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Head Fixed Field Coil System For Measuring Eye Movements in Freely Moving Monkeys

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***Abstract*— Coil systems have been a standard for measuring eye movements since they were first introduced [1]. These systems, which have been designed to work at low frequencies (20 KHz), generally require large field coils so that a uniform field can be established at the eye coil site. This configuration makes it virtually impossible to study eye movements in freely moving animals. In this paper, we describe the design of a coil system, which operates at radio frequencies (10 MHz). This system allows the use of compact coils with radii of 10 mm that are capable of accurately measuring eye movements in three dimensions during head free locomotion. This system opens the possibility for studying eye movements in freely moving monkeys under a wide range of conditions.**

I. Introduction

MAGNETIC field-based eye tracking systems are well known and widely used in both animals and humans [1-3]. The traditional system consists of large external field coils and small internal search coils mounted on the eye. Such systems have been used widely to measure eye movements in head-fixed animals and humans. Adapting large field coils to record eye movements during natural locomotion in subhuman primates is difficult, however, since locomotion induces head and eye movements that are frequently outside the range of the coil field. Consequently, it is virtually impossible to implement correction algorithms. The aim of our development was to eliminate this problem.

In our system, the field coil is an RF-generated field that communicates with an eye coil of approximately the same size. Because of its small size, the field coil can be placed in a cap, which fits on the monkeys head in a fixed orientation relative to the eye coil. Thus, it is similar to the communication between two antennae. As the eye coil moves with the eye, the coupling between the field and the eye coil is altered, and the voltage induced in the eye coil changes. While traditional systems use relatively low frequencies (10-80 kHz), our system works in the radio frequency (RF) band, increasing the signal-to-noise ratio, simplifying amplification and filtering during signal processing of the eye coil voltages. The intensity of the magnetic field is less then 0.5 μT. According to Environmental Health Criteria (EHC137), this value is well below the safety margin of 100, which is the limit of potentially hazardous levels. Thus, it is safe to use this system for mammals. Because of the specific configuration and field coil size, this design allowed us to place all system components on the animal's head and measure eye position (pitch, yaw and roll) directly in head coordinates.

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II. Methods

A. Theoretical Basis for Eye Coil System

The head coordinate frame used for the monkey will be defined as X pointing out of the monkey's nose, Y pointing out of the left ear, and Z pointing out of the top of the head. Oscillating magnetic fields are generated by coils, which are orthogonally place on top of the monkey's head. If the distance from the center of the field coil to the point where the field is of interest is much greater than the radius of the field coil, then the field takes the form of a dipole whose moment is **m** and whose direction is orthogonal to the plane of the coil (Fig 1A). The magnitude and direction of

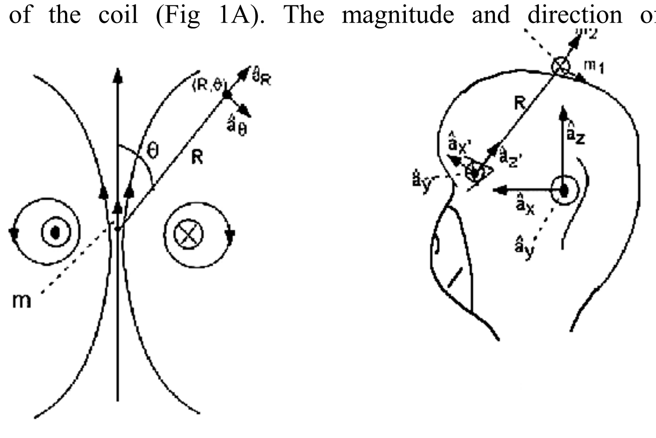

Fig.1 Generated field from a single coil and the corresponding placement of the field and eye coils on the animals head relative to the head coordinate frame

the magnetic field at a point (R, θ) as given in Fig 1, where μ_0 is the permeability of free space, I is the peak value of the current in the coil, N is the number of turns, and b is the radius of the field coil. Thus, the magnitude of the dipole moment, m, is the area of the coil multiplied by the peak current turns. The field generated at a point (R, θ) in spherical coordinates is inversely proportional to the cube of the distance from the center of the dipole and has components along the radial direction $\mathbf{a}_R$ and angular direction, $\mathbf{a}_\theta$. The magnetic field, **B**, is given as [4]:

$$\mathbf{B} = \frac{\mu_0 \mathrm{m}}{4\pi \mathrm{R}^3}(\mathbf{a}_\mathrm{R}\, 2\cos\theta + \mathbf{a}_\theta \sin\theta) \qquad (1)$$

