# OPTIMIZING VIDEO-OCULOGRAPHY SYSTEMS BY SIMULATING THE EFFECT OF SLIPPAGE ARTIFACTS

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**ABSTRACT**
Video-Oculography systems (VOG), video based systems for measuring eye movements, are widely available as a supporting tool for clinical diagnosis of eye movement. The main remaining weakness of these systems is the difficulty to distinguish between eye movements and movements of the camera with respect to the head. In our project we try to classify between movement of the eye and movement of the camera of the VOG system by examining the effect of eye movement and camera movement on the position changes of the center of the pupil and the reflection of a light source which is directly attached to the camera in the image data of VOG systems. Therefore we implemented a simulation model of the eye and of a VOG system to investigate the effect of pure eye movement, pure camera movement and combined eye-camera movement on the objects in the image data.

Keywords: eye movement measurement, video oculography, camera slippage

## 1. INTRODUCTION

Our central nervous system provides several mechanisms to keep the retinal image stable, which enables clear vision during spatial movement. For example, to ensure clear vision when the head moves rapidly, the Vestibulo-Ocular Reflex (VOR) transmits information about head rotations from the semicircular canals of the human balance system to the eye muscles, with only three neurons in between. Due to this direct link between the ocular and the vestibular systems, different pathologies of the vestibular system can directly influence the kinematics of eye movements. Several studies have shown that by studying eye movements, simple diagnostic tests can be used to identify vestibular pathologies (Cremer, Halmagyi, Curthoys and Todd 1998; Schneider, Glasauer, Dietrich, Kalla and Brandt 2004).

For the exact quantitative measurement of eye movements, three technologies are established: Electro-Oculography (EOG), Scleral Search Coils (SSC) and Video-Oculography (VOG). EOG and SSC are well accepted but have distinct disadvantages: EOG, which is still the most common technique for measuring eye movement in the clinical environment (Haslwanter and Ong 2008), cannot measure the torsional component of eye movements (Haslwanter and Clarke 2009). SSC is the golden standard for measuring eye movements in three dimensions, with very high spatial and temporal resolution; however it is semi-invasive and expensive, and thus cannot be used for clinical testing.

VOG systems measure the position of the eye relative to the head by tracking the absolute position of the pupil center in the image data. Different types of VOG systems have been developed for different applications:

- Table mounted systems require the head of the patient to be approximately stationary.
- Head mounted systems allow the patient to move freely.

An example for a head mounted VOG system is the *EyeSeeCam* VOG system (Dera, Böning, Bardins and Schneider 2006), which is available at our institute. The *EyeSeeCam* VOG System is shown in Figure 1.

Due to the progress of video technology, VOG systems have become much cheaper and are commonly used in research laboratories as well as in the clinical environment.

The main remaining weakness of head mounted VOG systems is the high sensitivity to motion artifacts of the camera relative to the head of the patient, the so called slippage: a camera movement of 1 mm already corresponds to an eye position error of 5°. Such slippage artifacts can easily occur in head mounted VOG systems when the patient moves his head rapidly. In some new systems, the developers have tried to minimize the slippage by attaching the system firmly to the head and keeping the overall weight of the system as low as possible. This approach can reduce motion induced slippage, which can occur when the head of the patient moves. But since the skin on the skull of the patient can always move, slippage artifacts cannot be eliminated completely in head mounted systems. The patient only has to raise his eyebrows or wrinkle his forehead to produce severe vertical slippage without moving his head at all. A compensation of these artifacts would increase the accuracy of VOG systems for all types of applications. We try to achieve this goal by using well established methods from the field of machine learning and computer vision.

