NEUROPHYSIOLOGICAL FEATURES OF HUMAN VISUAL SYSTEM IN AUGMENTED PHOTOGRAMMETRIC TECHNOLOGIES

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ABSTRACT:

Humans perceive the environment through sensory inputs which the brain processes appropriately for the stimulus. This is particularly true of visual cognition and interpretation of geospatial images. The virtual scene, imagined in the brain, is inherently related to neuro-physiological features of the human visual system and differs from the real world. The brain processes visual input by concentrating on specific components of the entire sensory realm so that the interesting features of a scene may be examined with greater attention to detail than peripheral stimuli. Visual attention, responsible for regulating sensory information to sensory channels of limited capacity, serves as a "selective filter", interrupting continuously the process of ocular observations by visual fixations. In this paper we analyze specific features of the human visual system involved with geospatial imagery analysis using tracking eyes movements and the requirements for hardware, suitable for corresponding treatment of geospatial images in augmented photogrammetric systems. The research encompasses the impact of spatial and temporal resolution of an eye-tracking system on accuracy of fixation identification from eye-tracking protocols.

1. INTRODUCTION

Humans perceive the environment through sensory inputs so that the brain can successfully process the stimulus of interest. This is particularly true of visual cognition and interpretation of geospatial images. The virtual scene, imagined in the brain, is inherently related to neuro-physiological features of human visual system and differs from the real world. The brain processes visual input by concentrating on specific components of the entire sensory realm so that the interesting features of a scene may be examined with greater attention to detail than peripheral stimuli. Visual attention, responsible for regulating sensory information to sensory channels of limited capacity, serves as a "selective filter", interrupting the continuous process of ocular observations by visual fixations. That is, human vision is a piecemeal process relying on the perceptual integration of small regions to construct a coherent representation of the whole.

(Jaimes et al., 2001) explore the way in which people look at images in different semantic categories (e.g., handshake, landscape), and directly relate those results to the computational approaches for automatic image classification, using the hypothesis that eye movements of human observers differ for images from different semantic categories, and that this information can be effectively used in automatic content-based classifiers.

A practitioner's first question when starting to work with an eye-tracker is: how accurate are acquired data? There are three ways to address this question depending on the degree of abstraction with which the user thinks about the study: at the level of the individual fixation, at the level of the individual scene, and at the level of an overall experience of a trained user. While the last two levels reflect the accuracy of displaying the viewing behavior of a user observing a particular scene, the first way to answer this question focuses on the equipment and addresses the accuracy of the individual fixations which, actually, represent measurements in augmented photogrammetric technologies.

The goal of this article is analysis of specific features of the human visual system with respect to treatment of geospatial imagery using tracking movements of eyes, and requirements to hardware suitable for corresponding treatment of geospatial images in augmented photogrammetric systems. Experimental research includes statistical analysis and impact of spatial and temporal resolution of an eye-tracking system based on the accuracy of fixation identification from eye-tracking protocols.

2. EYE MOVEMENTS IN VISUAL COGNITION

Neurophysiological and psychophysical literature on the human visual system suggests the field of view is inspected through brief fixations over small regions of interest. This allows perception of detail through the fovea. When visual attention is directed to a new area, fast eye movements (saccades) reposition the fovea. Foveal vision allows fine scrutiny of approximately 3% of the field of view but takes approximately 90% of viewing time, when Subtending 5 deg of visual angle occurs. A common goal of eye movement analysis is the detection of fixations in the eye movement signal over the given stimulus or within stimulus Regions of Interest (ROIs).

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2.1 Where and What in Vision

A visual scene, perceived by a human or an animal, is so complex that it is not possible to perceive the whole scene as one unit. Such a holistic perception would make the scene unique, rendering associations to other scenes and other perceptions impossible. Thus it is necessary to have a mechanism in the perceptual system that breaks down or fragments the scene to a more appropriate form of a representation.

It has been found (Mishkin et.al.,1983) that humans and higher animals represent visual information in at least two important subsystems: the *where-* and the *what* systems. The *where-system* only processes the *location* of the object in the scene. It does not represent the *kind* of object, but this is the task of the *what-system*. The two systems work independently of each other and never converge to one common representation (Goldman-Rakic,1993). Physiologically, they are separated throughout the entire cortical process of visual analysis.

