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Oculomatic: High speed, reliable, and accurate open-source eye tracking for humans and non-human primates

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HIGHLIGHTS

- *Oculomatic* is an easy to use open-source, modular hardware eye tracking system for use in humans or non human primates.
- *Oculomatic* provides fast (600 Hz), precise (<0.5°) eye tracking at low system latency (<1.8 ms).
- *Oculomatic* integrates directly into the electrophysiological signal stream via analog outputs and can be used for humans as well as non human primates.

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ABSTRACT

Background: Video-based noninvasive eye trackers are an extremely useful tool for many areas of research. Many open-source eye trackers are available but current open-source systems are not designed to track eye movements with the temporal resolution required to investigate the mechanisms of oculomotor behavior. Commercial systems are available but employ closed source hardware and software and are relatively expensive, limiting wide-spread use.
New method: Here we present *Oculomatic*, an open-source software and modular hardware solution to eye tracking for use in humans and non-human primates.
Results: Oculomatic features high temporal resolution (up to 600 Hz), real-time eye tracking with high spatial accuracy (<0.5°), and low system latency (~1.8 ms, 0.32 ms STD) at a relatively low-cost.
Comparison with existing method(s): Oculomatic compares favorably to our existing scleral search-coil system while being fully non invasive.
Conclusions: We propose that *Oculomatic* can support a wide range of research into the properties and neural mechanisms of oculomotor behavior.

1. Introduction

Studies ranging from basic visual psychophysics to complex social interactions require the measurement of eye position with low-latency, less than 10 ms. Precise measurements of eye position were pioneered using the scleral search coil technique by placing a small coil of wire embedded within a contact lens or directly implanted into the sclera (Robinson 1963; Judge et al., 1980). When placed within two magnetic fields in quadrature phase, a scleral search coil produces an induced current, which allows the reconstruction of the current eye position. Since this system is entirely analog until the current is converted at digital acquisition, the sampling frequency (>500 Hz) is limited by the analog to digital conversion as well as the magnetic fields encoding frequency (30 kHz). Hence, the accuracy («1°) of scleral search coil systems is limited only by the internal signal-to-noise. Circuit diagrams of scleral search coil systems are easy to obtain. As a result, most scleral search coil systems are nearly equivalent and the data produced is highly replicable. While scleral search coils provide good temporal resolution, spatial accuracy, and replicability, their primary drawback is the invasive nature of the procedure. In human studies, a potentially uncomfortable contact lens is used and discarded between subjects. In non-human primates (NHPs), chronic implantation of a search coil within the sclera requires a surgical placement under anesthesia (Judge et al., 1980). The interface between subcutaneous wires and the bone cement holding the con-

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nector means wire breakage is a common issue often requiring additional surgical intervention. Additionally, the strong magnetic fields required for using search coils can generate noise in modern electrophysiological data acquisition systems which can complicate subsequent data analysis.

As a non-invasive alternative to scleral search coils, a growing number of studies over the last 20 years have turned to video-based eye tracking. Historically, this method was focused on remote (not head mounted) eye tracking and was limited to expensive commercial products due to demanding hardware requirements. Nevertheless, being fully non-invasive and easily deployable has caused video-based eye tracking to increasingly become the primary tool for the study of human and NHP eye movements. Additionally, video based trackers can measure other ocular parameters such as the pupil size and torsion (even though the gold standard for torsion is still a 3 dimensional eye coil), making them even more versatile. One general requirement for optical methods is the need for fast imaging sensors and efficient algorithms to permit sampling over 200 Hz. Commercial products have become faster (up to 2000 Hz) and more accurate (<0.5°) but unfortunately not more accessible (price and transparency) in the past 10 years. The open-source/computer science community has invested a great deal into developing inexpensive, webcam-based, head-mounted eye-trackers for use in accessibility or marketing research scenarios, but such approaches have not been applied to precise psychophysics grade eye trackers. One likely reason for this is sheer necessity. In most applications, sampling rates of 120 Hz are sufficient since the vast majority of saccades lie within a spectrum of 20–200 ms depending on their amplitude (Bahill et al., 1975; Baloh et al., 1975). Recent studies comparing scleral eye coil systems with modern commercial optical systems demonstrate the benefits of using optical methods (Kimmel et al., 2012).

