Eyelid kinematics for virtual characters

By William Steptoe, Oyewole Oyekoya and Anthony Steed

When compared to gaze, animation of the eyelids has been largely overlooked in the computer graphics literature. Eyelid movement plays an important part both in conveying accurate gaze direction and in improving the visual appearance of virtual characters. Eyelids have two major motion components: lid saccades that follow the vertical rotation of the eyes, and blinking. Derived from literature in ophthalmology and psychology, this paper presents parametric models for both motion types, and emphasizes their dynamic temporal behaviour. Experimental validation classifies model-generated animation as similar to that encoded from expensive motion captured data, and significantly exceeding linearly interpolated animation. Copyright © 2010 John Wiley & Sons, Ltd.

Introduction

During vision, the human eyelids are in near-continuous motion, exhibiting blinks, and what Evinger et al. term lid saccades. Lid saccades are bilateral shifts of the eyelids initiated by changes in the vertical rotation of the eyes, so that the eyelids follow the direction of gaze to ensure they do not obscure the pupils. Blinking is the act of extremely brief closure of the eyelids, and may be voluntary or involuntary. Physiologically, the eyelids serve to protect the eye from debris and rays of harmful intensity, and also to regularly spread the tears and other secretions on the eye surface to keep it continually moist. Hence, eyelid movement is a ubiquitous element of human behaviour.

As both real-time and offline character animation advance, there is an ever-growing need to consider the broad scope of what gives rise to visual and behavioural realism. Increasingly sophisticated geometrical and behavioural models of humans and components of humans have been presented for applications including games, film and embodied conversational agents. When looking at a photograph or painting of a human, one typically spends 60% of the time looking at the eyes and 15% at the mouth. It is no surprise then, that much of this research has focussed on the face, and in particular the eyes.

Lee et al. identify the high correlation between the motion of the eyes and the corresponding eyelid movements as a possible extension to their gaze model. While some subsequent gaze models have incorporated some form of eyelid animation to complement gaze motion, eyelid animation has played a secondary role. Hence, the implementation details of realistic human eyelid dynamics has been left undefined. This paper presents two parametric models generating physiologically-accurate lid saccade and blink animations for virtual characters. The models are detailed algorithmically, together with an example implementation for avatar-mediated communication between users of networked immersive CAVE-like systems. The models are then validated against current methods of eyelid animation, including motion capture and linear interpolation, before discussion, limitations and future work are addressed.

Background

Lid Saccades

Lid saccades describe the rising and falling of the eyelids associated with upward or downward shifts in gaze direction. These saccadic lid movements exhibit characteristic trajectories and amplitude-maximum velocity relationships: upward lid saccades follow a smooth trajectory to final lid position, and the maximum velocity increases linearly with lid saccade amplitude, measured in degrees; maximum lid velocity during downward lid...
Figure 1. Two characters used during our experimental validation animated with linear blend skinning (left) and blend shapes (right).

saccades is best described by a power function showing a soft saturation with increasing amplitude. On average, lid saccades start some 5 milliseconds later than the concomitant eye saccades, but reach peak velocity at about the same time as the eye saccade. Concurrent lid and eye saccades in the downward direction have similar amplitudes and velocities, but lid saccades in the upward direction are often smaller and usually slower than the concomitant eye saccades. On average, downward saccadic lid movements have a shorter duration than upward lid movements at all amplitudes.

Downward lid saccades can exhibit an overshoot that takes the eyelid transiently lower than final lid position. Overshoots occur more frequently at larger target amplitudes, but there appears to be no consistent relationship between the target amplitude and the magnitude of the transient overshoot or its appearance. The eyes are also observed to overshoot during saccadic movement, but they are considerably less frequent than those in the lids, and transient overshoots of lid and eye saccades occur independently of one another. Finally, during steady fixation, the eyes often exhibit microsaccades (small fixational saccades) which function to refocus the fovea to maintain clear vision. Similarly, the eyelids often undergo small idiosyncratic movements of up to 5° when the eyes are stationary.

