

ACCURATE EYE CENTRE LOCALISATION BY MEANS OF GRADIENTS

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Abstract: The estimation of the eye centres is used in several computer vision applications such as face recognition or eye tracking. Especially for the latter, systems that are remote and rely on available light have become very popular and several methods for accurate eye centre localisation have been proposed. Nevertheless, these methods often fail to accurately estimate the eye centres in difficult scenarios, *e.g.* low resolution, low contrast, or occlusions. We therefore propose an approach for accurate and robust eye centre localisation by using image gradients. We derive a simple objective function, which only consists of dot products. The maximum of this function corresponds to the location where most gradient vectors intersect and thus to the eye's centre. Although simple, our method is invariant to changes in scale, pose, contrast and variations in illumination. We extensively evaluate our method on the very challenging BioID database for eye centre and iris localisation. Moreover, we compare our method with a wide range of state of the art methods and demonstrate that our method yields a significant improvement regarding both accuracy and robustness.

1 INTRODUCTION

The localisation of eye centres has significant importance in many computer vision applications such as human-computer interaction, face recognition, face matching, user attention or gaze estimation (Böhme et al., 2006). There are several techniques for eye centre localisation, some of them make use of a head-mounted device, others utilise a chin rest to limit head movements. Moreover, active infrared illumination is used to estimate the eye centres accurately through corneal reflections. Although these techniques allow for very accurate predictions of the eye centres and are often employed in commercial eye-gaze trackers, they are uncomfortable and less robust in daylight applications and outdoor scenarios. Therefore, available-light methods for eye centre detection have been proposed. These methods can roughly be divided into three groups: (i) feature-based methods, (ii) model-based methods, and (iii) hybrid methods. A survey on video-based eye detection and tracking can be found, for example, in (Hansen and Ji, 2010).

In this paper we describe a feature-based approach

for eye centre localisation that can efficiently and accurately locate and track eye centres in low resolution images and videos, *e.g.* in videos taken with a webcam. We follow a multi-stage scheme that is usually performed for feature-based eye centre localisation (see Figure 1), and we make the following contributions: (i) a novel approach for eye centre localisation, which defines the centre of a (semi-)circular pattern as the location where most of the image gradients intersect. Therefore, we derive a mathematical function that reaches its maximum at the centre of the circular pattern. By using this mathematical formulation a fast iterative scheme can be derived. (ii) We incorporate prior knowledge about the eye appearance and increase the robustness. (iii) We apply simple post-processing techniques to reduce problems that arise in the presence of glasses, reflections inside glasses, or prominent eyebrows. Furthermore, we evaluate the accuracy and the robustness to changes in lighting, contrast, and background by using the very challenging BioID database. The obtained results are extensively compared with state of the art methods for eye centre localisation.



Figure 1: Multi-stage approach for eye centre localisation. A face detector is applied first; based on the face location rough eye regions are extracted (left), which are then used for a precise estimation of each eye centre (middle and right).

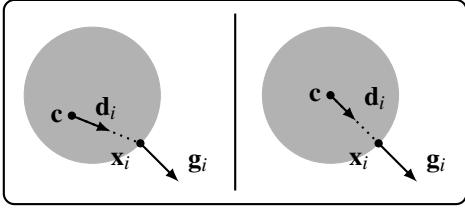


Figure 2: Artificial example with a dark circle on a light background, similar to the iris and the sclera. On the left the displacement vector \mathbf{d}_i and the gradient vector \mathbf{g}_i do not have the same orientation, whereas on the right both orientations are equal.

2 EYE CENTRE LOCALISATION

Geometrically, the centre of a circular object can be detected by analysing the vector field of image gradients, which has been used for eye centre localisation previously. Kothari and Mitchell, for example, proposed a method that exploits the flow field character that arises due to the strong contrast between iris and sclera (Kothari and Mitchell, 1996). They use the orientation of each gradient vector to draw a line through the whole image and they increase an accumulator bin each time one such line passes through it. The accumulator bin where most of the lines intersect thus represents the estimated eye centre. However, their approach is only defined in the discrete image space and a mathematical formulation is missing. Moreover, they don't consider problems that arise due to eyebrows, eyelids, or glasses.

