A Computer Aided Design Tool for Assessing the Visibility of Cockpit Displays

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Introduction

A large fraction of the life cycle cost of manufactured goods is determined during the design phase. Many engineering disciplines have developed mathematical models of critical properties of the object to be manufactured or its components that can be used to evaluate a potential design prior to actually building a prototype and testing it. Finite element models are now routinely used to evaluate the adequacy of hypothetical load bearing structures before they are actually constructed and subjected to loads. Similar modeling techniques have been applied to the layout of integrated circuits, the design of aircraft wings, and to design artificial hearts. Mathematical modeling techniques are used to eliminate designs that would have undesirable properties. The designs that are actually prototyped and tested therefore have a greater chance of meeting the design requirements. This reduces costs and the time required for development.

A second advantage of mathematical modeling is that it permits the evaluation of properties of designs that would be difficult or even impossible to empirically evaluate. For example, wind tunnels are used to evaluate and visualize laminar flow and turbulence, yet these properties are difficult to study when they are internal to structures as in the case of the flow of gases through engines or the flow of blood through the cardiovascular system. Computational fluid dynamics and computer graphics have made it possible to access and display fluid dynamics in both of these situations.

In the area of human performance very little has been done to aid the design engineer. For example, the cockpits of airplanes are designed by constructing full scale prototypes of the cockpit that are used in man-in-the-loop simulations of the handling and flight characteristics of the the aircraft. The avionics and displays in these systems are then modified in response to problems that are identified during the simulations. Since it is not possible to simulate the full range of ambient illumination encountered in real flight in today's flight simulators, displays that are adequate during the simulation phase are often found to be inadequate during real flight evaluations of the system. At this point the fix is often expensive and inadequate. To avoid or minimize these design problems human factors engineers employ design handbooks such as the Handbook of Perception and Human Performance (1986), but the rules and principles embodied in handbooks often do not anticipate the problems that are encountered when systems interact dynamically.

Visibility Modeling Tool

We are building a computer aided design tool that will answer "what if" questions about the visibility of visually displayed information. For example, "How much contrast and how large should letters be on a cockpit CRT display to be read without confusion, if bright sunlight is impinging upon the display surface, the pilot is light adapted to bright sunlight, and he is viewing the display in his parafovea?" The visibility modeling tool will be able to answer "what if" questions about chromatic contrast, apparent color stability, blur, the discriminability of symbols, motion thresholds, viewer adaptive states, and the impact of obstructions such as helmet margins, etc. Designs for displays that would be located in places that are likely to be obscured by other cockpit objects, or would be readable only if directly viewed, or easily "washed out" by bright sun light can be eliminated early in the design process. Good display designs require good visibility, therefore information visibility is an excellent first order assessment to eliminate inadequate designs.

The visibility modeling tool, VMT, is computer based and uses computer graphics to visualize the outcome of its analysis. It has three components: (1) a three dimensional geometric model of the environment called the "object space", (2) a model of eye position, fixation and focus that can be used to create retinal projections of the object space or "retrojections" of the retina into the object model space, and (3) mathematical models of early human visual processes that are used to evaluate human performance such as letter confusion and object motion sensitivity. The software for VMT is written in C, and is modular so components can be changed without affecting the entire application.

Object Space

We are using an application program called JACK© written to run on an Iris 4D™ computer system to model the object space. JACK was developed at the University of Pennsylvania's Computer Graphics Research Laboratory as an interactive system for manipulating human figure models (Badler, 1990). Objects modeled in JACK can be displayed as a 2D projection from any eye point. JACK permits a pilot manikin to be constructed that can be scaled to meet any anthropometric specification for body size. The manikin can be placed into a 3D space that contains the cockpit, its displays, other objects such as windows, aircraft, and other manikins. The manikin can be interactively manipulated within this space to sit in a chair, lean forward, turn its head, look out the window, etc. The cockpit model and objects are created by an application program called the Cockpit Display Editor which is an extension of an application program called MultiGen™.

Retinal Mapping

The location of the manikin's eyes and point of regard within the object space determine the geometry of a projection of the objects onto the manikin's retinas. We have developed a utility, based upon an application program developed by one of us (Arditi, 1988 & 1989), that allows us to project the objects in the modeling space onto the retinas of the manikin or conversely to "retroject" the retinas of the manikin into the object space. We call the "retrojection" of a retina onto surfaces in the object space the retinal "footprint." The footprint is a property of the retinal location, visual system function, the optics of the eye, and the objects in the space surrounding the eye.