**Blinks**

A blink is defined as the extremely brief closing and opening of the eyelids, and can be initiated by voluntary or involuntary stimuli. Involuntary reflex blinks are solely for the protection and efficient action of the eyes themselves, whereas the onset of voluntary blinks is entwined in human psychology, with personality, current activity, and mental state amongst others being influential. Regardless of their origin, all blinks exhibit a similar pattern: 10–12 milliseconds after the onset of orbicularis oculi (the facial muscle that closes the upper eyelid) activity, the lid rapidly lowers, after which Mueller’s muscle raises it more slowly to nearly its starting position. The maximum velocity observed during the down and up phases of a blink is a linear function of blink amplitude. This is defined by the current open state of the eyelids due, amongst others, to the angle of the final lid position set by the most recent lid saccade.

**Animating the Eyelids**

To the best of the authors’ knowledge, the computer graphics literature on virtual character animation has not presented physiologically-based models of human lid saccades or blinks. This is certainly not to say that current real-time and pre-rendered virtual characters have static eyelids, but rather that the problem of eyelid animation has generally been solved in an ad hoc way, using motion captured data or unrealistic linear interpolation. While animation generated from motion captured data can generally be considered physiologically-accurate, the process of capture and encoding is expensive, and often performed for specific implementations and characters. Thus, whilst a character’s eyelid animation may be sophisticated, often based on blend shapes or linear blend skinning as illustrated in Figure 1, the characteristics of human eyelid kinematics have not been presented in the literature.

Facial animation engines have often incorporated some form of eyelid motion to drive expressive characters for more believable human-agent interactions in virtual environments and telecommunication. The success of these systems depends on their ability to communicate recognizable emotions to the user rather to
consider the accurate dynamics of facial (and eyelid) movement, and hence, quantification of accurate eyelid and gaze movement has not been an explicit concern. Marker-based\textsuperscript{20} and optical\textsuperscript{21} facial performance capture techniques have been successful in recording the subtleties of an actor’s facial movements. This performance data can then be composited or learned to subsequently animate a character’s eyelids. Similar methods have also been successful when used in combination with gaze motion data, building on the high correlation of motion between the two\textsuperscript{7,22}. However, such data is often closely coupled to a particular character geometry, and thus is not easily parameterized to create a reusable procedural model.

Numerous models of gaze have been presented as stand-alone or a component of a larger behavioural simulation based on combinations of parametric, data-driven or statistical models of gaze\textsuperscript{6,23,24}. Concerning lid saccades, Steptoe and Steed\textsuperscript{25} demonstrated that their inclusion was a significant factor in enhancing the perception of realism of a humanoid character, but the dynamics were not formally defined. This is similar to Tateno \textit{et al.}\textsuperscript{26}, which implemented ‘enhanced’ (exaggerated more than double) eyelid deformation based upon an artist’s sketches of the eyes. Regarding blinks, there has been some work investigating the impact of blink rate. Takashima \textit{et al.}\textsuperscript{27} presented a study investigating the effect on observers’ subjective impressions of characters. The authors investigated a range of character classes, including humanoids of both sexes, cartoon-style humanoids, animals and unidentified life-forms. Results demonstrated that a character’s blink rate has a dramatic impact on an observer’s impression. A rate of about 18 blinks/minute was seen to give a friendly impression, a higher rate reduced the potency of the character, while a lower blink rate gave a more intelligent impression. Also, the impact of varying blink rate was greater with the humanoid representations than the cartoon-style characters\textsuperscript{27}. This final result recalls Garau’s notion of an interaction effect between the visual and behavioural components of characters, suggesting that high visual realism should be coupled with high behavioural realism, and similarly to low fidelities\textsuperscript{28}. A likely explanation for the existence of this coupling is that a character’s degree of visual realism gives rise to particular expectations of behavioural fidelity.

Itti \textit{et al.}\textsuperscript{8} incorporated blinks into their eye and head motion engine by implementing a simple heuristic to determine frequency of blink rate. Blinks lasted for a fixed period of 150 milliseconds, and no further details are provided. Bitouk and Nayar\textsuperscript{29} implement a similar method, taking 200 milliseconds for blink duration. Although not specific regarding lid saccades, a gaze model presented by Peters and O’Sullivan\textsuperscript{30} implements blinking correlated with gaze shifts by using vertical angle of gaze, presumably to infer a start position for the eyelids, as input to blink magnitude. While this may hint at the complexity of eyelid movements, details of kinematic behaviour have so far been left undefined.