The field coils on top of the head can therefore be situated so that their dipole moments form a left orthogonal coordinate frame, m_1, m_2, m_3. As a general rule, when θ=90°, the direction of the field is along $\mathbf{a}_\theta$, which is in a direction opposite to the dipole moment direction. When θ=0°, the field will be radial along the direction of the dipole. Thus, the dipole, $\mathbf{m}_1$ will generate a field at the eye in the direction $a_{x'}$:

$$\mathbf{a}_{x'} = \cos\varphi \mathbf{a}_x + \sin\varphi \mathbf{a}_z \qquad (2)$$

where ϕ is the angle of tilt of the m_1 from $-a_x$. For dipole $\mathbf{m}_2$, θ=0°, and the field will be radial and will generate a field $\mathbf{a}_{z'}$ at the eye given by:

$$\mathbf{a}_{z'} = -\sin\varphi \mathbf{a}_x + \cos\varphi \mathbf{a}_z \qquad (3)$$

Finally, dipole $\mathbf{m}_3$ will generate a field along the $\mathbf{a}_y$ axis such that

$$\mathbf{a}_{y'} = \mathbf{a}_y \qquad (4)$$

Thus the left handed coordinate frame established by the field coil dipole moments, if situated as shown on the head, generates a right handed magnetic field coordinate basis at a small region where the scleral search coils are situated on the eye. The rotation matrix associated with this coordinate frame relative to the head frame is given by a simple rotation about the y-axis:

$$R_F = \begin{bmatrix} \cos\phi & 0 & -\sin\phi \\ 0 & 1 & 0 \\ \sin\phi & 0 & \cos\phi \end{bmatrix} \qquad (5)$$

B. Voltage Generated in the Eye coil

The voltage, V_s induced in each eye coil is proportional to the rate of change, i.e., derivative, of magnetic flux through the eye coil:

$$V_s = -\frac{d\Phi_B}{dt} \qquad (6)$$

If it assumed that the magnetic field is approximately uniform over the eye coil, the flux is the product of field intensity multiplied by the equivalent area of the coil:

$$\Phi = B_s \bullet S_e \qquad (7)$$

where $B_s = B_0 \sin(\omega t)$, B_0 is the amplitude of magnetic field in a direction normal to the plane of the eye coil and S_e is area to the field coil plane multiplied by number of turns of the eye coil.

Thus, the output voltage can be given as:

$$V = B_0\, \omega S_e \sin(\alpha) \qquad (8)$$

where α is the complement of the angle between the normal to the eye coil and the direction of the magnetic field.

Scleral coil voltages can now be given as inner products of the normals to the scleral eye coils and the basis vectors established by the magnetic field coils. From this, the rotation matrix of the eye can be computed relative to this coordinate frame as R_B. The rotation matrix of the eye relative to the head frame, R, can be obtained by pre-multiplying R_B by R_F given by:

$$R = R_F^{-1} R_B \qquad (9)$$

C. Computing the Rotation Matrix of the Eye

For a given eye orientation, which will be considered as positive rotation, the projection of the normal to the perilimbal search coil onto the three axes $a_{x'}$, $a_{y'}$, $a_{z'}$ of the magnetic field coordinate frame is given by $c_1 = (c_{11}, c_{21}, c_{31})$, with

$$\begin{aligned} &c_{11}^2 + c_{21}^2 + c_{31}^2 = 1 \\ &c_{11} > 0 \end{aligned} \qquad (10)$$

For the coil on top of the eye, the projections are given as components of a vector $c_3' = (c_{13}', c_{23}', c_{33}')$ the following relationships exist:

$$\begin{aligned} &c'^2_{13} + c'^2_{23} + c'^2_{33} = 1 \\ &c'_{33} > 0 \end{aligned} \qquad (11)$$

The rotation matrix can be obtained by finding the orientation of a system of three orthonormal vectors that are fixed with respect to the eye and rotate with it. Three such vectors can be specified from the above parameters using the Gram-Schmidt orthonormalization procedure. That is, the first vector is chosen as c_1. The vector components of the next vector are chosen by subtracting *k* times the components of c_1 from c'_3 and normalizing the resultant vector. That is, choose:

$$\begin{aligned} c''_{13} &= c'_{13} - k c_{11} \\ c''_{23} &= c'_{23} - k c_{21} \\ c''_{33} &= c'_{33} - k c_{31} \end{aligned} \qquad (12)$$

where k is the inner product of c_3 with c_1 or

$$k = c_{11}c_{13} + c_{21}c_{23} + c_{31}c_{33} \qquad (13)$$

and

$$\| c''_3 \| = \sqrt{(c''_{13} + c''_{23} + c''_{33}} \qquad (14)$$

Now we can normalize the vector c''_3 to obtain $c_3 = (c_{13}, c_{23}, c_{33})$ where:

$$c_{13} = \frac{c''_{13}}{\| c''_3 \|}, \quad c_{23} = \frac{c''_{23}}{\| c''_3 \|}, \quad c_{33} = \frac{c''_{33}}{\| c''_3 \|} \qquad (15)$$

