The goal of the binocular eye movement system is to provide a single (rather than double) percept by bringing the images of a target onto corresponding retinal points in the two eyes. Hence, when the target moves in depth, the eyeball in each eye must be rotated by the muscles outside the eyeball, called extraocular muscles (Fig. 2A), to once again bring the images in register on the retinas. There are three pairs of extraocular muscles that are concerned with horizontal, vertical and oblique rotations of the eye. The very efficient pulley actions of these extraocular muscles and their multidimensional control of eye rotations can be fully appreciated by the mechanical engineer. In this monograph, we will be concerned primarily with the horizontal muscles, called the medial rectus and lateral rectus, that are reciprocally innervated and rotate the eye in the horizontal plane. The neural pathways for the control of horizontal eye movements are shown in Fig. 2B. The neural signals are formed in the higher neural centers and then sent to the oculomotor (3rd nerve) and abducens (6th nerve) nuclei, which in turn send signals to the horizontal recti muscles. These signals drive the two eyes in a coordinated fashion so that the lines of sight intersect at the target. The resulting images in the two retinas are combined by the brain to form a single percept. When a target is displaced in depth (e.g. between far (F) and near (N) positions in Fig. 3A), an angular difference between the near and far targets, $\alpha - \beta$ (called disparity), is created and causes the muscles to rotate the two eyes in opposite directions to track it in a disjunctive manner. A disjunctive or vergence response for a target displacement from far to near is called convergence, and that from near to far is called divergence. On the other hand, when a target is moved laterally from side to side (e.g. between positions T1 and T2 in Fig. 3B), the two eyes rotate in the same direction to track it in a conjunctive or conjugate manner. There are two types of conjugate eye movements — saccades that jump to follow rapid target displacements and pursuit eye movements that smoothly follow relatively slowly moving targets.

Basic Measurement Terms

The basic unit of measurement for the focusing or accommodation system is the diopter (D). A diopter is a unit of optical power that is equal to the reciprocal of the distance of the target from the corneal plane (or more

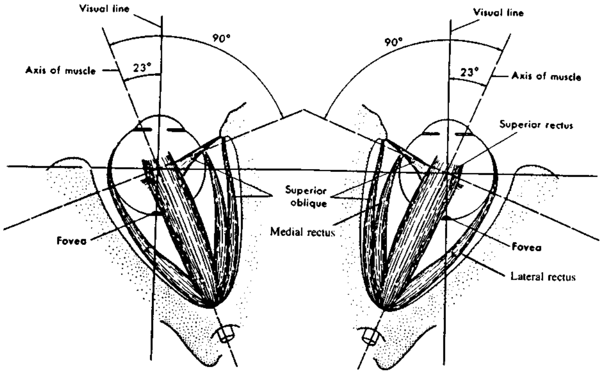

Fig. 2A The two eyes and the extraocular muscles as seen from above. The orientations of the muscles indicate their lines of action. Horizontal eye rotations, frequently used in daily life, are controlled by the medial and lateral recti muscles. The objective of the muscle-driven eye movements is to bring the target image onto the fovea (adapted from Moses,[111] p. 92, with permission).

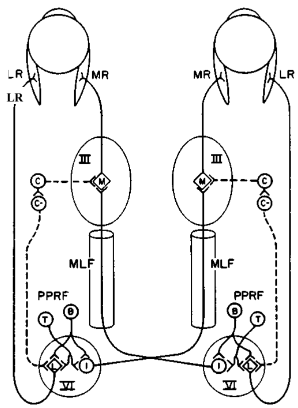

Fig. 2B Schematic representation of the neural circuitry for the control of horizontal eye movements. Horizontal burst (B) and tonic (T) neurons in the paramedian pontine reticular formation (PPRF) have the signals required for all conjugate horizontal eye movements. These PPRF neurons probably provide similar inputs to both lateral rectus motoneurons (L) and internuclear neurons (I) in the abducens nucleus (VI). Abducens internuclear neurons cross the midline and ascend in the medial longitudinal fasciculus (MLF) to the medial rectus motoneurons (M). A presumed convergence (C) input to the medial rectus motoneurons and its complementary (C-) input to the lateral rectus motoneuron are shown by dashed lines (reprinted from Mays,[103] p. 656, with permission).