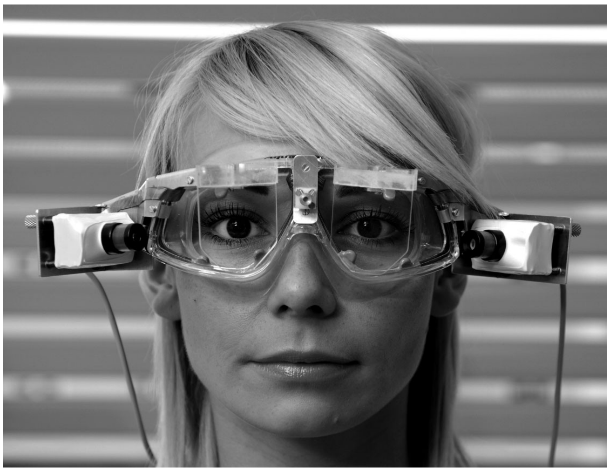

Figure 1: Image of the *EyeSeeCam*- VOG system which is available at our institution.

VOG systems typically determine the orientation of the eye by tracking the absolute position of the center of the pupil in the image. This approach breaks down when the camera moves with respect to the head. In that case, additional information is required to correctly measure eye position. In our approach, we try to distinguish between movement of the eye and movement of the camera of the VOG system by examining well defined features in the image data of VOG systems. The first feature is the center of the pupil, the second feature is a reflection of a light source on the front surface of the cornea, commonly referred to as the 1st Purkinje Reflection or Corneal Reflection. We additionally attached a light source to the VOG system directly next to the lens of the VOG system camera, so that it moves together with the camera. The features in the image can be seen in Figure 2.

We suppose that the distance between these two features in the image data changes in a characteristic way during movement of the eye and the camera. This should serve as a suitable classification criterion to reliably distinguish between movement of the eye, movement of the camera with respect to the head and combined eye camera movement.

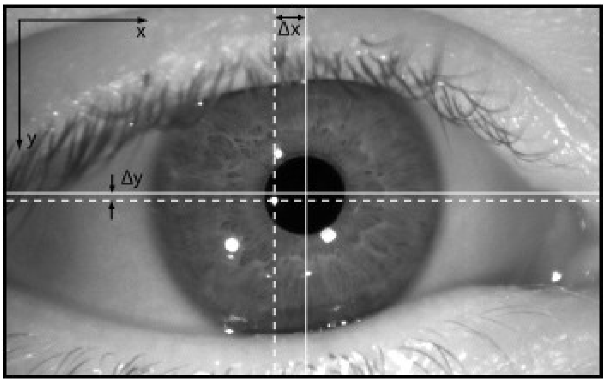


Figure 2: Typical image of a VOG recording showing the center of the pupil and the reflection of the additional mounted light source

Since VOG systems measure eye movement with a temporal resolution of up to 500 frames per second, a huge amount of data is collected even during short recordings. Manually labeling whether eye movement or slippage occurred in each frame would be tedious, and deciding which movement occurred just by looking at a single image is difficult. Therefore, we decided to develop a biomedical simulation model of the eye and a VOG system to investigate the effect of eye movement and slippage on the position of the pupil center and a reflection in the image data of the VOG system.

## 2. METHODS

We implemented the simulation model of the eye and the *EyeSeeCam* VOG system in MATLAB® R2008b (Natick MA, USA). We decided to use object oriented programming methods because our simulation model contains well defined objects like the eye and the camera. This enables encapsulation of all the parameters of the eye model and the model of the VOG camera, which can change for example when running the simulation with VOG systems from different manufacturers. To verify the correctness of our implementation we used test driven design methods.

### 2.1. Description of simulation model

Our eye model is based on Le Granges simplified eye model (Wyszecki and Styles 1982), which is an established simplified model of the human eye. In this model all dimensions of the eye are calculated from the length of the eye, the radius of the cornea and the radius of the limbus. Our simulation model of the eye consists of the components eyeball (bulbus), iris and cornea, where the center of the bulbus lies in the origin of the coordinate system.

The right handed coordinate system is specified in the following way:

- The x axis coincides with the line of sight.
- The y axis points to the left of the person wearing the VOG system.
- The z axis points upward.

The iris is modeled as a disk with a circular opening in the center, which represents the pupil. The center of the pupil is the center of this opening. The complexity of the model is reduced by modeling the eyeball as well as the cornea as two intersected spheres. To additionally enable simulations with real cornea surface data, we implemented the model of the cornea in such a way that measurements of a corneal topographer, a medical device for accurately measuring the topography of the cornea surface, can easily be included. Since the cornea surface is described by approximately 100 points when real cornea data is used, we reduced the computational time for rotating the model of the eye by rotating the model of the camera in the opposite direction. Rotations are implemented using quaternions (Haslwanter 1995).

