Introduction

Eye movements are accurate reflections of the brain's control strategy. Their function is to provide essential information about the visual scene under a wide variety of situations that are encountered in our daily lives. Therefore, understanding how eye movements are controlled in both normal and symptomatic individuals is one of the most important goals of vision scientists and bioengineers. This monograph provides a summary of significant research results on the quantitation of oculomotor behavior using control systems analysis techniques, based primarily on my research work over the past 20 years.

When one redirects gaze, neural command signals change the lens focus and rotate the two eyes to provide a clear and single image of the new target. It has been found that three primary oculomotor movements are involved in the automatic control of binocular gaze. *Accommodation*, or focusing, changes the lens power in response to change in depth of the target; *vergence* rotates the eyes symmetrically in opposite directions to point accurately at the binocularly fixated target; and *saccades* rotate the eyes in the same direction to accurately adjust for the lateral displacement of the target. These automatic adjustments can be represented in engineering block diagram form as three feedback control systems. Well-known engineering control systems theories can be used to study the feedback control of the models of these physiological processes.

This monograph is intended for both the engineer with relatively little physiology background and the vision scientist with relatively little engineering background. Basic physiology of eye movements as well as basic control systems theory are introduced to provide the background needed by the reader to understand the application of various engineering techniques to eye movement control systems. Due to the numerous control systems and visual science terms used, a table containing a glossary of terms has been included (Table 1). The monograph is divided into three sections. The "Introduction" reviews basic anatomy and physiology of eye movements, basic measurement terms, basic control systems concepts, and accommodation and eye movement instrumentation and measurement methodology. The "Static Analysis Techniques" section examines in detail simulations of the static

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Table 1 Glossary of Terms
(Adapted from Hung,[65] p. 306.)

Terms	Definition
ABIAS	Accommodative bias or tonic level.
AC	Accommodative convergence crosslink gain.
AC/A	Accommodative convergence to accommodation ratio.
Accommodation	A change in the optical power of the lens to minimize the retinal defocus.
ACG	Accommodative controller gain.
AD	The deadspace limit value for depth of focus.
AE	Accommodative error.
Amblyopia	Amblyopia is a reduction in monocular visual acuity that is not correctable by refractive means and is not attributable to obvious structural or pathological ocular anomalies.
Anomalous retinal correspondence	A type of correspondence between the two retinas, occurring frequently in strabismus, in which the fovea of one eye does not correspond to the fovea in the other eye, but instead to an extrafoveal area in that eye.
AR	Accommodative response.
AS	Accommodative stimulus.
BI	Base-in prism, providing a divergent stimulus.
$B_{nonlinear}$	Intercept term representing 16 possible combinations.
BO	Base-out prism, providing a convergent stimulus.
C	Subscript denoting a constant viewing distance.
CA	Convergence accommodation crosslink gain.
CA/C	Convergence accommodation to convergence ratio.
Deadspace operator	An ideal mathematical function that approximates the threshold of detection of a variable in a physiological system. If the absolute value of the input to the function is less than the threshold (with threshold being a positive number), then the output is zero. On the other hand, if the input is greater than the threshold, then the output is equal to: input − threshold. Further, if the input is less than −threshold, then the output is equal to: input + threshold.
Diopter (D)	A unit of optical power equal to the reciprocal of the distance of the target from the corneal plane of the subject measured in meters.

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Table 1 (Continued)

Term	Definition
Depth of focus (DOF)	The deadspace operator for accommodation. It is the range of an image, either in front of or behind the retina, that is perceived to be clear and sharp. It is assumed that this range corresponds to the limits in the size of the blur circle on the retina which can be tolerated without the perception of appreciable amount of blur. The DOF varies with pupil size, ranging from ± 0.15, ± 0.30 to ± 0.80 D for 8, 3 and 1 mm diameter pupil, respectively.
Emmetropia	Normal refractive condition in which distant objects are focused on the retina when accommodation in minimally stimulated.
Emmetropization	A change in the rate of axial growth which compensates for and reduces the effect of imposed retinal defocus, usually over a relatively long time interval.
Fixation disparity (FD)	Equal to the vergence error (VE), or difference between vergence stimulus (VS) and response (VR), under the binocular viewing condition. Eso FD describes a response which is more convergent than the stimulus, and Exo FD describes a response which is less convergent than the stimulus.
Hyperopia	A refractive condition in which distant objects are focused behind the retina when accommodation in minimally stimulated.
Hysteresis	A difference in the response path for stimulus in the forward and reverse directions, such as that seen in the magnetization curves.
L	Lens value; or subscript denoting the lens viewing condition.
Meter angle (MA)	A measure of vergence angle equal to the reciprocal of the distance of a target from the centers of rotations of the eyes of a binocularly viewing subject measured in meters. The interpupillary distance is implied in the use of MA.
Myopia	A refractive condition in which distant objects are focused in front of the retina when accommodation in minimally stimulated.
Nystagmus	A regular, repetitive, and usually rapid involuntary movement or rotation of the eye that is either oscillatory or has slow and fast phases in alternate directions.
P	Prism value; or subscript denoting the prism viewing condition.