The fovea of the eye is the retinal region that contains the greatest density of photoreceptors and therefore is the retinal region of greatest acuity. Fig. 1 is a top down view of the eyes fixated on a point in object space slightly in front of a surface. The lines with arrows emanating from each eye represents the line of sight for that eye, notice the lines of sight intersect at the fixation point. The foveas are circular retinal regions that are centered on the line of sight in each eye. The foveal retrojections are represented by the cones in object space centered on the lines of sight in each eye. The shaded area in each cone is determined by the optical blur function or depth of field for each eye and corresponds to the region in object space of greatest resolution. The footprint of the retinal region of greatest acuity on a surface in object space is shown in Fig. 2. Note that because this surface is located behind the fixation point, the foveal footprint is two disjoint areas on the surface.

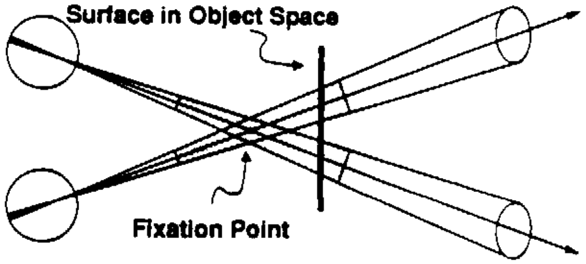

Figure 1. Top down view of the manikin's eyes in object space. The shaded area is a 2D slice of the volume of greatest acuity.

The perception of a scene at any moment in time is the product of a series of eye movements that take place in the 500 to 2000 msec immediately proceeding it. By defining a sequence of fixations that represent the eye movements during this temporal interval, it is possible to compute the union of high acuity regions for both eyes and all fixation points within this interval. The footprint of the union of these foveal retrojections on the surface in Fig. 1 would be the region of high acuity on this surface. Suppose that a fixation sequence is selected that corresponds to a frequent pilot scanning pattern during flight and that the surface corresponds to the instrument panel. The footprint of high acuity can be used to locate displays that must be assessable to the pilot during this scanning pattern or to evaluate the visibility of display symbology located on them.

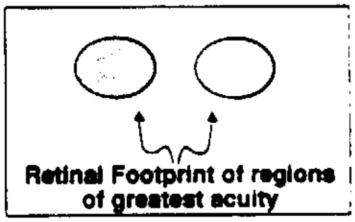

Figure 2. The retinal footprint of the foveas on the surface that intersects the greatest acuity volume in Fig. 1.

Receptor spacing alone is not adequate to specify display legibility. The retina and its associated processing is heterogeneous with respect to both spatial and temporal stimulus energy. A letter that is easily identified when it is imaged on central visual field may be hard to identify when imaged in the peripheral field and, in general, flicker is easier to see in the periphery than in the central field. The performance of the human visual system also depends upon the adaptive state of the observer; the same stimulus that is easily seen by a dark adapted observer may be invisible to an observer adapted to bright sun light or recently exposed to a pulse of bright light. Finally, to predict legibility one must also know the properties of the ambient illumination, the reflective and emissive properties of the displays and surfaces; that is, the physical characteristics of the images that would be formed on real retinas.

Using simple models of physiological mechanisms that are early in the human spatial vision pathway, Carlson and Cohen (1980) and Watson and Fitzhugh (1989) have been able to predict letter confusion of foveally viewed letters as a function of font type and letter contrast. These models take into account all of the features of the stimulus and the observer listed above, although they are limited in terms of the extent of the parameter space of conditions over which they can be employed or over which they have been empirically validated. We have been expanding these and similar models to take into account a larger range of stimulus and observer characteristics; for example, increasing the range of stimulus illumination levels and taking into account retinal locus.

For a particular letter font and size and assuming good focus, we can use the early vision models to identify the retinal regions wherein these letters would be readable at a specified level of confusion, say 5% confusion. This retinal region can then be retrojected back onto surfaces in object space. Instead of retrojecting photoreceptor densities, which are properties of the retina which are correlated with acuity, we can retroject a performance criteria such as letter confusions. Just as with acuity, we must take into account optical blur and therefore the retrojections form finite volumes in object space. The intersection of this volume with surfaces define a performance footprint of the visual system.

Our software, which is modular and integrated, can just as well be used to predict the letter confusions of text written on specified locations in the object space. In this mode, the VMT operator specifies the stimulus and observer conditions (i.e. where the manikin is located, its fixation, and state of adaptation) and then evokes the early vision model to compute an estimate of letter confusion. For example, the VMT operator can ask questions about letter confusion for say 12 point Geneva text viewed with a fixed geometry of the manikin and surface as a function of ambient light level.

We are currently building our system to evaluate the legibility of characters produced by CRT displays in the cockpit environment over a range of illuminations that span total darkness to bright sun light. Our goal is to gradually expand the capabilities of our system to encompass a broader range of stimulus, and human observer situations as well as a broader range of human visual performances.

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