Gaze-Contingent Simulations of Visual Defects in Virtual Environment: Challenges and Limitations

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Abstract
Building gaze contingent displays (GCD) for visual defect simulation in virtual environments can be a very challenging task. The technology is not fully developed, and practices are not entirely established and standardized. This paper will discuss the motivation and challenges in building a gaze-contingent display system to simulate visual deficiencies for real life scenarios. We will share the observations we made while building such a system and outline the issues associated with different aspects of the gaze-contingent system. These issues specifically involve tracking, displays and development. We hope that our observations will contribute to better GCDs for virtual environments with complex visual simulations.

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Gaze-contingent display; VR simulations;

ACM Classification Keywords
H.5.2 User Interfaces: *Evaluation/methodology*

General Terms
Design

Introduction
Simulations of virtual worlds that take into account the current pose of the eye can be used to present images

Definitions

Visual field map is a functional map of an eye's visual capabilities and is defined in terms of retinal layout.

Spatial resolution of the retina is at its highest in the centre of the visual field and then it gradually drops towards the periphery.

Gaze Contingent Display (GCD) is an application where the display is directly affected by the user's gaze.

to particular locations of the retina rather than to the mobile eye itself. Such a display is known as a gaze-contingent display and has been studied in the context of oculomotor control, reading, image compression and other applications. Such a technique also permits the simulation of arbitrary visual fields (the region of space that produces visible sensation in a stationary eye). Ophthalmologists often measure visual field maps or descriptions of visual capabilities over space, which can be used to characterize visual fields. Visual field defects are common in visual disorders that negatively impact activities like reading, working, walking or driving. Advances in eye tracking instruments, graphics hardware, processing speed and software have made it now practical to simulate normal and diseased visual fields in real-time while interacting with rich natural environments during complex tasks. Furthermore, GCD can not only simulate existing visual defects [4] but can also enhance vision for low vision aids.

We believe this provides an opportunity for eye tracking researchers to make significant contributions to patient education, occupational therapy and to treatment and diagnosis of serious, debilitating eye disease. However, the techniques have not reached their full potential in terms of GCD implementation. More sophisticated techniques are required for visual simulations and visual enhancements. Below we identified some of the opportunities and challenges of GCD visual field simulation.

Gaze-Contingent Display

Duchowski [2] divides gaze-driven interactive systems into selective systems and gaze-contingent display (GCD) systems. While in the first case, the user has to consciously direct his gaze at a point of interest in order to indicate selection, GCD displays are often based on a more transparent interaction with the system, where the user does not have to consciously signal regions of interest but rather concentrate on a primary task. For GCD systems the user should either not notice or not need to be explicitly cognizant that changes in image content arise from their eye movements. To achieve this, the system developer needs to understand the mechanisms of human perception that can be utilized, the purpose of GCD application and challenges that need to be solved.

Visual Field and Function

Visual field simulations can present realistic simulations of the onset and development of serious eye diseases. They can be used as a tool to not only educate the public and healthcare professionals, but to study the effects of visual field defects and quantify these effects on the performance of experimental controls and repeatability rather than using patient populations. Realistic simulations would incorporate gaze-contingent displays that support natural head and eye movements (as opposed to requiring them to fix their gaze on a particular feature as is required in many optometric or ophthalmic instruments).

The human visual system is diverse but most GCD systems control only one feature at a time. The most commonly utilized features are *spatial and temporal resolution*. Variable spatial resolution is useful for bandwidth and detail reduction: by reducing display resolution in the retinal periphery to minimize the information that will be displayed, rendered or transmitted. The eye's temporal limits can be exploited for GCD hiding of a display's refresh rate and other system latencies, although very few GCD systems have controlled temporal resolution in complex natural scenes [1].

Realistic Environments

GCD can be a powerful research tool in virtual reality (VR) simulations. In particular, it is safer to control and replicate high-risk scenarios such as self-motion and navigation. For example, GCD visual field restriction has been studied for goal-directed walking [3] but little work has targeted more general visual fields or GCD in driving simulators.

It is important to remember that complex real-time interactive scenarios were very challenging for early GCD technology. Rendering computations and processes happened at CPU level; pixel processing introduced latency and hence limited display and rendering complexity. Nowadays, most of the graphical computations are passed to the GPU as are many other processes, allowing faster and more complex computations.

Practical Challenges

Obtaining realistic simulations for complex tasks such as driving entails several requirements. The first requirement is a real-time simulation that can track a driver's eye location and orientation when they move their head or eye. The second is the ability to map a visual deficit to the retinal topology of the driver's eye. These requirements enable an interactive gaze-driven system that can update the graphics so that the simulated ocular damage is mapped in real-time to the retinal image. Challenges and limitations to this vision arise in the context of gaze (eye tracking), contingency (implementation), display and data handling.

Gaze (Tracking)

The eye tracker must measure angular position with high accuracy during a range of eye movements from smooth pursuit of moving objects to micro-saccades around fixation targets. The device should also be able to tolerate noise or interference caused by physiological sources such as movement or blinking and environmental sources such as reflections of shiny surfaces. In order to preserve realism in a simulated environment, gaze tracking technology should not limit users natural movements and support enough field of view (the extent of a virtually observed scene without head movement) or/and field of regards (the extent of a virtually observed scene with head and body movement). Furthermore, when selecting an appropriate gaze-tracking system for GCD applications, it is important to consider and measure latency that is introduced as a result. Signal processing algorithms can significantly impact latency. For example, filtering can reduce noise often at the expense of latency.

Contingency (Implementation)

GCD simulation platforms should be agile and allow rapid development of new scenarios and experiments. Game engines are attractive, and enable easy customization and integration of components such as physics engines, collision systems, sound simulation, mesh animation, particle systems and advanced lighting and shadows. Script-driven experimental configuration allows less technical users to easily specify scene environment, trial sequence and duration without needing to program them directly. Flexibility of the system is critical. Specifically, to match the particular experiment, software components should be modular and tracking devices should be easily interchangeable and configurable. Finally, the system should properly simulate images of the virtual scene with easy modeling and representation of visual defects.

The most common and important delay measurement in context of GCD is the end-to-end latency. It measures the delay between a gaze change and the resultant change in the GCD. We used custom hardware based on mechanical eye surrogates and optoelectronic light detection to estimate latency, and attributed it to components based on high-precision time-stamping.

Display

The display is often a limiting factor beyond normal considerations of resolution, brightness, contrast and color. For example, dynamic range limits some specific simulations such as glare. Update rate and latency are critical contributors to end-end latency: the inability to update the display fast enough after saccade can significantly impair simulation of visual fields.

Data Handling

Data recording should accommodate both explicit (direct responses from concrete questions) and implicit data (behavioral data such as steering, gaze patterns). One of the benefits of having a gaze-contingent experimental platform is the ability to collect gaze data in real time and register them with the state of the virtual environment. However, the main problem that remains is how to analyze the given data to achieve meaningful and significant results. From our experience, we think that it is important to mark the recorded data as much as possible, including eye movement types and action events during the eye movement. This will allow filtering data and produce processed data sets that are easier to compare and correlate.

Conclusion and future work

The opportunities for GCD simulations of complex virtual worlds become more prominent with technological evolution. We also believe that now is the time to introduce GCD displays for education, study of behavioral impact, and evaluation of coping strategies for visual diseases and disorders. Here we identified aspects that should be further developed to make GCD system easier to integrate. We believe that working toward standardized processes with special attention towards latency control will help system developers quickly integrate new virtual scenes, tracking devices and experimental scenarios.

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