In this work, we also analyse the vector field of image gradients but derive a novel mathematical formulation of the vector field characteristics. Therefore, we mathematically describe the relationship between a possible centre and the orientations of all image gradients. Let \mathbf{c} be a possible centre and \mathbf{g}_i the gradient vector at position \mathbf{x}_i . Then, the normalised displacement vector \mathbf{d}_i should have the same orientation (except for the sign) as the gradient \mathbf{g}_i (see Fig. 2). If we use the vector field of (image) gradients, we can exploit this vector field by computing the dot products between the normalised displacement vectors (related

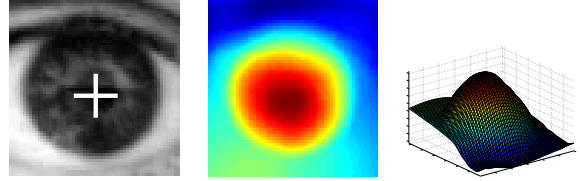


Figure 3: Evaluation of (1) for an exemplary pupil with the detected centre marked in white (left). The objective function achieves a strong maximum at the centre of the pupil; 2-dimensional plot (centre) and 3-dimensional plot (right).

to a fixed centre) and the gradient vectors \mathbf{g}_i . The optimal centre \mathbf{c}^* of a circular object in an image with pixel positions $\mathbf{x}_i, i \in \{1, \dots, N\}$, is then given by

$$\mathbf{c}^* = \arg \max_{\mathbf{c}} \left\{ \frac{1}{N} \sum_{i=1}^N (\mathbf{d}_i^T \mathbf{g}_i)^2 \right\}, \quad (1)$$

$$\mathbf{d}_i = \frac{\mathbf{x}_i - \mathbf{c}}{\|\mathbf{x}_i - \mathbf{c}\|_2}, \quad \forall i: \|\mathbf{g}_i\|_2 = 1. \quad (2)$$

The displacement vectors \mathbf{d}_i are scaled to unit length in order to obtain an equal weight for all pixel positions. In order to improve robustness to linear changes in lighting and contrast the gradient vectors should also be scaled to unit length. An example evaluation of the sum of dot products for different centres is shown in Fig. 3, where the objective function yields a strong maximum at the centre of the pupil.

Computational complexity can be decreased by considering only gradient vectors with a significant magnitude, *i.e.* ignoring gradients in homogeneous regions. In order to obtain the image gradients, we compute the partial derivatives $\mathbf{g}_i = (\partial I(x_i, y_i) / \partial x_i, \partial I(x_i, y_i) / \partial y_i)^T$, but other methods for computing image gradients will not change the behaviour of the objective function significantly.

2.1 Prior knowledge and postprocessing

Under some conditions, the maximum is not well defined, or there are local maxima that lead to wrong centre estimates. For example, dominant eyelids and eyelashes or wrinkles in combination with a low contrast between iris and sclera can lead to wrong estimates. Therefore, we propose to incorporate prior knowledge about the eye in order to increase robustness. Since the pupil is usually dark compared to sclera and skin, we apply a weight w_c for each possible centre \mathbf{c} such that dark centres are more likely than bright centres. Integrating this into the objective function leads to:

$$\arg \max_{\mathbf{c}} \frac{1}{N} \sum_{i=1}^N w_c (\mathbf{d}_i^T \mathbf{g}_i)^2, \quad (3)$$

where $w_c = I^*(c_x, c_y)$ is the grey value at (c_x, c_y) of the smoothed and inverted input image I^* . The image needs to be smoothed, *e.g.* by a Gaussian filter, in order to avoid problems that arise due to bright outliers such as reflections of glasses. The values of the new objective function is rather insensitive to changes in the parameters of the low-pass filter.

The proposed summation of weighted squared dot products yields accurate results if the image contains the eye. However, when applying the multi-stage scheme described in Figure 1, the rough eye regions sometimes also contain other structures such as hair, eyebrows, or glasses. Especially, hair and strong reflections in glasses show significant image gradients that do not have the same orientation as the image gradients of the pupil and the iris; hence the estimation of the eye centres might be wrong. We therefore propose a postprocessing step in order to overcome these problems. We apply a threshold on the objective function, based on the maximum value, and remove all remaining values that are connected to one of the image borders. Then, we determine the maximum of the remaining values and use its position as centre estimate. Based on our experiments the value of this threshold doesn't have a significant influence on the centre estimates, we suggest to set this threshold to 90% of the overall maximum.

3 EVALUATION

For our evaluation we have chosen the BioID database, since it is the most challenging set of images for eye centre localisation and many recent results are available. The database consists of 1521 grey level images of 23 different subjects and has been taken in different locations and at different day-times, which result in variable illumination conditions comparable to outdoor scenes. In addition to the changes in illumination, the position of the subjects change as well as their pose. Moreover, several subjects wear glasses and some subjects have curled hair near to the eye centres. In some images the eyes are closed and the head is turned away from the camera or strongly affected by shadows. In few images the eyes are even completely hidden by strong reflections on the glasses. Because of these conditions, the BioID database is considered as one the most challenging database that reflects realistic conditions. The image quality and the image size (286×384) is approximately equal to the quality of a low-resolution webcam. The left and right eye centres are annotated and provided together with the images.