We determined the parameters of the *EyeSeeCam* VOG system by taking a scaled photograph where all parameters could be measured manually. The camera of the VOG system is modeled as a simplified pinhole camera. The location of the pinhole and the image plane in the camera were estimated from the image of the VOG system. Using this model of the camera the points in space can be projected into the image plane using central projection, where the pinhole acts as the focal point of the projection.

### 2.2. Determination of the reflection

Once the camera model is placed relative to the eye model, we determine the positions where a reflection can occur on the surface of the cornea using ray tracing methods. In our simplified simulation model, we know roughly where the reflection appears. To enable simulation with real cornea data we implemented a more general approach for finding the reflection, since real cornea surfaces are not spherical. Therefore we generate a dense search grid with an angular dimension of 5° and a resolution of 0.1° on the cornea surface in the horizontal and vertical direction.

Each point of the search grid is interpolated between the real cornea surface points of the cornea model. The search grid includes all points were reflections can occur. For every point in the search grid, we then calculate an error value. This error value is 0 if the following conditions are fulfilled (for an illustration refer to Figure 3):

- The vectors *p*, *n*, *l* lie in the same plane
- The angle of incidence $\alpha$ equals the angle of reflection $\beta$

In Figure 3 *p* is the vector from the point on the cornea surface to the pinhole of the camera, *l* is the vector from the point on the cornea to the light source on the camera and *n* is the normal vector in the point on the cornea relative to the surface of the cornea.

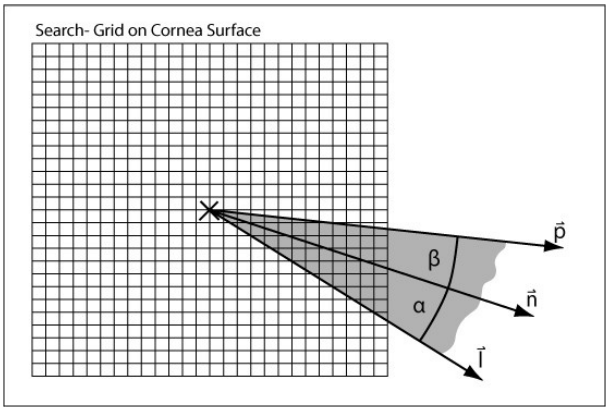

Figure 3: Detection of the reflection on the front surface of the cornea: For a given point in the search grid the error value is defined by the three vectors *p*, *n*, *l*, where *p* is the vector from the point on the cornea surface to the pinhole of the camera, *l* is the vector from the point on the cornea to the light source on the camera and *n* is the normal vector in the point on the cornea surface.

We then calculate the error value in a vectorized manner to reduce computation time, since the search grid contains 2500 possible reflection points. When we simulate the cornea as a sphere, we know that only one reflection can occur, so currently we are taking the point on the cornea surface with the minimum error value as the reflection of the light source. For real cornea data, a specific threshold for the error value has to be specified for finding multiple reflections on the surface. Once the point on the cornea surface where the reflection appears is found, we project this point in space into the image plane of the camera to get the position of the reflection in the image of the VOG system.

### 2.3. Determination of the pupil center

To accurately determine the center of the pupil on the cornea surface, we project the points on the pupil edge (the points on the edge of the circular opening in the iris disk) onto the surface of the cornea under consideration of Snell's Law (Law of Refraction), with an aqueous refraction index of the corneal front surface of 1.37. For each point of the pupil edge, we again generate a search grid, angular dimension 5° with 0.1° angular resolution, centered at the intersection point of the cornea surface with the vector from the pupil edge point to the pinhole of the camera. Similar to the determination of the reflection, we specify an error value which is 0 if the following conditions are fulfilled:

- The vectors *p*, *n*, *i* lie in the same plane
- The angles $\alpha$ and $\beta$ fulfill Snell's law

Figure 4 illustrates this approach, where *p* is the vector from the point on the cornea surface to the pinhole of the camera, *n* is the normal vector in the point on the cornea relative to the surface of the cornea and *i* is the vector from the point on the cornea surface to the pupil edge point.