The *where-system* builds up a *spatial relation map*, where no information about the form of the object is represented. This form of representation can be used for *variable binding* in collaboration with the *what-system*. The *what-system* represents *categories* of objects, without any information about their spatial location.

In natural environments, a significant problem is to *attend* to a stimuli of interest. The *where-system* is a part of the attention process, since the *where-system* supplies information about where to foveate in the scene. The fovea in the retina is exclusively concerned with form perception, not with the location of the objects in the scene.

2.2 Attention

When the brain processes a visual scene, some of the elements of the scene are put in focus by various attention mechanisms (Posner, 1990). It is obvious that attention must be a very important property for identification and for learning in biological as well as artificial systems- many researches are focused on attention mechanisms necessary for grasping spatial relations. In a natural scene, one of the basic problems is to locate and identify objects and their parts.

2.3 Saccades

When the brain analyses a visual scene, it must combine the representations obtained from different domains. One hypothesis underlying the simulations states that attention shifts from domain to domain in a *sequential* way (Crick, 1984). Since information about the form and other features of particular objects can be obtained only when the object is foveated, different objects can be attended to only through *saccadic* movements of the eye.

These rapid eye movements, which are made at the rate of about three per second, orient the high-acuity foveal region of the eye over targets of interest in a visual scene. The characteristic properties of saccadic eye movements (or saccades) have been well studied (Carpenter, 1988). The high velocity of saccades, reaching up to 700° per second for large movements, serves to minimize the time in flight, so that most of the time is spent fixating chosen targets.

Saccades are known to be ballistic, for example, their final location is computed prior to making the movement, and the trajectory of the movement is uninterrupted by incoming visual signals. Furthermore, owing to the structure of the retina, the central 1.5° of the visual field is represented with a visual resolution that is many times greater than that of the periphery. Saccades subserve the important function of bringing high resolution foveal region onto targets of interest in the visual scene.

Initial eye movement studies suggest that the primary role of saccades might be to compensate for the lack of resolution over the visual field by "painting" an image into an internal memory. It was proposed that the saccadic movements and their resultant fixations allowed the formation of a visual-motor memory ("scan path") that could be used for encoding objects and scenes (Noton and Stark, 1971). However, a number of studies, starting from Yarbus' classical work (Yarbus, 1967), have suggested that gaze changes are most often directed according to the ongoing demands of the task at hand.

The task-specific use of gaze is best understood for reading text (O'Regan, 1990) where the eyes fixate almost every word, sometimes skipping over smaller function words. In addition, it is known, that saccade size during reading is modulated according to the specific nature of the pattern recognition task at hand (Kowler and Anton, 1987).

2.4 Fixations

It is generally agreed that visual and cognitive processing do occur during fixations (Just and Carpenter, 1984). Fixation identification is an inherently statistical description of observed eye movement behaviors. The process of fixation identification - separating and labeling fixations and saccades in eye-tracking protocols - is an essential part of eye-movement data analysis and can have a dramatic impact on higher-level analyses.

Common analysis metrics include fixation or gaze durations, saccadic velocities, saccadic amplitudes, and various transition-based parameters between fixations and/or regions of interest (Salvucci and Goldberg, 2000). The analysis of fixations and saccades requires some form of *fixation identification* (or simply *identification*) - that is, the translation from raw eye-movement data points to fixation locations (and implicitly the saccades between them) on the visual display.

While it is generally agreed upon that visual and cognitive processing do occur during fixations, it is less clear exactly when fixations start and when they end. Regardless of the precision and flexibility associated with identification algorithms, the identification problem is still a subjective process. Therefore one efficient way to validate these algorithms is to compare resultant fixations to an observer's subjective impressions.

For spatial characteristics, three criteria have been identified that distinguish three primary types of algorithms: velocity-based, dispersion-based, and area-based (Salvucci and

Goldberg, 2000). Velocity-based algorithms emphasize the velocity information in the eye-tracking protocols, taking advantage of the fact that fixation points have low velocities and saccade points have high velocities. Dispersion-based algorithms emphasize the dispersion (i.e., spread distance) of various fixation points, under the assumption that fixation points generally occur near one another. Area-based algorithms identify points within given areas of interest (AOIs) that represent relevant visual targets.