Given the advantages of optical eye trackers, we believe that there is an immediate need for open-source eye tracking techniques that can be used to study human and NHP eye movements in a psychophysical research environment. Here, we introduce *Oculomatic*, an open-source eye tracking software that can be used with off-the-shelf and affordable machine vision imaging sensors. In developing *Oculomatic*, we have used commercial off-the-shelf components to reduce the overall cost of the final system and allow wide distribution. Since the software as well as hardware recommendations are transparent, it is easy for the user to change the setup to their particular need and application; we have focused on our primary need, namely tracking of head-fixed NHP (*Macaca mulatta*) eye movements. In designing the system, we have evaluated multiple existing eye tracking algorithms (Swirski et al., 2012; Kassner et al., 2014; Javadi et al., 2015) for their ability to accurately track pupil location in NHPs as well as their computational burden. Our final solution uses binary image moments, an approach which is robust, easily modified to specific needs, and can be handled by affordable off-the-shelf hardware without relying on specialized implementations on embedded hardware systems. The final system and software can be quickly acquired and easily set up using a simple executable and costs less than $1000 at the time of publication.

2. Methods and materials

2.1. Hardware

Oculomatic is a full eye tracking system that entails a real time tracking software and recommendations for off-the-shelf hardware. The hardware can be adapted to the users' needs. The required hardware contains the following elements: Camera module, lens, IR-Light source, mounting solution, data acquisition device, and a general purpose PC (Fig. 1). Additional detailed resources can be found in the supplementary materials.

Table 1
Recommended Point Grey sensor modules (pricing as of March 2016).

Part #	FPS	Resolution	Price
CM3-U3-13Y3M-CS	590	320 × 240	$350
FL3-U3-13Y3M-C	600	320 × 240	$590
FL3-U3-13SM2-CS	240	640 × 480	$500

Most eye tracking solutions for the NHP require the integration of eye signals within the electrophysiological signal chain. This integration is fairly simple for scleral eye coil systems, since all computations and filtering are performed on analog signals and the resulting horizontal and vertical pupil positions are represented as voltages; these voltages can be adjusted by the experimenter by setting the DC gains and offsets independently. In *Oculomatic* we have opted to maintain this traditional approach. The primary output of the digital x and y pupil position is normalized to the image sensor size and gain is adjusted by the experimenter. Centering the voltages is achieved by pressing a button when the subject fixates on the x,y = 0 position on the screen. Voltages are output using a National Instruments DAQ card using the NI-DAQmx proprietary library. Any National Instruments card that offers 2 or more analog outputs at 10 or higher bits should be sufficient for use with *Oculomatic*. Our recommendation is the low-cost NI USB-6001 DAQ since it requires no additional breakout boards. A low-cost breakout circuit board can be cheaply acquired for the PCI and PCIe NI-DAQ boards, the schematics (EAGLE files) can be downloaded from our Github repository (link to repository can be found in the additional information). Currently, we recommend using a Windows operating system since it is the only OS that fully supports NI-DAQ adapters. We have a prototype version of *Oculomatic* working under a Linux OS using the comedi library (comedi.org). However, the DAQ adapters supported by comedi are limited to mostly older legacy devices.

Computers used by *Oculomatic* should have the following minimum specifications: a modern, 4th generation, Core i5/i7 Intel processor or equivalent, 8GB of RAM and a native USB3.0 controller to connect the camera module. Older computers might be equipped with third party controllers that can cause compatibility issues (for reference consult: Point Grey website https://www.ptgrey.com/). If the required temporal resolution is below 300 Hz, most modern laptops will suffice. On a modern core i7, we were able to simultaneously record neural data as well as run *Oculomatic* without any interference or decrease in temporal resolution using the PCI interface. We caution against the use of the same USB host controller for both electrophysiology and *Oculomatic*. If the used PC only has one controller we urge the user to purchase an additional USB3.0 PCIe card if high channel count electrophysiological signals are acquired through the same host.

Supported image sensors can be obtained from Point Grey Research (www.ptgrey.com). We have tested three different monocolor modules without infra-red (IR) cut-off filters (see Table 1).

The lens should be chosen according to the requirements of each setup. C-Mount lenses are more versatile since they can be mounted to C and CS-Mount camera modules, while CS-Mount lenses cannot be mounted to C-Mount cameras. We recommend a light-sensitive lens, with F-stops of 0.8–1.4, such as Fujinon (YV10X5HR4A-2 for CS-Mount) or fixed focal length lenses such as Tamron (23FM25SP for C-Mount).

IR illumination systems operating at either 850 nm (visible) or 920 nm (invisible) can be purchased from many online vendors. We recommend an inexpensive (<$20) light source driven by 12 V DC power supply, such as those available on amazon.com (e.g. Crazy Cart 48-LED CCTV).