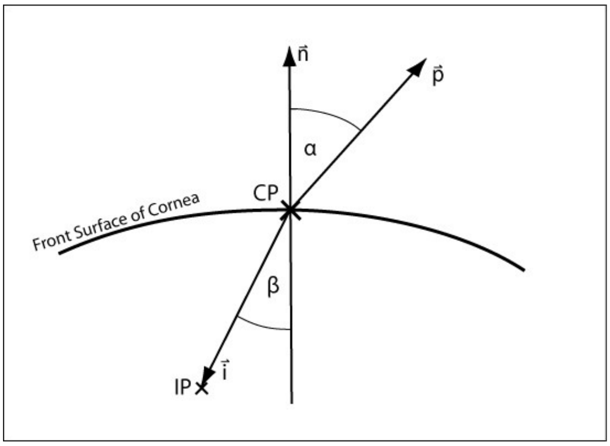


Figure 4: A point on the inner border of the iris (IP) is projected onto the front surface of the cornea using Snell's law, where CP is a point on the cornea, *n* is the normal vector in this point, *p* is the vector from CP to the pinhole of the VOG camera and *i* is the vector from CP to IP. If Snell's law is fulfilled and all three vectors lie in one plane the corresponding error value is minimal.

To reduce computation time for calculating the error values of all 2500 possible points, we parallelized the computation of the error values. The point with the minimum error value is taken as the projection of the corresponding pupil edge point onto the surface of the cornea.

After finding all pupil edge points on the cornea surface, we project these points into the image plane to get the corresponding image coordinates of the pupil border points. To accurately determine the center of the pupil with sub-pixel resolution we do an ellipse fit (Taubin 1991) on these points in the image. The center of the pupil in the image is the center of the fitted ellipse, which is common practice in VOG systems.

The positions of the pupil center and the reflection in the image can be examined by placing the camera at a fixed position relative to the eye. Different kinds of movement are simply a sequence of specific relative positions of the model of the VOG system camera relative to the model of the eye. For every relative position we then determine the location of the reflection and the pupil center in the image of the VOG system.

## 3. RESULTS

We have implemented the 3D simulation model of the eyeball and the VOG system using object oriented programming methods in MATLAB. With our simulation model we can simulate the effect of eye movement without slippage, slippage without eye movement and combined eye camera movement on the positions of the pupil center and corneal reflections in the image plane of the VOG camera. Since we used an object oriented approach, our simulation model contains modular objects with well defined interfaces. Therefore VOG systems from different manufacturers or real cornea topography data can be easily included in our simulations.

To measure the computational time for one typical simulation track we performed a simulation of pure eye rotation from -10° to +10° in 1° steps in both vertical and horizontal direction. This results in a total of 441 eye-position setups. The computational time of this simulation was 1873 seconds, which gives an average computation time of about 4.2 seconds per eye-position setup. This simulation run was executed on a PC with a Intel Core 2 CPU, 2.13 GHz and 1.98 GB RAM running Windows XP.

To verify the correctness of our simplified simulation model, we compared the results from our simulations to manually measured position values of the pupil center and the reflection in the image data of the *EyeSeeCam* system. We separated this verification process in two steps, one for verifying the simulation of pure eye rotation and another for verifying the correctness of the pure vertical slippage. The main reason for splitting this verification process is the fact that in a first approximation the motion of the eyeball during natural eye movement can be interpreted as a simple rotation about a fixed rotation center which coincides with the center of the bulbus. The motion pattern of vertical slippage, which typically occurs for example when the patient wearing the VOG system wrinkles his forehead, is a more complex movement. In a first approximation we supposed that vertical slippage can be modeled as a pure vertical translation (along the positive z axis) with a maximum translation value of about 10 mm.