A third orthonormal vector, $c_1=(c_{11}, c_{21}, c_{31})$ can be obtained from the cross product, $c_2=c_3 \wedge c_1$, giving:

$$\begin{aligned} c_{12} &= c_{23}c_{31} - c_{21}c_{33} \\ c_{22} &= c_{33}c_{11} - c_{13}c_{31} \\ c_{32} &= c_{13}c_{21} - c_{23}c_{11} \end{aligned} \qquad (16)$$

The set of unit vectors $\{c_1, c_2, c_3\}$ form an orthonormal basis for the eye which can specify the rotation matrix, R_B, at any instant of time as follows:

$$R_B = \begin{bmatrix} c_{11} & c_{12} & c_{13} \\ c_{21} & c_{22} & c_{23} \\ c_{31} & c_{32} & c_{33} \end{bmatrix} \qquad (17)$$

From this rotation matrix the rotation matrix relative to the head can be obtained as:

$$R = R_F^{-1} R_B = \begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{bmatrix} \qquad (18)$$

The axis-angle associated with the eye rotation in head coordinates can be obtained from the Euler-Rodriguez relationships [5]:

$$\Phi = \cos^{-1} \frac{TrR - 1}{2}$$

where the TrR=$r_{11}+r_{22}+r_{33}$

and

$$\begin{bmatrix} n_1 \\ n_2 \\ n_3 \end{bmatrix} = \begin{bmatrix} \dfrac{r_{32} - r_{23}}{2\sin\Phi} \\ \dfrac{r_{13} - r_{31}}{2\sin\Phi} \\ \dfrac{r_{21} - r_{12}}{2\sin\Phi} \end{bmatrix} \qquad (19)$$

The components of eye movement are

$$\begin{aligned} \text{Torsion} &= \Phi n_1 \\ \text{Pitch} = &= \Phi n_2 \\ \text{Yaw} = &= \Phi n_3 \end{aligned} \qquad (20)$$

III. Implementation

A. Field Coil Arrangement

Field coils are wound on a plastic cube and located on the top of the animal head under the aluminum cap. One of cube axes (normal to x-coil plane) is directed to the eye ball (Fig.2).

The size of each coil is 2 cm (area of 4 cm^2). Due to this particular configuration, the fields produced by each coil are very close to orthogonal in the eye area.

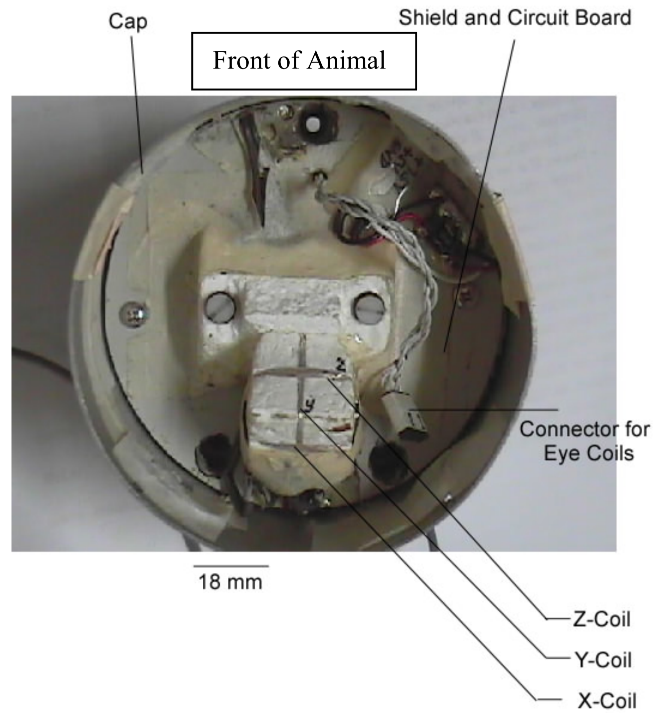

Fig. 2. Coil configuration inside cap worn by animal. Coils are tilted to point towards eye.

B. Electrical Circuit Description

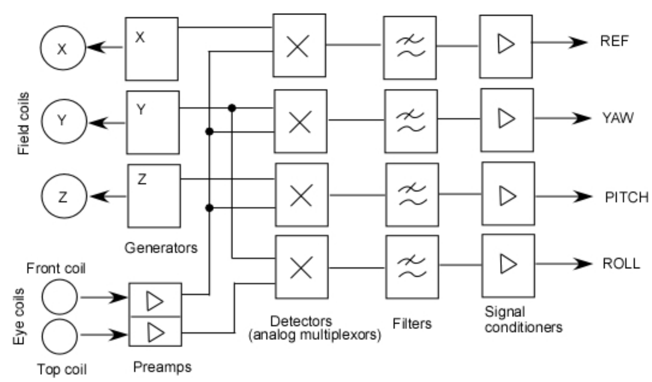

Fig. 3. Schematic block diagram.

