Decreasing the Measurement Time of Blood Sugar Tests using Particle Filtering

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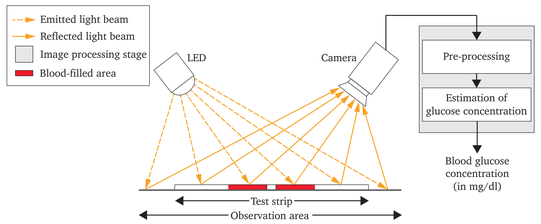
Motivation and Application

- Frequent self-monitoring of blood sugar levels is essential for diabetics
- Using a novel photometric measurement setup for hand-held devices requires a much smaller blood sample volume.
- The usability of hand-held glucometers is crucially affected by the measurement time

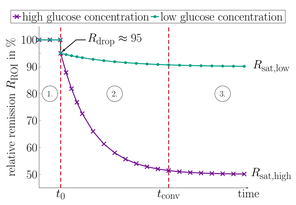
Image-based Photometric Measurement Setup

How do we measure the glucose concentration of a blood sample in hand-held devices?

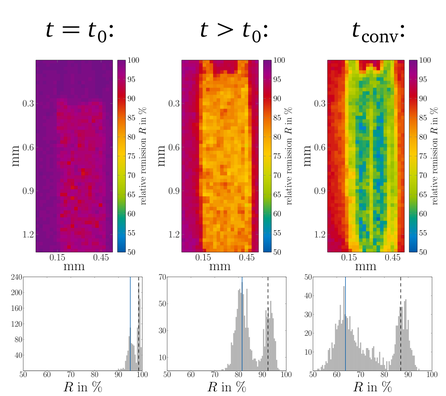


Novel photometric measurement setup

- The region of interest (ROI) is the blood-filled area of the test strip
- We measure the amount of light reflected from the ROI: the relative remission R_{ROI}
- R_{ROI} can directly be mapped to the underlying glucose concentration C in the blood



Idealized kinetic curves



Real measurement images and histograms at different stages of the observed chemical reaction

- Typically, the kinetic curve reveals three stages of the chemical reaction:
  1. Constant intensity stage for $t < t_0$
  2. Moistening period for $t \geq t_0$
  3. Convergence at $t = t_{\text{conv}}$

Goals

- Decrease the measurement time of blood sugar tests using hand-held glucometers
- Become independent of computationally costly statistical clustering methods for segmentation of the ROI and the remainder of the test-strip

Challenges

- Obtain a reliable estimate of the required relative remission value R_{sat} at an early stage of the chemical reaction

Modeling and State-Space Approach

- The temporal behavior of the chemical reaction for $t \geq t_0$ can be modeled as:

$$R(t) = (R_{\text{drop}} - R_{\text{sat}}) \cdot \mathrm{e}^{\tau(t-t_0)} + R_{\text{sat}}$$

How can we use this model to decrease the measurement time?

- True final remission value R_{sat} is the hidden state of the system
- Pixels of the pre-processed image are the available observations
- System model:

$$R_{\text{sat},t} = R_{\text{sat},t-1} + u_{t-1} \quad \text{with } u_t \sim \mathcal{N}(0, \sigma_u^2) \;\forall\; t \in \mathbb{R}$$

- Observation model (pixels):

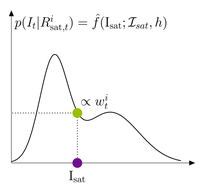
$$\mathrm{I}_t(m,n) = (R_{\text{drop}} - R_{\text{sat},t}) \cdot \mathrm{e}^{\tau \cdot (t-t_0)} + R_{\text{sat},t} \quad \forall\; (m,n) \in M \times N$$

Particle Filtering

- Recursive Bayesian filtering approach to estimate the state from incoming observations
- Particle filter: approximate the filtering distribution by N_p samples, so-called *particles*, as

$$p(R_{\text{sat},t} | \mathrm{I}_{1:t}) \approx \sum_{i=1}^{N_p} w_t^i \; \delta(R_{\text{sat},t} - R_{\text{sat},t}^i)$$

- Update weights w_t^i by evaluating the likelihood $p(\mathrm{I}_t | R_{\text{sat},t}^i)$ at the predicted image pixel value I_{sat}
- Likelihood: kernel density estimate $\hat{f}$ of the PDF of propagated pixel intensities $\mathcal{I}_{\text{sat}} = \{\mathrm{I}_{\text{sat}}^j\}_{j=1}^{M \times N}$



Likelihood for the proposed particle filter

- At each time instant t: obtain an estimate of the state of the system by

$$\hat{R}_{\text{sat},t}^{\text{MMSE}} \approx \sum_{i=1}^{N_p} w_t^i \; R_{\text{sat},t}^i$$

Results using Real Measurements

Measurement Setup & Simulation Parameters

- 78 real measurement videos of 20 s duration captured at 30 frames per second were provided by Roche Diagnostics GmbH, Mannheim, Germany
- 16 different known underlying glucose concentrations (ranging from 30 mg/dl to 550 mg/dl) are investigated
- Decay rate τ in the model is estimated from the test set
- 2 fixed, overlapping image regions are chosen as particle filter inputs
- Particle filter uses $N_p = 500$ particles per image region

Results

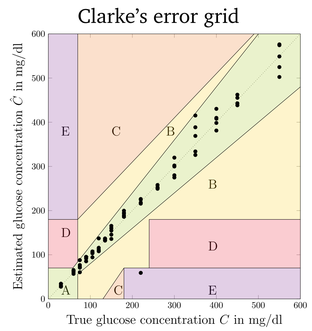
- Average testing time is reduced by approximately 50% - even up to 65% for single measurements
- (Clinical) accuracy and precision of results are comparable to the state-of-the-art method
- The average computational costs per frame are reduced by approximately 60%

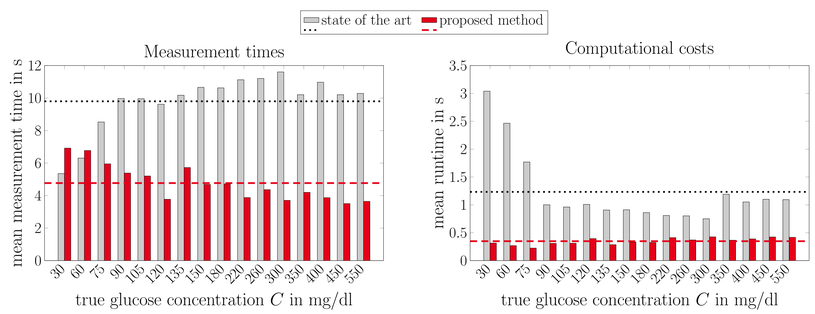
Variation coefficient:

	Ref	New
$C \leq 100$	0.37	1.06
$C > 100$	0.01	0.02
Overall	**0.10**	**0.28**

gMAD in mg/dl:

	Ref	New
$C \leq 75$	11.41	7.56
$C > 75$	8.03	11.55
Overall	**8.64**	**10.83**





Conclusions

- Proposed method can drastically decrease the measurement time of blood sugar tests
- Results obtained using real measurements are comparable to the state-of-the-art method
- Computational costs can be mitigated by omitting statistical segmentation procedures