Pupillary dilation response estimation

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Image analysis pipeline:

1. *Apply a 2D bilateral filtering*: The original image is obtained from a noisy infra-red camera sensor. A reasonable assumption is that the image is corrupted by an additive Gaussian noise. The bilateral filter is a natural choice to remove this noise while preserving edges. The filter has a similar result to the well known anisotropic diffusion filter, but is not iterative and can be computed efficiently in a single iteration.

A single frame from a typical sequence is shown in Fig 1a. The output of applying the bilateral filter is shown in Fig 1b. The result is a smoother version of the original frame. Notice that the smoothing operation did not degrade or smeared pupil edges.

2. *Apply a Hough transform for circle detection:* We assume that the pupil has almost perfect circular shape. We used a circular Hough transform to obtain an initial estimation to the center and radius of the pupil. An example for the circle detected is shown in Fig 2a. Values of the initial estimation are discrete and may result a circle that is not optimal with respect to the given image (see zoom-in on two areas of the fitted circle; fig 2b and 2c). In addition, missing edges that did not pass the edge-detection threshold may not contribute to the optimal circle.

3. *Refined circle detection*: To obtain a better fit to the given data, we use a localized edge search along the normal direction at each point on the circle. The gradient is sampled with sub-pixel accuracy along each normal direction and the position of the largest gradient is saved as $\{x_i, y_i\}$ (Fig 3). If all points lie on a perfect circle, they should satisfy Eq1.

Eq1: $(x_i - c_x)^2 + (y_i - c_y)^2 = r^2$

However, the gradient is corrupted by noise and in practice all points will not lie on a circle. Thus, we search for the "optimal" circle, by minimizing the algebraic error, given in Eq2. Eq2 can be rearranged into a linear form, by introducing three slack variables: a_1, a_2, a_3, as written in Eq3. Rearranging Eq3 into matrix form gives an over determined system (Eq4). The least squares solution gives the optimal circle (c_x, c_y, r).

Eq2: $x_i^2 - 2x_i c_x + c_x^2 + y_i^2 - 2y_i c_y + c_y^2 - r^2 = 0$

Eq3: $x_i^2 + y_i^2 + a_1 x + a_2 y + a_3 = 0$

Eq4: $\left[X, Y, 1\right] \begin{bmatrix} a_1 \\ a_2 \\ a_3 \end{bmatrix} = \left[-X^2 - Y^2\right]$

Eq5: $$c_x = -\frac{a_1}{2} \qquad c_y = -\frac{a_2}{2} \qquad r = \sqrt{a_3 - c_x^2 - c_y^2}$$

Using this approach we managed to obtain sub-pixel accuracy for the fitted circle.

4. *Segmentation of the Pecten*: The Pecten edge is depicted in images as a contour that separates bright and dark retinal regions (Fig 4). The contour may vary in shape (not a straight line). We found it difficult to obtain a good contour segmentation using a fixed intensity threshold. This is probably due to the non-uniform illumination on the retinal surface. The contour was segmented using a local analysis of each horizontal line inside the detected circle. An example for a horizontal line is shown in Fig 4. The strongest descend in intensity typically corresponded to the transition between bright and dark area, and indicated the Pecten position along that line. The intensity curve was filtered using a small median filter window to remove spikes, smoothed using Gaussian window and finally used to obtain a smooth estimation for the intensity derivative. Empirically, we found the local maximum in the derivative profile to be a good indication to the Pecten position along that line. Various heuristics were used to rule out false matches, such as ones that rise due to high specular reflections. Finally, a smooth approximating spline was fitted to the set of points to obtain a smooth curve (Fig 5).

Fig.1 – A single frame from original video sequence before (a) and after (b) noise removal using bilateral filtering.