An electrical block diagram of the system is shown in Fig. 3. Three independent field generators produce alternating voltage of approximately 10 Volts in the field coils. The frequencies in the horizontal, vertical and torsional are approximately 10, 11, and 12 MHz, respectively. These field coils induce signals in both eye coils whose amplitudes range from 100-500 uV. These signals are processed by linear wide band preamplifiers (AD600 by Analog Devices, Inc), that have adjustable gains and very low phase distortions. This is important because to detect signals obtained from the eye coils, we use analog multipliers as synchronous (phase sensitive) detectors (LM1496). Reference carriers are taken from the branches of the field coils. The detected signals go through a low-pass filter to remove high frequency components. After conditioning (amplification, offset correction), performed by OP413, signals are ready to be recorded. They can be passed to data acquisition hardware over conventional cable, may be digitized by an embedded mixed signal microcontroller and transmitted over a radio channel or stored in flash memory for future processing.

IV. Experiments

During system testing we have performed several eye motion recordings of a Cynomolgus monkey. The animal was placed on 3-axis rotator and rotated around vertical, horizontal and naso-occipital axes at constant angular velocities of 30°/s and 60°/s. Using low velocity component, we were able to calibrate gain of the eye movements for pitch, yaw and roll. A typical piece of eye position data is shown on Fig.4. This is a recording of the changes in horizontal (yaw) eye position during 60°/s rotation about vertical axis in light, which induced nystagmus (Fig.4). The signal-to-noise ratio was about 23 dB, which corresponded to angular noise of about 0.4° p-p in a frequency range of 0-300 Hz.

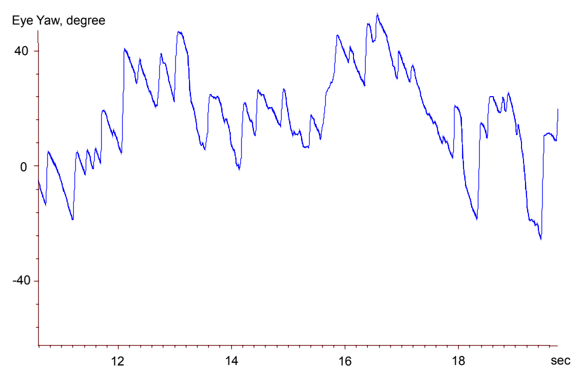

Fig. 4. Recording of yaw eye movements from the system

V. Conclusion

We have developed a novel methodology for measuring eye movements using an RF-based head fixed coil system. Because of the higher frequency compared to conventional coil systems, this system is smaller and was adapted for measuring eye movements in head free locomoting primates.

Since we maintain constant electromagnetic field intensity and frequency, the output signal is proportional to the angle of eye movement with an error less then 5% in the range of +/- 30°. The precision of the system is better then 0.2°. The system can be battery powered and wireless. The time of continuous operation using standard 9V battery is about 3 h.

Using two orthogonal field coils and placing the field coil system on the top of the head, one can measure pitch, yaw and roll of the eyes using the coils on the front and top of the eye. This method requires preliminary calibration because direct measuring of magnetic field is difficult.

Another option is to use a third field coil orthogonal to the other two. This allows one to measure the third voltage and use it as a reference for gain calibration. Offset calibration is still required because of the variation of the positions of the eye coils on the eye. This method is much more accurate because we exclude field intensity dependence and the influence of the presence of head tissue and other objects.

References

[1] D. A. Robinson, "A method of measuring eye movement using a scleral search coil in a magnetic field," *IEEE Trans. Biomed. Eng. BME*, vol. 10, pp. 137-145, 1963.

[2] H. Collewijn, J. Van der Steen, L. Ferman, and T. C. Jansen, "Human ocular counterroll: assessment of static and dynamic properties from electromagnetic scleral coil recordings," *Exp. Brain Res.*, vol. 59, pp. 185-196, 1985.

[3] S. J. Judge, B. J. Richmond, and F. C. Chu, "Implantation of magnetic search coils for measurement of eye position: an improved method," *Vision Res*, vol. 20, pp. 535-538, 1980.

[4] D. Cheng, *Field and Wave Electromagnetics*, Second Edition ed. Reading, Mass: Addison Wesley, 1992.

[5] T. Raphan, "Modeling control of eye orientation in three dimensions. I. Role of muscle pulleys in determining saccadic trajectory," *J. Neurophysiol.*, vol. 79, pp. 2653-2667, 1998.