This paper aims to fill gaps in the literature by presenting models for lid saccades and blinks based on the eyelid dynamics of normal humans. We do not aim to cover the social impact of our models (for instance on perceived emotional state), nor do we investigate input parameter adjustment (for instance to investigate how blink rate or speed is perceived). Rather, we present generalized parametric animation models, which simulate the normal properties of human eyelid kinematics.

### Eyelid Kinematics Models

#### Parameterization

The equations presented in Tables 1 and 2 are taken from empirical studies of eyelid movements in normal subjects presented by Evinger \textit{et al.}\textsuperscript{1}. The metrics are based on data recorded from a comprehensive study measuring upper eyelid movements in normal human subjects. It should be noted that while the lower eyelids also exhibit motion during blinks and lid saccades,

<table>
<thead>
<tr>
<th>E#</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>E1</td>
<td>( D=33.2+5.9A-0.069A^2 )</td>
</tr>
<tr>
<td>E2</td>
<td>( D=98.9+3.6A-0.042A^2 )</td>
</tr>
<tr>
<td>E3</td>
<td>( V=45.31A^0.599 )</td>
</tr>
<tr>
<td>E4</td>
<td>( V=13.3A-14.82 )</td>
</tr>
</tbody>
</table>

**Table 1. Equations acting as input to the lid saccade model.**

<table>
<thead>
<tr>
<th>E#</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>E5</td>
<td>( D=36.3+1.4A-0.016A^2 )</td>
</tr>
<tr>
<td>E6</td>
<td>( D=87.9+4.3A-0.047A^2 )</td>
</tr>
<tr>
<td>E7</td>
<td>( V=29.2A-35.9 )</td>
</tr>
<tr>
<td>E8</td>
<td>( V=13.5A-5.87 )</td>
</tr>
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**Table 2. Equations acting as input to the blink model.**
their dynamics have never been measured without large intersubject variability\textsuperscript{31}. Compared to the upper eyelid, lower eyelid movements are relatively minor, with amplitudes of just a quarter of a corresponding upper eyelid movement\textsuperscript{32}. They are also entirely passive, resulting from the transmission of forces of other muscles such as the levator, which contracts or relaxes to initiate upper eyelid movement\textsuperscript{31}. Consequently, our models do not consider lower eyelid movement explicitly, but we developed our character rigs so that slight lower eyelid movement is coupled to the movements of the upper eyelids, thereby exhibiting motion in the order of one quarter to that performed by the upper eyelid.

Regarding blinks, a small amount of intersubject variability across a wide range of blink amplitudes and conditions has been noted\textsuperscript{1}. Thus, whether a blink originates from reflex, voluntary or spontaneous causes, over 95\% of the more than 400 blinks obtained from nine subjects fell within a narrow window of velocities that the following equations describe. Likewise, when defining the characteristics of lid saccades, a similar relationship to blink dynamics between amplitude and maximum velocity also exists\textsuperscript{1}.

Common to lid saccades and blinks are the up- and down-phases of movement. In the case of blinks, the down-phase refers to the initial downward movement of the eyelid \((E1\text{ and }E3)\), and the up-phase refers to the subsequent upward movement \((E2\text{ and }E4)\) returning the lids to their resting position informed by vertical eye rotation. In contrast, lid saccades exhibit only one phase of movement, which depends on the vertical direction of the eye saccade: an upward shift in gaze initiates a corresponding upward motion of the eyelids defined with up-phase properties \((E5\text{ and }E7)\), while a downward gaze shift initiates movements exhibiting down-phase dynamics \((E6\text{ and }E8)\).

\(E1\) defines the duration \((D)\) of the down-phase of a lid saccade, given an amplitude of lid movement as measured in degrees \((A)\). \(E2\) defines the duration \((D)\) of the up-phase of a lid saccade, given an amplitude of lid movement \((A)\). \(E3\) defines the maximum velocity \(V\) for the down-phase of a lid saccade, given an amplitude of lid movement \((A)\). \(E4\) defines the maximum velocity \(V\) for the up-phase of a lid saccade, given an amplitude of lid movement \((A)\).