Temporal characteristics (Salvucci and Goldberg, 2000) include two criteria: whether the algorithm uses duration information, and whether the algorithm is locally adaptive. The use of duration information is guided by the fact that fixations are rarely less than 100 ms and often in the range of 200-400 ms. The incorporation of local adaptiveness allows the interpretation of a given data point to be influenced by the interpretation of temporally adjacent points; this is useful, for instance, to compensate for differences between 'steady-eyed' individuals and those who show large and frequent eye movements.

3. EYE-TRACKING TECHNIQUES AND SYSTEMS

Several methods and corresponding systems can be used to track a subject's gaze, each having advantages and disadvantages. Some systems use coils of fine wire held in place on the eye with tight-fitting annular contact lenses (Robinson, 1963). Eye position is tracked by monitoring the signals induced in the coils by large transmitting coils in a frame surrounding the subject. Scleral coil eye-trackers offer high spatial and temporal resolution, but limit movement and require the cornea to be anesthetized to prevent pain due to the annular contact lens.

Systems offering high spatial and temporal resolution are the dual-Purkinje eye-trackers (Cornsweet, 1973). These eye-trackers shine an infrared illuminator at the eye, and monitor the reflections from the first surface of the cornea and the rear surface of the eye-lens (the second optical element in the eye). Monitoring both images allows eye movements to be detected independent of head translations, which otherwise cause artifacts. Limbus trackers track horizontal eye movements by measuring the differential reflectance at the left and right boundaries between the sclera (the 'white of the eye') and the pupil. Vertical eye movements are measured by tracking the position of the lower eyelid. While the limbus tracker provides high temporal resolution, the eye position signal suffers from inaccuracy, and there is significant cross-talk between horizontal and vertical eye movements.

The general eye-tracking hardware requirements and related issues were addressed in (Proceedings, 1999). Below is a summary of requirements, considered through the prism of applicability of eye-tracking systems in geospatial image analysis and augmented photogrammetry.

Sampling rate. The average duration of fixations while observe geo-spatial imagery vary from 200 to 800 ms, so the sampling rate can be as low as 50 Hz. This however could not be sufficient to get clear velocity traces.

FOV/measurement range. Horizontal 30° and Vertical 20° are sufficient, and also cover most geo-spatial image analysis and photogrammetric applications. At larger vertical eye movements the eyelid starts to obscure the pupil to such an extent that good recordings are often no longer possible.

Illumination. Infrared (IR) light has the advantage that the pupil border is much sharper than in the visible light. The NASA-limits for the illumination intensity are 10 mW/cm^2. It is important to note that according to many standards, for example ANSI, the time integral of the illumination intensity with pulsed light has to be significantly below that of continuous illumination.

Pupil center detection. There exists a general agreement that a simple "center of gravity" algorithm is not sufficient to detect the center of the pupil. A photogrammetric system requires precise 3D measurements, thus, clear-cut pupil center detection is necessary to determine torsion with necessary precision.

Center of rotation ("d"-value). Investigations in the 60's have already demonstrated that the eye does not show a "ball-in-socket" behavior, but instead rotates about points that depend on a) the direction of the rotation, and b) the eye position. To account for this complex behavior, some current eye models for the interpretation of eye movements data assume a different axis of rotations for horizontal and vertical eye movements. In these models the eye movement is described in a Hemholtz- or Fick-system, and the displacement between the two axes of rotation is labeled "d" (Schreiber, 1999; Kopula, 1996).

Light/dark changes of pupil and iris. When the pupil contracts, the iris patterns do not move along a radial line, instead the iris "twists" during the contraction. This implies that a simple linear scaling of the iral pattern, which is sometimes used to compensate for the contraction and expansion of the pupil, is not sufficient for an accurate determination of iris patterns. To keep the size of the pupil constant, either constrictors or dilators might be used.

Visual – optical axis. The shift between the visual axis and the optical axis of the eye varies between subjects, and is on average about 5°. The magnitude of this effect on 3D recordings depends on "where the eye looks out of the pupil", in other words the intersection of the visual axis with the pupil.

