Comparison of eye movement filters used in HCI

Oleg Špakov
School of Information Sciences
University of Tampere, Finland

Introduction

Raw data of eye movements contains noise which must be filtered out before using gaze points in gaze-controlled interface. Descriptions of a dozen of various filters for smoothing online signal from eye tracking devices can be found in literature. We have conducted an empirical study to compare them to reveal the factors that make smoothing robust and accurate.

Algorithms

1. Filters with weighted averaging over dynamic time window (*TWW*)
2. "On-off" filters with weighted averaging, with complex (*Woo*) and simple (*AWoo*) saccade detection.
3. Weighted Gaussian filter (W_G)
4. Two-mode low-pass filter (*LP2*)
5. Kalman filter
6. Savitzky-Golay filter (*SG*)

The filters with weighted averaging (*TWW*, *Woo* and *AWoo*) were implemented in 3 versions, each with distinct gaze point weight assigning functions:

- Linear: $W_i = 1$
- Triangular: $W_i = N - i + 1$
- Gaussian: $W_i = exp(-(i-1)^2 / 2\sigma^2)$

where *i* changes from *1* (most recent) to *N*.

***TWW* filters** [Kumar 2008, van der Kamp & Sundstedt 2011] use minimum time window to calculate the average when the current gaze point is further than some threshold from the average of few last gaze points (saccade mode), and gradually increases it while the gaze is relatively stable (fixation mode) until the maximum allowed time window is reached.

***Woo* filters** [Jimenez et al. 2008, Veneri et al. 2010] store close gaze points in a buffer that is used to calculate the average. The buffer is cleared out when a saccade is detected. It happens when 2 last consecutive gaze points are located further than some threshold from the average of other points. The "saccadic" gaze points are not filtered.

***AWoo* filters** are identical to *Woo* filters, but uses simpler saccade detection method: only one gaze point is used to detect saccades.

W_G filter just averages the gaze points that has its weight greater and 0.05 and does not detect saccades.

***LP2* filter** [Olsson 2007] measures the difference of averages of two adjacent groups of samples to detect saccades. It apply distinct coefficient *T* in the following formula to calculate the output value:

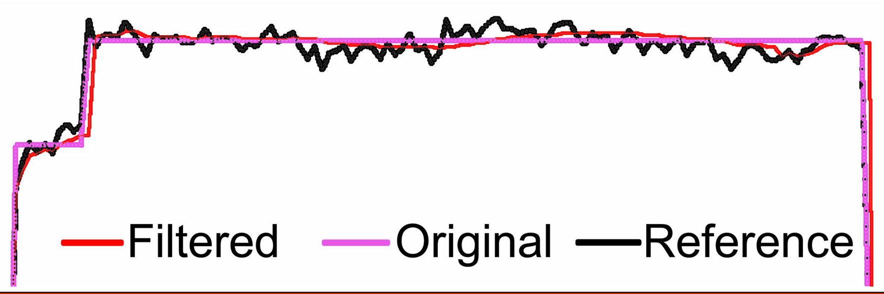
$$Output_i = (Input_i + \alpha * Output_{i-1}) / (1 + \alpha)$$

$$\alpha = T / sampling\_interval$$

Kalman filter [Komogotrsev 2007] predicts gaze point location and its movement speed, and based on the difference between predicted and measured points corrects the prediction model parameters.

***SG* filter** [Nyström 2010] with signal approximation by the second order polynomial function is usually used to smooth off-line signal, and was selected for comparison only.

The filters were tested against 2 offline filters that produced the referencing signal: one with moving averaging of 7 points (N_7), another with averaging over all points in fixations (N_∞).