\(E5\) defines the duration \((D)\) of the down-phase of a blink, given an amplitude of lid movement \((A)\). \(E6\) defines the duration \((D)\) of the up-phase of a blink, given an amplitude of lid movement \((A)\). \(E7\) defines the maximum velocity \(V\) for the down-phase of a blink, given an amplitude of lid movement \((A)\). \(E8\) defines the maximum velocity \(V\) for the up-phase of a blink, given an amplitude of lid movement \((A)\).

**Eyelid Saccade Model**

Figure 2 presents the state diagram detailing the mechanics of the lid saccade model:

1. The model takes gaze data as initial input. This may be generated by a gaze model or eye tracker. Given an eye movement, any vertical amplitude shift is calculated by comparing the current vertical rotation of the eye with the input rotation.
2. This positive or negative (indicating an upward or downward shift) angle is then thresholded, possibly along with a signal sent from the source of gaze input to determine if the gaze motion is indeed a saccade or a minor or smooth pursuit movement.
3. Before output from this classification is used, the final eyelid position is calculated by taking into account an overshoot function, and critically, the properties of the character itself under control: this final position depends the method of animation (for instance ‘bone’ rotation in a linear blend skin character, or blend shape weights if interpolating between geometries).
4. The controlling thread then splits depending on the classification of the input gaze motion: absence of a saccade assumes the movement as minor (for instance associated with a microsaccade or smooth pursuit) and sets the eyelids in their final position in a single frame before quitting. Execution continues if a saccade is detected.
5. If a saccade has been detected, vertical amplitude shift acts as input to \(E1\) (in the case of a downward saccade) or \(E2\) (for an upward shift) in order to determine the duration of the lid saccade.
6. The number of frames is then calculated (based on graphical frame rate) using \(N=DF\), where \(N\) is number of frames, \(D\) is duration of lid saccade, and \(F\) is frames-per-second (fps).
7. Either \(E3\) (downward saccade) or \(E4\) (upward saccade) is then used to calculate the mean velocity of each frame of the lid saccade.
8. The eyelid values for the particular character are then determined for each frame using a variation of distance = speed x time: \(Af=Vf(D/N/Nf)\), where \(Af\) is the amplitude for a given frame, \(Vf\) is mean velocity of the frame, \(D\) is the total duration of the lid saccade, \(N\) is number of frames and \(Nf\) is current frame being calculated.
Finally, for each of the calculated frames, the character’s eyelid is set appropriately, animating the lid saccade.

**Blink Model**

Figure 3 presents the state diagram detailing the mechanics of the blink model. Screen-captures of a model-generated blink are shown in Figure 4.

1. Upon receiving a blink signal (from an eye tracker or gaze model for instance), the current position of the character’s eyelids are stored in order for the model to return them following completion of the blink.
2. Based upon the current state and the ‘eyelid fully closed’ state of the specific character’s eyelids, the angular amplitude of the blink motion is calculated.
3. Amplitude then acts as input to $E_5$ when calculating the down-phase and $E_6$ for the up-phase in order to determine the duration of the phases of the blink.
4. The number of frames is then calculated based on the graphical fps using $N = DF$, where $N$ is number of frames, $D$ is duration of the blink, and $F$ is fps.
5. $E_7$ (down-phase) and $E_8$ (up-phase) are then used to calculate the mean velocity of each frame of the blink motion for both phases.
6. The eyelid values for the specific character are then calculated for each frame using $Af = Vf(D/Nf)$, where $Af$ is the amplitude for a given frame, $Vf$ is mean velocity of the frame, $D$ is the total duration of the down or up phase of the blink, $N$ is number of frames and $Nf$ is current frame being calculated.
7. The calculated frames are iterated, animating the blink.
8. Finally, character’s initial eyelid state is restored, and control returns to the lid saccade model if it is operating.