Optical effects of cornea. The distortion of the iral image by the cornea is regarded as small, and has been neglected so far. However, different types of optical reflections from the cornea can lead to artifacts in the calculation of ocular torsion.

Camera slippage compensation. Camera slippage with respect to the head is one of the most serious difficulties facing precise eye-tracing systems: a movement of the camera by only 1° appears in the image like a gaze shift of more than 5°. A compensation of such slippage will definitely be necessary for high acceleration movements.

Calibration. Calibration of precise eye-tracking systems is a keystone of the augmented photogrammetric systems. Depending on chosen technique and hardware calibration involves the following major steps: 1) Photometric calibrating the video cameras; 2) Estimating the positions of the IR LEDs in order to estimate the cornea center; 3) Resolving the geometric properties of the monitors; 4) Determining the

relationship between video cameras and the screen to transform camera and monitor coordinate systems; and 5) Determining the angle between visual-optical axis.

4. ACCURACY OF EYE-TRACKING SYSTEMS

Video-oculography provides a high resolution, non-invasive method for recording eye movements in three dimensions. However measurement errors will occur, particularly for ocular torsion estimates, if the video camera orientation with respect to the eye is not taken into account (Peterka and Merfeld, 1996).

The classification registration errors follow into two categories (Splechtna, 2002): *static* errors, which occur even when the user remains still, and *dynamic* errors caused by system delays when the user moves. Correct static registration is the fundamental step in achieving correct overall registration of eye-tracking in augmented photogrammetric technologies. The lower limit is bound by the resolving power of the human eye itself. The central part of the retina, called the fovea, has the highest density of color detecting cones, about 120 arc degrees, corresponding to a spacing of half-minute arc (Jain, 1989). Observers can differentiate between a dark and light bar grating when each bar subtends about a one-minute arc, and under special circumstances they can detect even smaller differences (Doenges, 1985). Thus, the angular accuracy required is a small fraction of a degree. However, existing eye-trackers are not capable of providing one-minute arc degree in accuracy, so the achievable accuracy is much worse than that ultimate lower bound. In practice, errors of a few pixels are detectable in modern eye-trackers.

The four main sources of static errors stated by (Azuma, 1994) are: optical distortion, errors in the tracking system, mechanical misalignments and incorrect viewing parameters (e.g., field of view, tracker-to-eye position and orientation, interpupillary distance).

Distortion in the optics. Optical distortions exist in most camera and lens systems, both in the cameras that record the real environment and in the optics used for the display. Because distortions are usually a function of radial distance away from the optical axis, wide field-of-view displays can be especially vulnerable to this error. Cameras and displays may also have nonlinear distortions that cause these errors (Deering, 1992).

Errors in the tracking system. Errors in the reported outputs from tracking and sensing systems are often the most serious type of static registration errors. These distortions are not easy to measure and eliminate because this requires another "3-D ruler" that is more accurate than the tracker being tested. These errors are often non-systematic and difficult to fully characterize.

Mechanical misalignments. Mechanical misalignments are discrepancies between the model or specification of the hardware and the actual physical properties of the real system. For example, the combiners, optics, and monitors may not be at the expected distances or orientations with respect to each other.

Incorrect viewing parameters. Incorrect viewing parameters, the last major source of static registration errors, can be thought of as a special case of alignment errors where calibration techniques can be applied. Viewing parameters specify how to convert the reported head or camera locations into viewing matrices used by scene generators to draw the graphic images. These parameters include center of projection and viewport dimensions; offset, both in translation and orientation, between the location of the head tracker and the user's eyes; field of view.

The above sources of errors differ by their nature and weight of "errors". While some errors could be compensated by employing corresponding calibration techniques, the other might be eliminated by optimization of inherent parameters of an eye-tracking system, such as spatial and temporal resolutions.