For verification of the simulation of pure eye rotation, we manually measured the position of the pupil center and the position of the center of the reflection on the cornea at fixed eye positions in the image data of the *EyeSeeCam* VOG System. We decided to use well defined positions which are also used during the calibration process of the VOG system at horizontal and vertical values of 0° and ±8.5°. Our experimental data indicated that the initial camera orientation significantly effects the position of the features in the image. By iterating over different orientations and locations of the camera relative to the eye we obtained simulation results which matched the positions of the features in the image data of the *EyeSeeCam* system when we initially rotated the camera system 4.5° about the y axis followed by a rotation of 14° about the z axis. After translating the camera -2.6 mm along the y axis and 0.45 mm along the z axis the results from our simulation matched the results from the image data.

For a system verification compared the 2D vector from the center of the pupil to the center of the reflection in the image data of the VOG system to our simulation result. We measured a RMS error in the horizontal direction of 1.9 pixel and a RMS error of 2.68 pixel in the vertical direction. Supposing that a rotation of the eye about 1 mm on the surface of the cornea is equal to a translation of 15 pixel in the image data of the VOG system when the distance from the center of the eye to the front surface of the cornea is approximately 12.6 mm, this error of our simulated feature positions equals to an error in eye position of 0.59° for horizontal and 0.82° for vertical eye rotations.

## 4. DISCUSSION

Currently we are working on the slippage verification of the simulation results. We want to focus on the vertical component of camera slippage, since this component currently cannot be eliminated.

In our current model of the *EyeSeeCam* system all parameters of the camera imaging system are measured from a scaled photography or typical values are taken as a first approximation. To overcome these assumptions we try to determine the exact values for the projection of arbitrary points in space into the image plane of the VOG system camera by applying a calibration method proposed by Zhang (1998).

To additionally verify our simulation model, we want to compare our simulation results to a similar simulation model of a Head Mounted Display System (Hua and Krishnaswamy 2006) where the features in the image data of the camera are calculated using the first-order imaging matrices for spherical surfaces and mirrors.

Since purely vertical slippage is currently unknown, we additionally plan to measure the change in position and orientation of the VOG system camera using the *Lukotronic*® system AS 200 (Innsbruck, Austria), a system that can detect 3D positions of markers with a temporal resolution of ~1ms and a spatial resolution of up to 100µm at a distance of 1.5m.

Based on our simulation results we plan to develop robust algorithms to accurately determine between pure eye movement, pure camera movement and combined eye camera movement.


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## 7. AUTHORS BIOGRAPHY

DI(FH) **Michael Platz** studied Electronics at the University of Applied Sciences Technikum Wien (Vienna, Austria) with an emphasis on Biomedical technologies and Audio-Video technologies. After one year working at a research group at the Institute of Biomedical Technologies and Physics at the AKH Wien he started to work at the Upper Austria University of Applied Sciences as a Research Associate. After two years he was offered a PhD position where he is currently writing his Doctoral thesis at the Institute for Computational Perception, Johannes Kepler University Linz, Austria. His current work focuses on Computer Vision and Machine Learning. During his thesis he cooperates with medical practitioners to overcome the last remaining problems of using VOG as a standard diagnostic tool in the clinical environment.

Dr. **James K. Y. Ong** is a trained mathematician and optometrist. He has experience in the areas of dynamical systems and operations analysis, as well as vision science and cognitive psychology. His current role is to find ways to apply technology to improve health outcomes. The current focus of his research is to measure torsional eye movements from video data, in order to help medical practitioners to diagnose benign paroxysmal positional vertigo.

PD Prof. (FH) Dr. **Thomas Haslwanter** started out at the University of Innsbruck, Austria, with theoretical work in the areas of quantum optics and laser theory. For his PhD at the Swiss Federal Institute of Technology (ETH Zurich, Switzerland) he switched into the field of neuroscience, working on the control of eye and head movements. After postdoc positions at the University of Sydney (Australia) and the University of Tuebingen (Germany) he returned to the ETH Zurich, focusing more and more on medical applications of his research work on dizziness. Since 2004 he has been living in Linz, Austria. After two years as scientific head of the Department of Medical Informatics at Upper Austrian Research , a non-profit organization, he became professor for Biomechanics at the Upper Austrian University of Applied Sciences in Linz. Current research activities center on video-oculography, and on movement kinematics in three dimensions.