**Sample Implementation of Combined Models**

Blink motions are informed by the open angle of the eyelids when a blink is initiated, which in turn is dependent on the open state of the eyelids as informed by most recent lid saccade. Hence, while the blink and lid saccade
models are independent, they must also act concurrently, and with knowledge of one another, in order to generate realistic animation of the two major components of human eyelid motion. Figure 5 shows a sample implementation in which both models operate concurrently. This implementation was used in an immersive avatar-mediated communication system to drive the real-time oculisic behaviour of avatars, including gaze and pupil size, as shown in Steptoe et al.\textsuperscript{33}. In this implementation, eye tracking is used to deliver gaze data, which acts as input to the lid saccade model. The operation of the lid saccade model may then be interrupted by blink signals: detected by the eye tracker; generated from a gaze model\textsuperscript{34}; or inferred from other behavioural tracking devices including microphones monitoring verbal utterances, or body tracking monitoring gestures. Following completion of a blink, the lid saccade model then resumes control.

**Model Validation**

**Motion Capture and Encoding**

Validation of our models was performed by comparing against two common forms of implementation: motion capture and a linear interpolation. We captured a series of blinks and lid saccades from a normal human subject using a Casio® EXILIM Pro EX-F1 digital camera capable of taking 60 full-HD (1920×1080) still photographs per second. During each second of burst-shooting, images of the subject’s eyes were captured at 16.7 millisecond
interval, thus capturing the current state of the subject’s eyelids during a blink or saccade at a consistent temporal rate. Sequences of photographs depicting blinks and lid saccades formed the basis to encode the eyelid animations in two of our virtual characters using 3DS Max® (Autodesk®) and Poser® (Smith Micro®) as illustrated in Figure 6.

The encoded motion captured animation (three blinks and three lid saccades) was rendered at 800×600 pixels at 60 fps. Identical starting parameters for each of the motion captured blinks (vertical eye angle) and lid saccades (vertical shift of eye angle) were then used as input to the models, and the resulting animations were rendered in the two characters at the same resolution and fps. Simple linear animation was also generated for each blink and lid saccade using the same starting parameters and matching the number of frames in the motion captured versions. In summary, we generated a series of videos of blinks and lid saccades which were animated using three different methods: motion capture, our models as described in the previous section and simple linear interpolation.

**Experiment**

The following experiment aimed to validate our models, by comparing model-generated animations to motion captured dynamics and to simple linear interpolation. The experiment also served to verify that the encoded motion captured animations were accurate. Ten participants from the graphics group at UCL were recruited, who were all experienced in 3D animation and visualization. The participants were asked to rank the animations over two stages: the first stage addressed the perceived realism of the eyelid motions, asking participants to rank animations in order of what they believe to be the most human-like movement; the second stage of evaluation involved ranking the animations in terms of similarity to the source. An experimental interface was built, in which animations from each condition were compositized and synchronized in one video. To negate the influence of placement, the positions of the animation conditions were shuffled, so that each motion (three blinks, three lid saccades) was viewed and ranked six times. Figure 7 (left) illustrates the realism stage, in which the three animation conditions (capture, model and linear) were viewed and rated for each blink and lid saccade. Figure 7 (right) shows the similarity to source stage, in which the initial source human eyelid motion captured using the camera is positioned at the top-left of the video. The source video is surrounded by the generated animations from the three conditions, which again, were viewed and rated for each
Figure 7. Experimental validation interface. Left: Participants ranked animations in terms of realism. Right: Participants then ranked animations in terms of similarity to the source video positioned in the top-left of the interface.

blink and lid saccade six times, with varying placement. The realism task was performed prior to the similarity to source task in order to eliminate the interexperimental effect of participants’ judgements of the former being influenced by what they remember from the latter.

Results

The validity of the models and also of the motion capture encoding is strongly supported by our results. Figure 8 shows combined blink and lid saccade results from the realism and similarity rankings (normalized to 1). When ranking similarity to the source video, the motion captured animations scored 97.9% of its potential score aggregated from all ten participants. Repeated measures two-way analysis of variance (ANOVA) calculations revealed high consistency between participants (\( p = .94 \)), and also that each participant was consistent in their own ratings (\( p = .47 \)). In addition to these rankings, we presented a number of versions of the animations to various other group members during the encoding process for comment and modification. Thus, we can confirm the faithfulness of the motion capture encoding to the original human movements with some confidence.

In comparison, and as should be reasonably expected, the model-generated animations were ranked significantly less similar to the source video than the motion captured versions, at 68.4% similarity. The linear animations were ranked lowest, with a 36.5% similarity to the source. Repeated measures two-way ANOVA calculations revealed a statistically significant difference between the animation classes, and post hoc Tukey tests indicated differences to lie between all pairs (\( p < .01 \)).