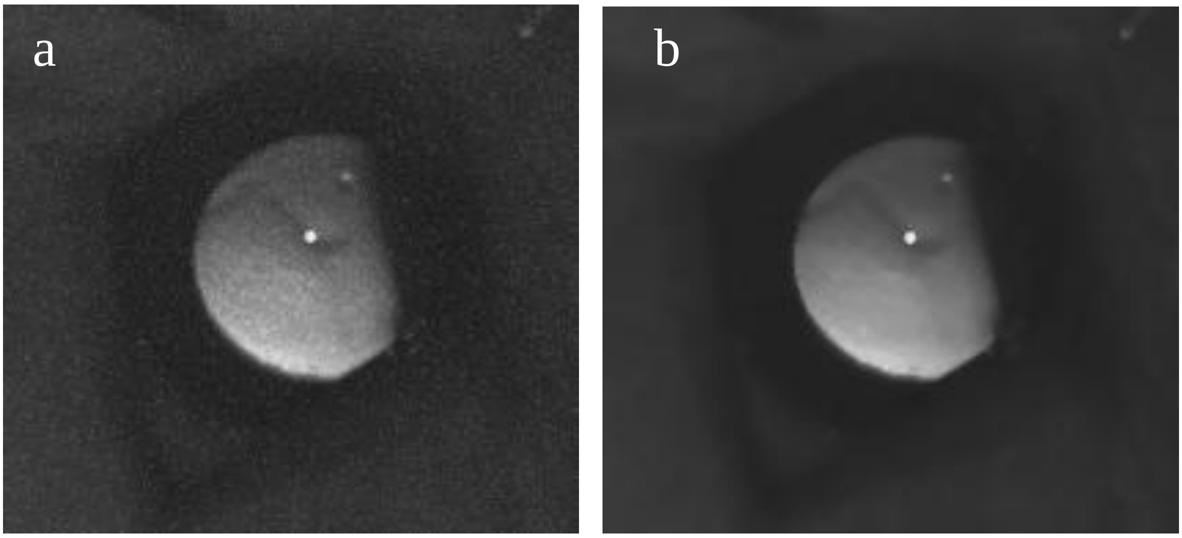

Fig 2 – Initial detected circle. The right two images (b and c) are close-up of the two squares on the left (a).

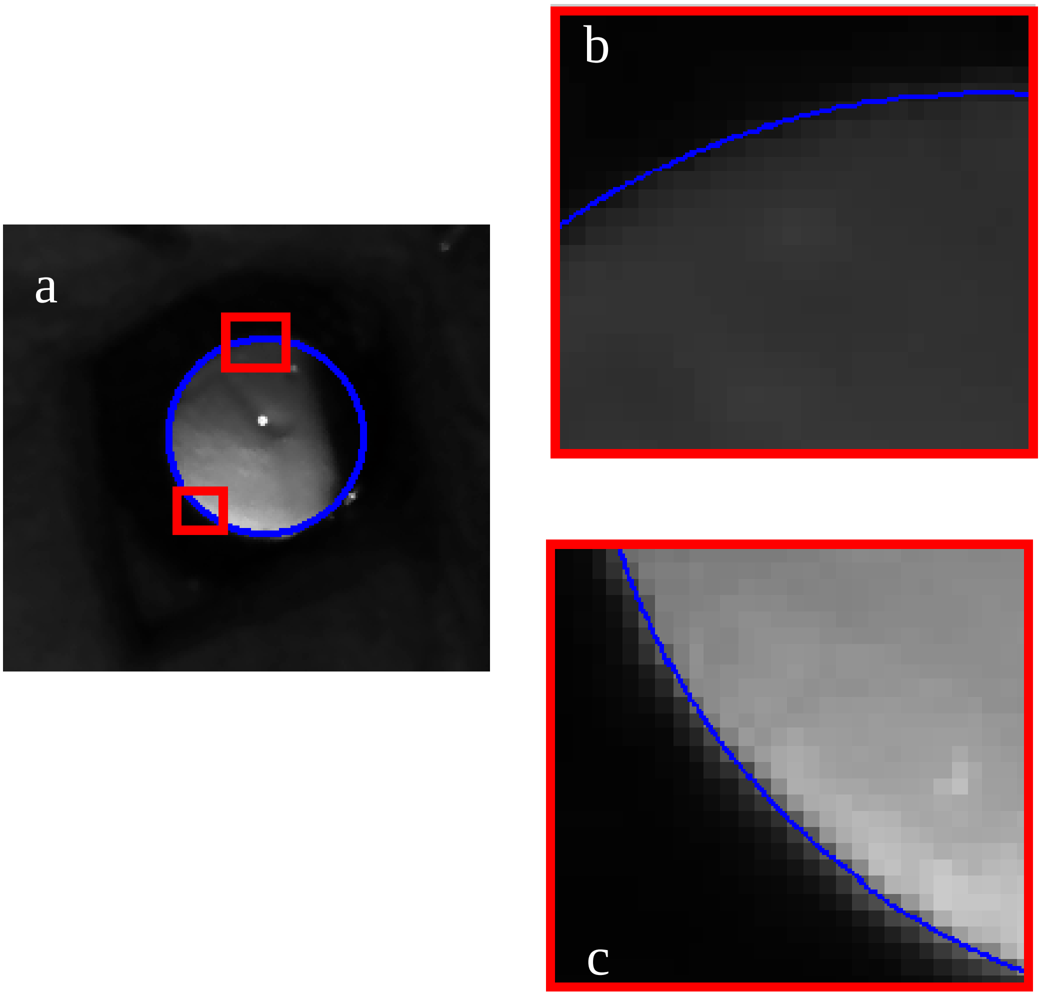

Fig. 3 – Highest gradient is searched along the normal direction at each point along the initial circle estimation.