5. EXPERIMENTAL RESEARCH

Our experimental researches were aimed on investigation of basic eye-tracking hardware parameters (spatial resolution of CCD and sampling rate of frame-grabber) and their impact on accuracy of fixation identification from eye-tracking protocols. Figure 1 illustrates typical eye-paths while observing a test image on the screen. Blue and red scan-paths are from the left and right eye respectively; black circle outlines a zoom area with number of fixations, depicted as black boxes in Figure 2.
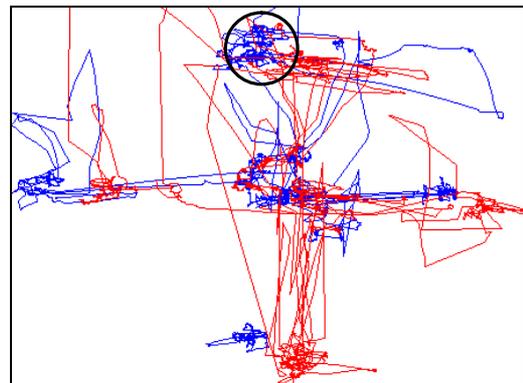
Figure 1. Eye-paths while observing a test object; left and right eyes are in blue and red, respectively
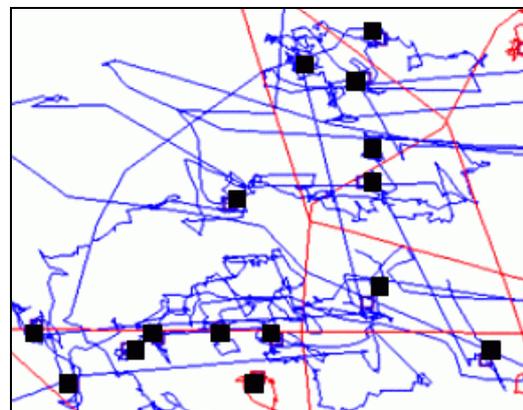
Figure 2. Zoom of fixation area: scan paths at 1280x1024 resolution at 250 fps sampling rate

Comparative study of fixation identification algorithms (Salvucci and Goldberg, 2002) suggests dispersion-threshold method as a fast and robust mechanism for identification of fixations. This method is also quite reliable in applications, requiring real time data analysis, which is a critical aspect in real-time photogrammetry applications.

Table 1 illustrates impact of camera resolution and sampling rate on accuracy of fixation identification. The source data have been acquired by eye-tracking systems with CCD size 1280x1024 pixels at 250 frames per second and spatially and temporally down-sampled. Identification of fixations have been implemented using Dispersion-Threshold Identification (I-DT) with the fixation duration threshold of 250 ms and the dispersion threshold of 25 pixels, constant for all resolutions and sample rates in our experiments.

	Sample interval, ms	Fixation duration, ms	RMSE in coord, pix	Velocity, pix/sec	Nr.of samples in fixations
Sample rate: 250 frames per second					
1280x1024	4	324,6	2,85	198,7	81,1
960x768	4	328,0	2,86	215,6	82,0
728x582	4	326,5	2,99	227,7	81,6
500x576	4	327,4	3,00	222,2	81,8
360x288	4	340,2	3,32	235,1	85,1
CCD size: 1280x1024					
250 fps	4	324,6	2,85	198,7	81,1
125 fps	8	334,7	3,00	166,8	41,8
050 fps	20	339,9	3,64	115,5	17,0
025 fps	40	350,5	5,51	75,9	8,8
010 fps	100	331,3	15,48	22,8	3,6
CCD size and sample rate					
1280x1024 250 fps	4	324,6	2,85	198,7	81,1
728x582 125 fps	8	330,8	3,04	175,2	41,4
500x576 050 fps	20	334,8	3,71	121,2	16,7
360x288 010 fps	100	335,1	15,98	23,7	3,6

Table 1. Impact of camera resolution and sampling rate on accuracy of fixation identification

Among many parameters which could be extracted and studied from eye movement protocols, coordinates and duration of fixations have major interests for accurate measurements of objects on static images. Table 1 represents sample interval (i.e. video frames acquisition interval), duration of identified fixation (i.e. time of relatively stable position of an eye), errors in determining of coordinates of fixation, mean velocity of eye tremors and drifts during fixations and average number of samples in fixations.