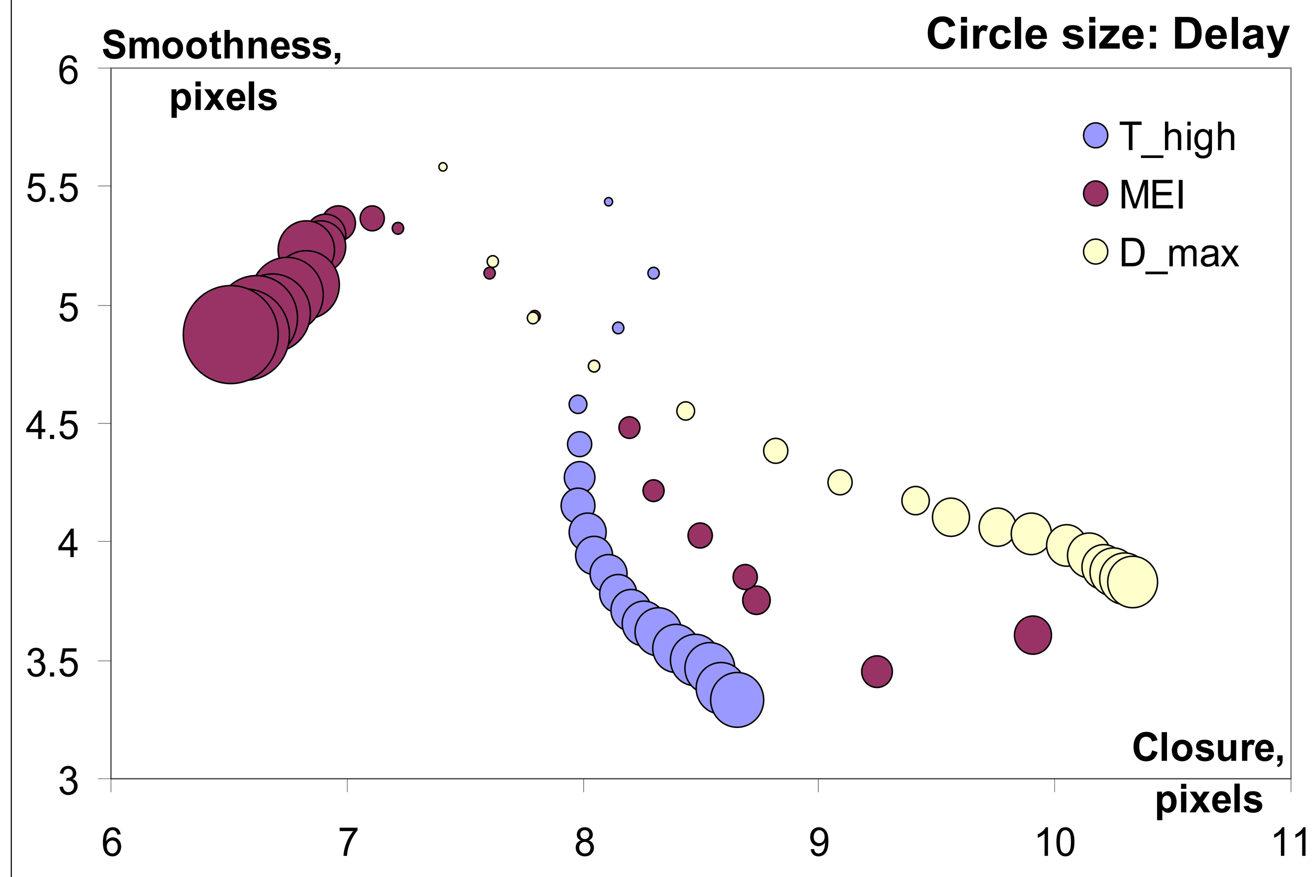


Comparison criteria

The comparison of filters was based on three criteria: a) **introduced delay**, b) **smoothness**, and c) **closeness** to the referencing signal. The closeness was estimated as *RMS* of the distances between points of the referencing and filtered signals. Smoothness was estimated as *RMS* of distances between actual and predicted data points of the filtered signal.