We perform the multi-stage scheme described in

Figure 1, where the position of the face is detected first. Therefore, we apply a boosted cascade face detector that proved to be effective and accurate on several benchmarks (Viola and Jones, 2004). Based on the position of the detected face and anthropometric relations, we extract rough eye regions relative to the size of the detected face. The rough eye regions are then used to estimate the eye centres accurately by applying the proposed approach.

As accuracy measure for the estimated eye centres, we evaluate the *normalised error*, which indicates the error obtained by the worst of both eye estimations. This measure was introduced by Jesorsky *et al.* and is defined as:

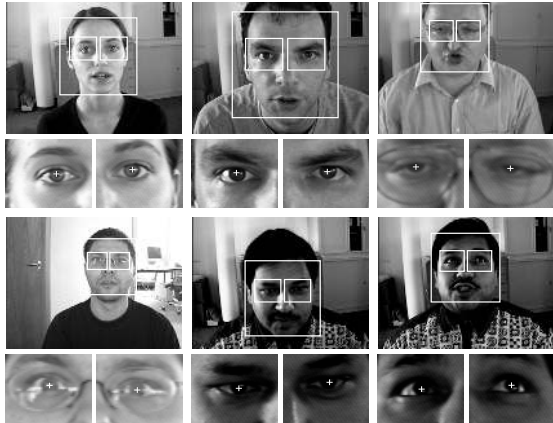
$$e \leq \frac{1}{d} \max(e_l, e_r) \quad , \quad (4)$$

where e_l, e_r are the Euclidean distances between the estimated and the correct left and right eye centres, and d is the distance between the correct eye centres. When analysing the performance of an approach for eye localisation this measure has the following characteristics: (i) $e \leq 0.25 \approx$ distance between the eye centre and the eye corners, (ii) $e \leq 0.10 \approx$ diameter of the iris, and (iii) $e \leq 0.05 \approx$ diameter of the pupil. Thus, an approach that should be used for eye tracking must not only provide a high performance for $e \leq 0.25$, but must yield good results for $e \leq 0.05$. An error of slightly less than or equal to 0.25 will only indicate that the estimated centre might be located within the eye, but this estimation cannot be used to perform accurate eye tracking. When comparing with state of the art methods we therefore focus on the performance that is obtained for $e \ll 0.25$.

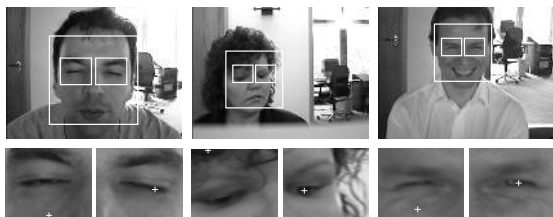
Since in some other published articles the normalised error is used in a non-standard way, we also provide the measures $e_{\text{better}} \leq \frac{1}{d} \min(e_l, e_r)$ and $e_{\text{avg}} \leq \frac{1}{2d} (e_l + e_r)$ in order to give an upper bound as well as an averaged error.

3.1 Results

The qualitative results of the proposed approach are shown in Figure 4. It can be observed that our approach yields accurate centre estimations not only for images containing dominant pupils, but also in the presence of glasses, shadows, low contrast, or strands of hair. This demonstrates the robustness and proves that our approach can successfully deal with several severe problems that arise in realistic scenarios. Our approach yields inaccurate estimations if the eyes are (almost) closed or strong reflections of the glasses occur (last row). Then, the gradient orientations of the pupil and the iris are affected by "noise" and hence their contribution to the sum of squared dot products



(a) accurate eye centre estimations



(b) inaccurate eye centre estimations

Figure 4: Sample images of accurate and inaccurate results for eye centre localisation on the BioID database. The estimated centres are depicted by white crosses. Note that, the estimated centres might be difficult to identify due to low printer resolution.

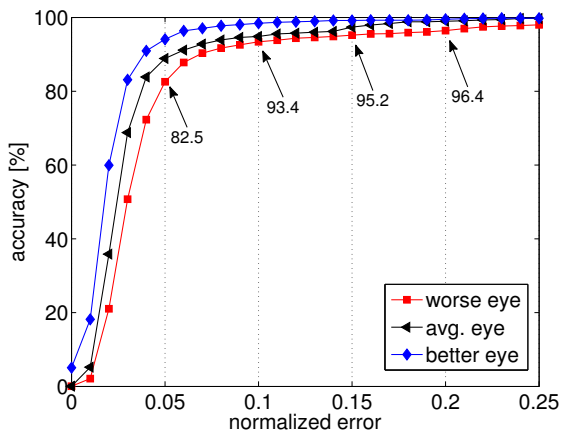


Figure 5: Quantitative analysis of the proposed approach for the BioID database. In order to give upper and lower bounds, the accuracy versus the minimum (better eye, e_{better}), the maximum (worse eye, e) and the average (avg. eye, e_{avg}) normalized error are shown. Some characteristic values are given explicitly.

is less than the contribution of the gradients around the eyebrow or eyelid.

