation between spatio-temporal aliasing and simulator performance, current knowledge related to visual information requirements for closed-loop control can be used to infer that velocity perception decrements resulting from spatio-temporal aliasing will have an impact on simulator task performance. The impact is likely to be dependent on the particular vehicle and task, as well as other display characteristics. The impact of aliasing is expected to affect higher spatial resolution display systems to a greater extent than lower resolution systems.

Because real-time techniques to reduce or eliminate spatio-temporal aliasing do not currently exist, the method with the most potential to reduce this artifact is an increase in the refresh rate. Although this would reduce spatio-temporal aliasing, it would not eliminate it in all applications and tasks, except possibly at rates exceeding 240Hz. It is possible that the saliency of any remaining spatio-temporal aliasing artifacts could be further reduced by modulating the spatial frequency content of the image, possibly through manipulation of spatial anti-aliasing techniques that are applied in real time.

Technology advances are enabling the development of higher resolution systems. These higher resolution systems will be more vulnerable to spatial-temporal aliasing. The perceptual and performance effects of spatio-temporal aliasing are varied, and objective measures of the impact of this artifact do not currently exist although oculometric analysis represents a promising new approach. Much work remains to be done in this area.

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Author's Biographies

Dr. Barbara Sweet is an Aerospace Engineer in the Human Systems Integration Division at NASA Ames Research Center. Since joining NASA in 1984, she has worked in helicopter handling-qualities research, simulation facility development and management, and human-factors research. Her research has focused on the use of visual cues to accomplish vehicular control (such as piloting an aircraft). This work has included the development of models of human control behavior that account for perspective scene viewing. She is also a pilot, with commercial ratings in both airplanes and helicopters, and flight instructor and instrument flight instructor ratings in airplanes.

Dr. Leland Stone is a senior Research Psychologist working in the Human Systems Integration Division at NASA Ames Research Center. He received a M.S.E degree from the University of California at Berkeley in 1983 examining non-linear models of the visuomotor transformations underlying smooth pursuit eye movements. He received a Ph.D. in Neuroscience from the University of California at San Francisco examining the neural signal processing of the visual and vestibular motion cues underlying voluntary gaze control in monkeys. Since coming to NASA in 1987, his research has focused on the sensorimotor integration underlying the active perception of motion and location with an emphasis on using eye movements to monitor human perceptual and cognitive processing in aerospace relevant tasks.

Dr. Dorion Liston is a Neuroscience Ph.D. (UCSD 2005) with experience in oculomotor systems. His research has focused on the neural systems underlying target selection for voluntary eye movements, and modeling those mechanisms. This work includes investigations into the coordination between smooth pursuit and saccadic eye movements, the mechanism underlying choice behavior for saccadic eye movements, and the mechanism that combines prior information with sensory signals to guide eye movement choices. He works as a Research Associate for San Jose State University in the Human Systems Integration Division at NASA Ames.

Dr. Timothy M. Hebert is a Computer Engineer Ph.D. with 8+ years of experience designing and implementing software platforms for visual inspection and integrated control applications. As the Principal Software Development Engineer for VDC Display Systems, he is responsible for the software projects that support the company's primary product line of projectors. Over the past three years, He successfully integrated full resolution CCD cameras into the projector line to allow automatic correction of the projector's geometry, color convergence, and electrical focus. Dr. Hebert developed image analysis routines to locate, classify and compensate for geometric inconsistencies within the projected image (e.g. keystone, pincushion, skew, etc). His current research focuses on the developments necessary to being new projector technologies into high-end military simulators. He earned his Doctoral degree in Computer Engineering from the University of Louisiana, Lafayette in 1998. He is a member of IEEE, SID, and ACM.