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Table 1 (Continued)

Term	Definition
Panum's fusional area (PFA)	The deadspace operator in vergence. It is an area on the retina in one eye, which when stimulated simultaneously with a single specific point on the retina in the other eye, will give rise to a single fused percept. Its diameter increases with target eccentricity, and ranges from about 6–12 min of arc near the fovea to about 20–40 min of arc at 15 deg eccentricity.
Phoria	The angle of the two eyes in the absence of adequate fusion relative to binocular fixation on the target (e.g. one eye blocked). Esophoria describes an angle of the two eyes which is more convergent than exact alignment of the two eyes with the target. On the other hand, exophoria describes a more divergent angle than exact alignment with the target.
Saccade	Rapid same-direction rotations of the two eyes to fix on a target that is displaced laterally in space, such as during reading.
Strabismus (or tropia)	An anomaly of binocular vision under normal viewing conditions wherein one visual axis fails to intersect the object of regard, and thus bifoveal fixation is not attained (cross-eyed).
VBIAS	Vergence bias or tonic level.
VCG	Vergence controller gain.
VD	The deadspace limit value for Panum's fusional area.
VE	Vergence error.
Vergence	Oppositely-directed rotations of the eyes to bring them into alignment with a target in depth.
VR	Vergence response.
VS	Vergence stimulus.

accommodation and vergence systems, linear and nonlinear analysis of cross-link interactions, contributions due to proximal effects, and sensitivity analysis of accommodation and vergence to parameter variations. The "Dynamic Analysis Techniques" section examines in detail the main sequence as a tool for characterizing the dynamic characteristics of the three oculomotor systems, accommodative root locus stability analysis, vergence dual-mode model,

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accommodation dual-mode characteristics, adaptation model of accommodation and vergence, nearwork-induced transient myopia (NITM) model, refractive error development model and emmetropization, and model of saccade-vergence interactions.

Basic Anatomy and Physiology of Eye Movements

The goal of the accommodation, or focusing, system is to provide a clear and sharp image of an object on the retina. Figure 1A shows a cross-sectional view of the interior of the human eyeball. Light rays enter the eye first through the transparent cornea, which comprises about 2/3 of the fixed refractive power of the eye. The rays then pass through the opening in the iris, called the pupil, and is refracted by the transparent lens, which comprises the remaining 1/3 of the fixed optical power. The lens has, in addition, a variable component that is controlled by the ciliary muscle (which is part of the ciliary body) through its action via the zonular fibers located between the ciliary body and the lens. In this way, the light rays of a target at different distances can be focused by the variable-powered lens onto the fovea, which is a small high-acuity region on the retina. The act of focusing from a far (F) to a near (N) target is called accommodation (Fig. 1B). Moreover, the image can be focused within a certain range either in front of or behind the retina, thus providing a small amount of retinal-defocus, and still be perceived as clear and sharp. This is called the depth-of-focus or DOF (not explicitly shown in Fig. 1B). However, if the retinal-defocus is outside the DOF, the image is perceived to be blurred, and accommodative feedback is used to change the lens power and reduce this blur to a minimum. In general, for viewing of objects closer than about 1 m, the resultant image is focused behind the retina and the accommodative response is said to "lag" the stimulus. Although retinal-defocus, and hence the perceived blur, is an even-error signal (for stimuli given in diopters rather than linear displacement units)[4] that does not provide a direction sense of the error, other optical cues such as chromatic aberration, where light rays of shorter wavelength (e.g. blue) are refracted more than those of longer wavelength (e.g. red), and spherical aberration, where peripheral rays impinging on a lens are refracted more than central rays, as well as

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