The quantitative results of the proposed method are shown in Figure 5, where the accuracy measures e , e_{better} , and e_{avg} are illustrated. By using the standard definition of the normalised error, Eq. (4), our approach yields an accuracy of 82.5% for pupil localisation ($e \leq 0.05$), which indicates that the centres detected by our approach are located within the pupil with high probability and can therefore be used for eye tracking applications. For iris localisation ($e \leq 0.10$), the estimated centres lie within the iris with a probability of 93.4%, which will further increase if images with closed eyes are left out.

3.2 Comparison with state of the art

We extensively compare our method with state of the art methods that have been applied to the BioID images as well. For comparison we evaluate the performance for different values of the normalised error e in order to obtain a characteristic curve (see Fig. 5 “worse eye”), which we will call *worse eye characteristic* (WEC). The WEC is roughly similar to the well-known receiver operator characteristic (ROC) and can be analysed in several ways. As mentioned previously, it depends on the application which e should be applied in order to compare different methods, e.g. for eye tracking applications a high performance for $e \leq 0.05$ is required, whereas for applications that use the overall eye position such as face matching comparing the performance for $e \leq 0.25$ will be more appropriate. In order to compare the overall performance, i.e. for different e , the area under the WEC can be used. Unfortunately, the WEC of other methods is often not available, and we therefore compare the methods for a discretised $e \in \{0.05, 0.10, 0.15, 0.20, 0.25\}$. Furthermore, we also evaluate the rank of each method, which is roughly inversely proportional to the area under the WEC.

The comparison between our method and state of the art methods is shown in Tab. 1. If the performance for $e \in \{0.05, 0.10, 0.15, 0.20, 0.25\}$ was not provided by the authors explicitly, but a WEC is shown, we measured the values accurately from the WEC. Note that, for some methods, the authors evaluated the performance only for few values of e , see for example (Chen et al., 2006) or (Zhou and Geng, 2004). It can be seen that our method performs only 2% worse in average compared to the best method for each e . For example, the method proposed by Valenti and Gevers yields a performance of 84.1% for $e \leq 0.05$, whereas our method yields a performance of 82.5%. How-

Method	$e \leq 0.05$	$e \leq 0.10$	$e \leq 0.15$	$e \leq 0.20$	$e \leq 0.25$	Remarks
(Asadifard and Shanbezadeh, 2010)	47.0%	86.0%	89.0%	93.0%	96.0%	(*), (●)
(Kroon et al., 2008)	65.0%	87.0%	–	–	98.8%	
(Valenti and Gevers, 2008)	77.2%	82.1%	(86.2%)	(93.8%)	96.4%	MIC, (●)
(Valenti and Gevers, 2008)	84.1%	90.9%	(93.8%)	(97.0%)	98.5%	MIC+SIFT+kNN
(Türkan et al., 2007)	(18.6%)	73.7%	(94.2%)	(98.7%)	99.6%	
(Campadelli et al., 2006)	62.0%	85.2%	87.6%	91.6%	96.1%	
(Niu et al., 2006)	(75.0%)	93.0%	(95.8%)	(96.4%)	(97.0%)	
(Chen et al., 2006)	–	89.7%	–	–	95.7%	
(Asteriadis et al., 2006)	(44.0%)	81.7%	(92.6%)	(96.0%)	97.4%	(●)
(Hamouz et al., 2005)	(58.6%)	(75.0%)	(80.8%)	(87.6%)	(91.0%)	
(Zhou and Geng, 2004)	–	–	–	–	94.8%	(●)
(Cristinacce et al., 2004)	(57.0%)	96.0%	(96.5%)	(97.0%)	(97.1%)	
(Behnke, 2002)	(37.0%)	(86.0%)	(95.0%)	(97.5%)	(98.0%)	
(Jesorsky et al., 2001)	(38.0%)	(78.8%)	(84.7%)	(87.2%)	91.8%	
our method	82.5%	93.4%	95.2%	96.4%	98.0%	(●)