In terms of realism, the animation generated using the models received 88.7% of the total votes that the motion captured animations scored, while the linear animation score was low at 47% of the motion capture. Repeated measures two-way ANOVA calculations revealed a highly significant difference between the realism of the animation types (\( p < .01 \)). Post hoc Tukey tests showed that the significant differences lay between the linear animation and both other classes of model (\( p < .01 \)) and motion capture (\( p < .01 \)). There was no statistically significant difference found between the model-generated animations and those encoded from the motion capture data, promoting the validity of the models. Again, a high consistency between participants was found, strengthening the subjective votes.

Finally, Figure 9 presents the dynamics of each animation class during a single blink (averaged from the three captured blinks). The \( y \)-axis represents the upper eyelid position, with a value of 1 being completely closed, while the \( x \)-axis represents time in frames. It is important to note, that while the graph suggests potential for optimization of the model, it is not critical for the model’s profile to exactly match the motion capture curve: the intention of the models is to present a generalized simulation of the kinematic behaviour of the eyelids, whereas Figure 9 (and this analysis) is based on small number of blinks captured from a single person. Hence, while...
the parametric input to the models may be modified to achieve a more precise fit in this particular instance, the aim of this section is to more generally validate the models compared to alternative methods of animation.

Discussion

Previous work animating the eyelids of virtual characters has failed to define the kinematic behaviour of lid saccades and blinks, typically bypassing the problem by using facial motion capture or implementing crude approximations. In our model validation experiment, motion captured animation scored highest in terms of realism, but a statistical difference to the models’ scores not found. Therefore, while motion captured data may potentially provide superior animation than our models, a key problem with the method is that it is expensive to capture and encode, and is often used for a singular implementation. Our blink and lid saccade models adapt to the a character’s current state (blink magnitude or eye saccade angle), autonomously generating motion that is physiologically-accurate. In contrast, to achieve similar accuracy and variability using motion capture, a considerable amount of data including a number of blinks and lid saccades are likely to be required to be captured and processed. Our models provide modifiable parametric approximations of eyelid dynamics which were rated as statistically similar to encoded human motion in terms of realism.

A limitation of the models is that they describe only ‘normal’ human eyelid dynamics. Due to the difficulty of recording other situations in a controlled situation, there is limited data in the ophthalmology and physiology literature. However, the parametric nature of model control ensures that adjustment to specific emotional states (such as surprise) or medical conditions (such as ptosis) is straightforward. Characters featuring linear blend skinning and blend shapes were demonstrated during experimental validation, as shown in Figure 1, but the models may also be implemented with other methods of facial animation. Adjusting input parameter values is likely to influence how observers perceive a character. For instance, reduction of the down-phase blink velocity may indicate fatigue. The lid saccade model takes gaze data as its initial input. Therefore, the model automatically adjusts to the control method. Hence, if gaze is driven by an eye tracker in real-time as presented in Steptoe et al., the model will respond according to the wearer’s gaze behaviour, which is likely to reflect their current emotional or mood state: increased and rapid eye saccades will be matched with lively lid saccades, thereby communicating vital nonverbal information to an observer or interactional partner in avatar-mediated communication. Similarly, negative or submissive traits of avoiding eye contact and frequently looking downwards is likely to be exaggerated by the corresponding model-generated lid saccades, which naturally display the closed-state of the eyes.

Conclusions

This paper presented two parametric models generating physiologically-accurate animation of the components of eyelid kinematics for virtual characters. The lid saccade model generates realistic motion based on vertical shifts in a given gaze signal, while the blink model animates realistic blink motion given a current eyelid position. The quality of the models was validated by comparing against motion captured data, and observers judged the realism of the simulated and captured animations as statistically identical. Future work will focus on the impact of parameter modification of the eyelid models, particularly in social, avatar-mediated communication. Additionally, different forms and fidelities of virtual characters will be investigated, including non-humanoids. We suggest that as virtual characters move ever-closer towards both photo- and behavioural-realism, it is essential to consider the subtleties of human behaviour in order to achieve the high levels of believability for our applications.

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References


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