Optimization

Each filter was optimized to ensure its best performance. The optimization targeted filters' parameters, which were adjust so that the comparison criteria were the best (or somewhat balanced) when the filter was applied to the data used in this study. Below is an example of changes in relations of smoothness, closure and delay when the parameters of *LP2* algorithm changes within certain ranges.

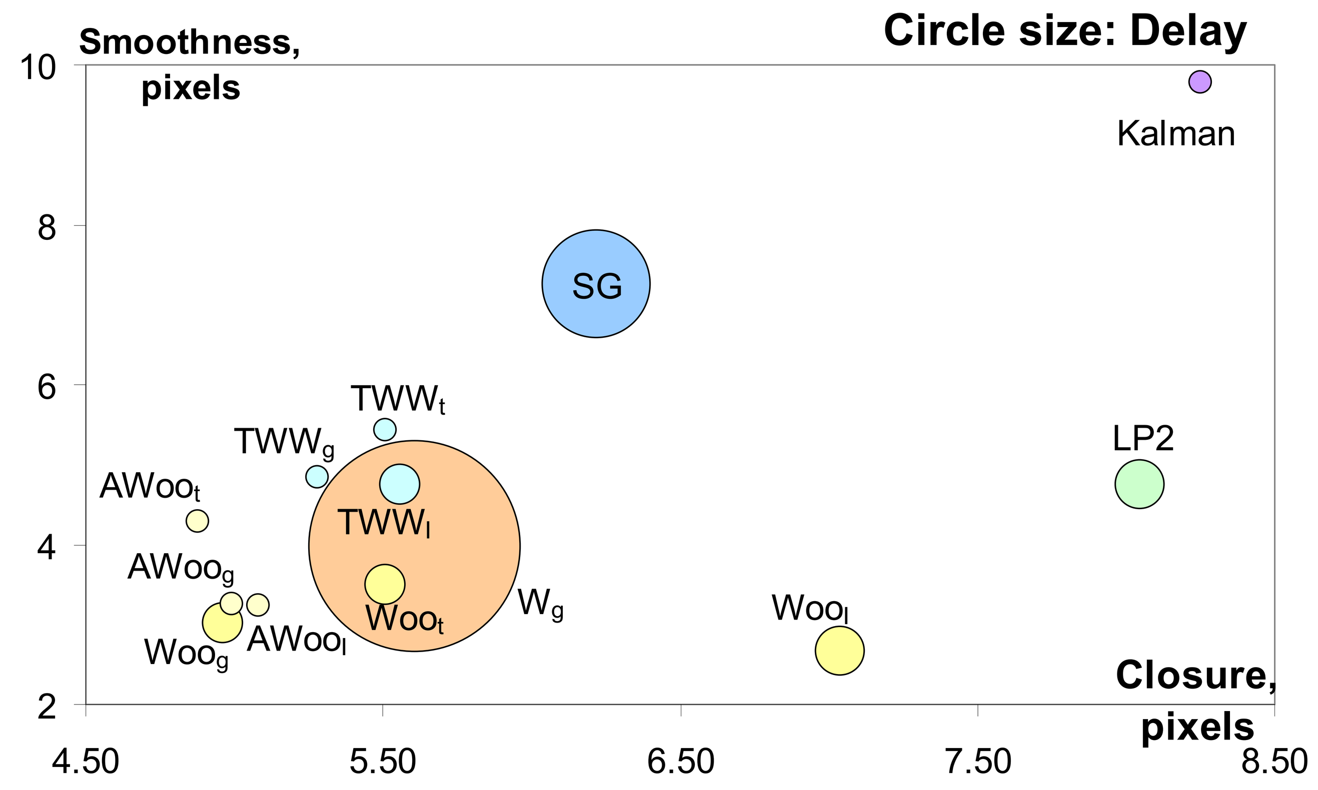


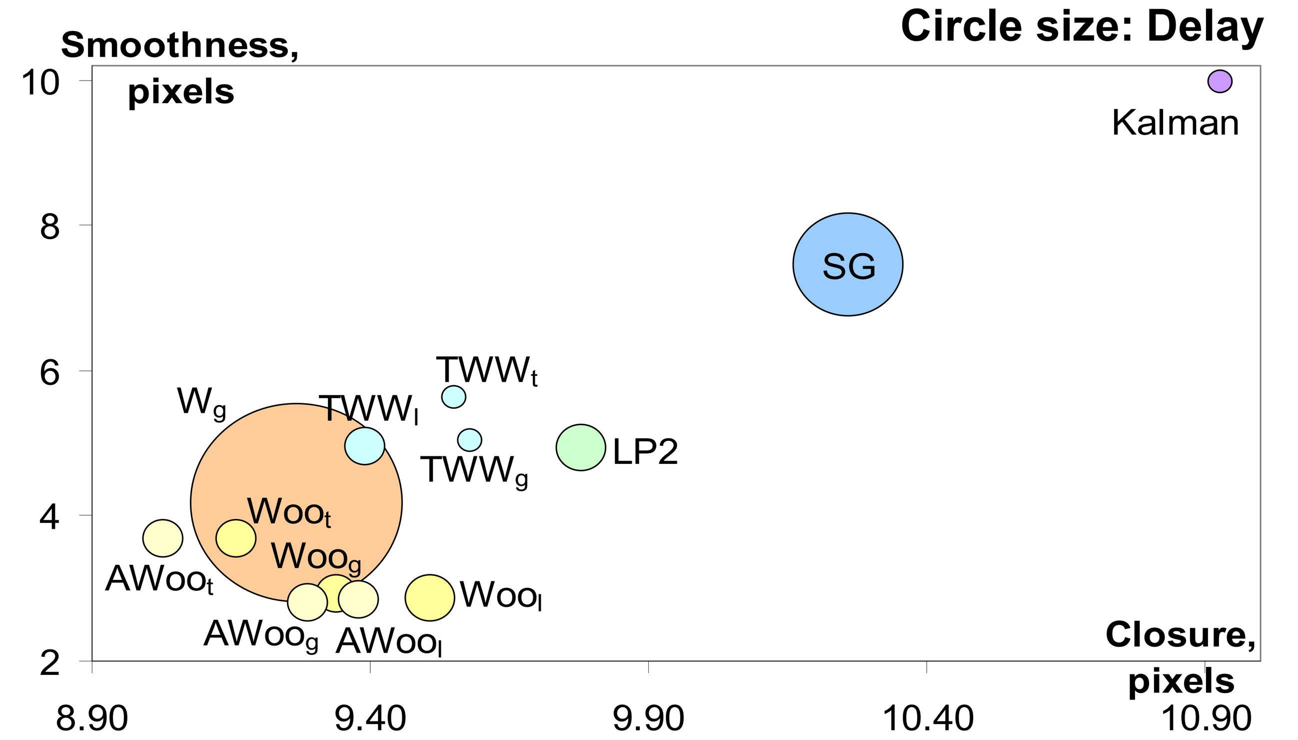
Data

Eleven participants were observing 50 small targets (dark 6x6 pixels rectangles) appearing sequentially in 25 screen locations and remained visible for 2 seconds. Gaze direction was measured by Tobii T60 eye tracker.

Results

The relations between delay, closure and smoothness for each algorithm when compared against N_7 (upper) and N_∞ (lower) referencing signals are shown below:





Conclusions

Savitzky-Golay, *Kalman* and W_G filters were recognized as clear outliers. All other kinds of weighted (*Woo*, *AWoo*, and *TWW*) filters have shown good smoothing capabilities, especially *AWoo* filter, for which all estimated values were among the best in both tests.

This comparison shows that the key requirement for designing filters for eye movements is **signal state detection:** filtering parameters should be separate for fixations and saccades. Other routine can be quite simple, such as weighted averaging.