Table 1: Comparison of the performance for eye detection on the BioID database. Brackets indicate values that have been accurately measured from author’s graphs. (*) Images with closed eyes and glasses were omitted. (●) Methods that don’t involve any kind of learning or model scheme. Since some authors didn’t provide any graphical evaluation of the performance, e.g. by using a WEC curve, intermediate values couldn’t be estimated – these missing values are denoted by “–”.

ever, Valenti and Gevers reported that their method, which uses mean-shift clustering, SIFT features, and a k nearest neighbour classifier, will produce unstable centre estimations when applying it to eye tracking with several images per second. Hence, our method can be considered as one of the best methods for accurate eye centre localisation. Furthermore, our method has significantly less computational complexity compared to that of Valenti and Gevers, since it requires neither clustering nor a classifier. Comparing those methods that do not involve any kind of learning scheme, our method achieves the best performance by far (82.5% for $e \leq 0.05$). For iris location ($e \leq 0.10$), our method achieves the second best performance (93.4%); only the method by Cristinacce *et al.* yields a significant improvement (96.0%) – however, this improvement implies, again, a higher computational complexity compared to our method, which is solely based on dot products. For higher normalised errors, e.g. $e \leq 0.15$, $e \leq 0.20$, or $e \leq 0.25$, our method performs comparable to other methods.

A comparison based on the ranks of the performances is shown in Tab. 2. It can be seen clearly, that there isn’t one single method that performs superior for all values of e . Exemplarily, the method proposed by Türkan *et al.* achieves accurate estimations for detecting the overall eye centres, i.e. $e \leq 0.20$ and $e \leq 0.25$, but it fails for iris localisation ($e \leq 0.10$) and pupil localisation ($e \leq 0.05$) with rank 13 in both cases. In contrast, our method ranks 2nd for both pupil and iris localisation and ranks 3rd and 4th for larger e . Hence, our method doesn’t yield the best result for one single e , but if we evaluate the average

rank our method yields the best result (3.0). Compared to the method with the second best average rank (3.4, Valenti and Gevers, MIC+SIFT+kNN) our method is not only superior according to the average rank, but also the variance of the individual ranks is significantly less, and the complexity is much lower.

In total, our method performs comparable to other state of the art methods when looking for a particular e , but it yields the best average performance over all values of e . Hence, our method proves to be powerful for several problems such as eye centre localisation ($e \leq 0.05$), iris localisation ($e \leq 0.10$), and eye localisation ($e \leq 0.25$). Comparing only those methods that do not apply any learning scheme, our method achieves significant improvements for the more difficult tasks, i.e. 5% improvement for $e \leq 0.05$, 7% for $e \leq 0.10$, and 2.6% for $e \leq 0.15$.

4 CONCLUSIONS

We propose a novel algorithm for accurate eye centre localisation based on image gradients. For every pixel, we compute the squared dot product between the displacement vector of a centre candidate and the image gradient. The position of the maximum then corresponds to the position where most image gradients intersect. Our method yields low computational complexity and is invariant to rotation and linear changes in illumination. Compared to several state of the art methods, our method yields a very high accuracy for special scenarios such as pupil localisa-

Method	$e \leq 0.05$	$e \leq 0.10$	$e \leq 0.15$	$e \leq 0.20$	$e \leq 0.25$	avg. rank
(Asadifard and Shanbezadeh, 2010)	9	7	8	7	10	8.2
(Kroon et al., 2008)	5	6	–	–	2	4.3
(Valenti and Gevers, 2008)	3	9	10	6	8	7.2
(Valenti and Gevers, 2008)	1	4	6	3	3	3.4
(Türkan et al., 2007)	13	13	5	1	1	6.6
(Campadelli et al., 2006)	6	8	9	8	9	8.0
(Niu et al., 2006)	4	3	2	4	7	4.0
(Chen et al., 2006)	–	5	–	–	11	8.0
(Asteriadis et al., 2006)	10	10	7	5	5	7.4
(Hamouz et al., 2005)	7	12	12	9	14	10.8
(Zhou and Geng, 2004)	–	–	–	–	12	12.0
(Cristinacce et al., 2004)	8	1	1	3	6	3.8
(Behnke, 2002)	12	7	4	2	4	5.8
(Jesorsky et al., 2001)	11	11	11	10	13	11.2
our method	2	2	3	4	4	3.0

Table 2: Comparison of ranks of each method according to its performance shown in Tab. 1.

tion (2nd place) and ranks in 1st place if the average performance over several scenarios, *e.g.* pupil localisation, iris localisation, and overall eye localisation, is evaluated. Our method can be applied to several (real-time) applications that require a high accuracy such as eye tracking or medical imaging analysis (cell tracking).

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