Table 1 illustrates variation of the above parameters depending on camera resolution, sample rate (frequency) and their combinations. As the coordinates of objects have the highest priority in metric technologies, the corresponding parameter (RMSE of fixations' position) has drawn our major attention. The first part of the table illustrates the idea that temporal resolution has major priority over spatial resolution in eye-

tracking systems, aimed on measurements of static objects. The results clearly show that change of spatial resolution from 1280x1024 pixels down to 360x288 pixels does not entail coarsening of fixation coordinates on such a dramatic scale: RMSE in coordinates change from 2.85 pixels to 3.32 pixels only.

The second part of the table (opposite), illustrates significant loss of accuracy in coordinates when changing sampling rate at fixed spatial resolution (from 2.85 pixels at 250 frames per second to 15.48 pixels at 10 frames per second). The third part of the table demonstrates impact of combined changes – both spatial and temporal resolution, outlining the balance between spatial resolution and sampling rate of eye-tracker's CCD and frame grabber.

The data, provided in Table 1, are averaged from series of experiments with eye-tracking protocols. Figures 4 and 5 illustrate particular data analysis – matching of fixations, identified from different source data.
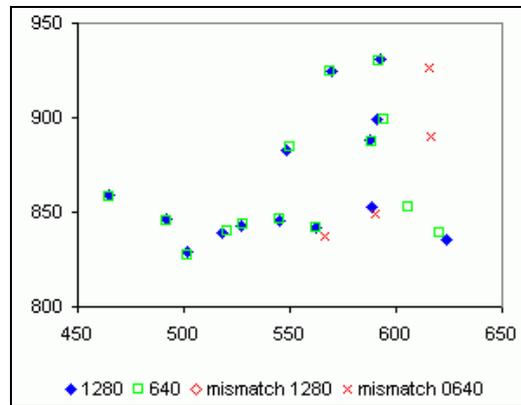
Figure 3. Fixation matching results; blue - fixations detected at 1280x1024/250fps, green - fixations detected at 640x480/50fps; red – fixation mismatches
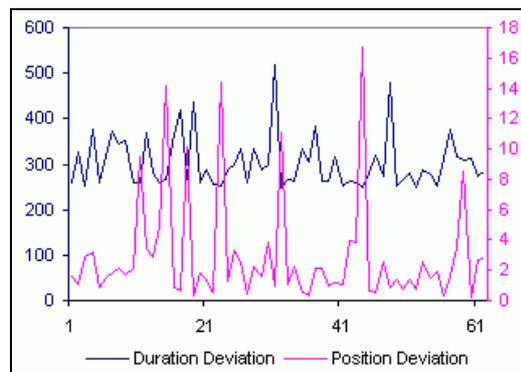
Figure 4. Fixation matching results 1280x1024/250fps vs. 640x480/50fps: blue - deviations in duration of fixations (ms); purple – deviations in coordinates of fixations (pixels)

6. CONCLUSION AND OUTLOOK: EYE-TRACKING IN AUGMENTED PHOTOGRAMMETRY

Spatial and temporal data about eye movements, compiled while observing geospatial imagery, bear the meaningful

information that could be successfully used in modern augmented photogrammetry.

Fixations, identified in eye-tracking protocols, could be interpreted as coordinates of the featured points of an object being observed in the image. Such a way of utilizing eye-tracking data leads to the establishment of "*eyegrammetry*" - a new branch of photogrammetry, which synthesize human visual abilities and fundamentals of classic stereometry for fast and highly reliable real-time 3D measurements.

Registration ways "of where and how" allow us to look and explore not only how humans perceive the environment through the visual inputs, but helps us understand how our mind can process the stimulus of interest in visual cognition, which is particularly true to interpretation of geospatial images. Such interpretation requires substantial knowledge about the scene under consideration. Knowledge about the type of scene - airport, suburban housing development, urban surroundings - helps to understand low-level and intermediate level image analysis and how it will impel high-level interpretation by limiting the search for plausible consistent scene models. Eye-tracking could be successfully used for developing a visual knowledge acquisition tool for acquiring knowledge from image interpreters. Such a tool, allowing a human classifier to identify features of interest by pointing an image with a gaze, could monitor the expert's eye movements and record all steps of the natural process of classification of geospatial images by image interpreter. This could bring the revolutionary progress in automated image interpretation and knowledge elicitation for Geographic Expert Systems.

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