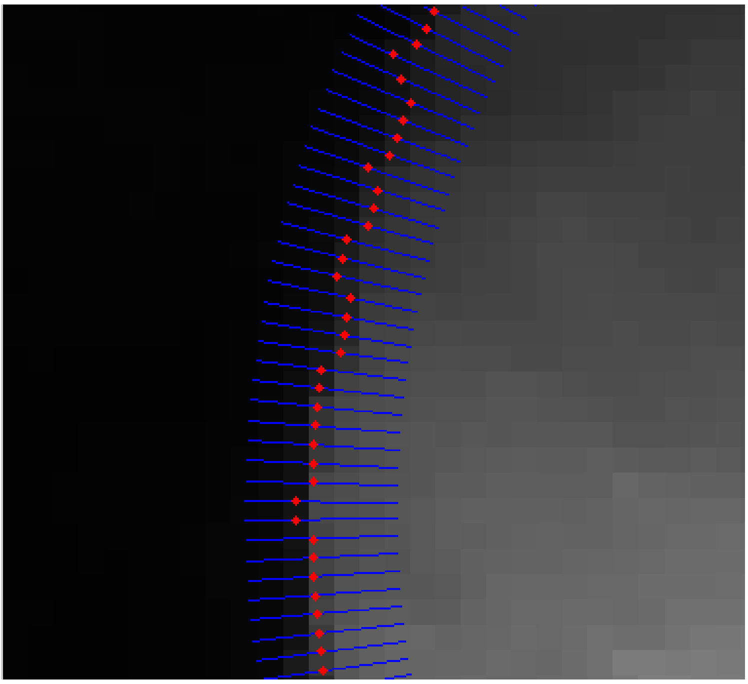

Fig. 4 – Local search for Pecten position along a single horizontal line (marked in blue). Intensity samples are marked with small circles. Smoothed version is shown as a black solid line. The derivative (x10, for visualization purposes) is plotted as a dashed line. Notice that the maxima in the derivative correlate to the intersection of the Pecten curve with the horizontal line.

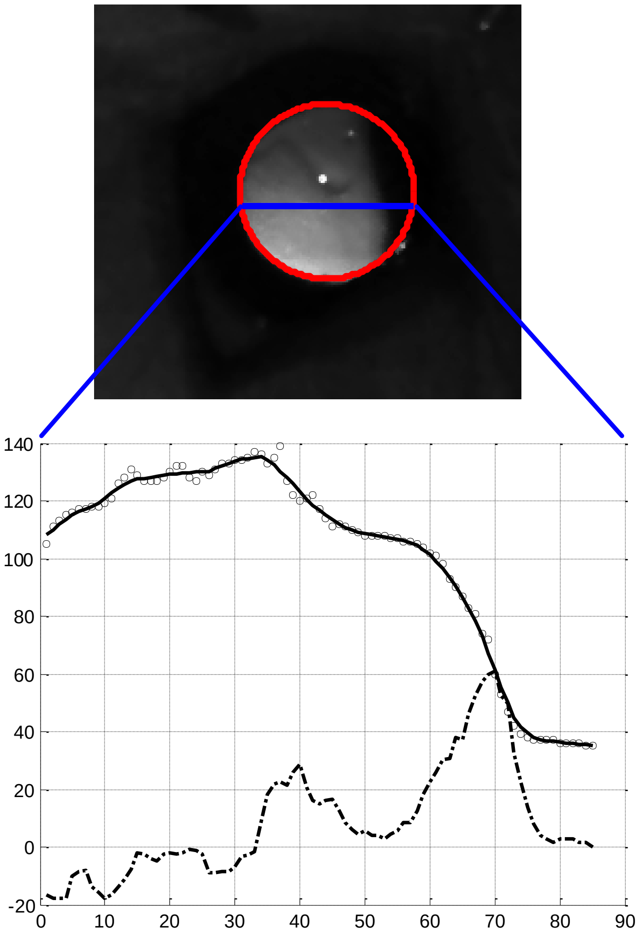

Fig. 5 – Final output. Pecten curve is shown as a solid green line.