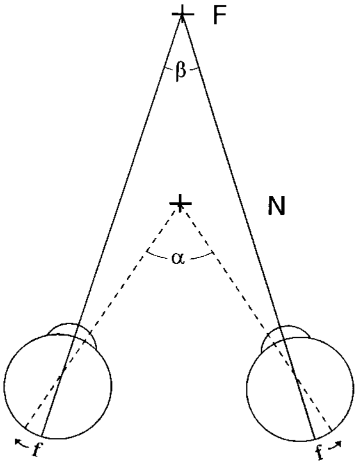

Fig. 3A Binocular fixation of the target at far (F). Rotation of the two eyes in opposite directions (called vergence) brings the near (N) target image onto the foveas. The brain combines the two retinal images into a single percept. The difference in angle between the N and F targets, or $\alpha - \beta$, is called the disparity.

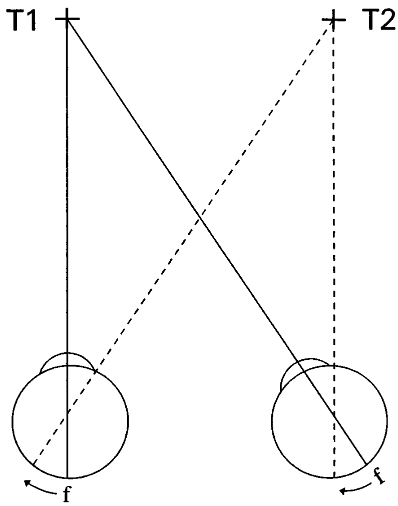

Fig. 3B Binocular fixation initially at target T1. Rotation of the two eyes in the same direction (called version: consisting of fast saccades and slower pursuit eye movements) brings the image of target T2 onto the foveas. Note that the relative angle between the two eyes, or disparity, remains the same.

precisely, the principle plane, which is located 1.35 mm behind the corneal surface[46]) of the subject measured in meters. For example, a target 2 m away requires only 0.5 D of accommodative change, whereas a target 0.5 m away would require 2 D of accommodative change to focus on it clearly.

There are several units of measurement for vergence eye movements. Meter angle (MA), which is used in basic research, is a measure of vergence angle equal to the reciprocal of the distance of a target from the centers of rotations (about 13.5 mm behind the corneal surface[1]) of the two eyes of a binocularly viewing subject measured in meters, and thus is analogous to the diopter used for accommodation. Prism diopter (Δ), which is used in the clinic, is a unit of measure of convergence angle, where 1 Δ is equivalent to 1 cm of lateral displacement at 1 m distance, and is based on the interpupillary distance (PD). Both MA and Δ can be converted to degrees of visual angle.[64] Thus for example, a target 0.5 m in front of a subject with 6.0 cm PD has visual angles of 2 MA (= 1/0.5 m), 12 Δ (= 6 cm * 2 MA), or 6.84 deg (= 2 MA * 6 Δ/MA * 0.57 deg/Δ).

Degrees of visual angle is also used for versional eye movement measurements. The visual angle is the angle formed by the lines of sight from an eye (e.g. left eye) to the two targets (T1 and T2; Fig. 3B).

Basic Control System Concepts

A basic feedback control system block diagram is shown in Fig. 4A. The Laplace operator s is a complex variable equal to $\sigma + j\omega$, which provides information about damping and oscillatory characteristics of a system. The reason for operating in the Laplace domain is that many complicated dynamic operations in the time domain become much simpler mathematical operations

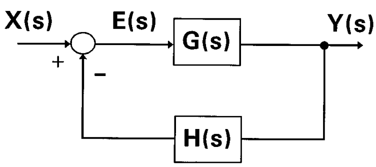

Fig. 4A Block diagram of a simple feedback control system.