

Thesis Title: A Physics-Informed Image Analytics Approach to Colorimetric Sensing in Paper-Based Microfluidics

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ABSTRACT

Paper Microfluidic Point of Care (POC) Colorimetric Analyte Detection works hold the potential of democratizing the primary healthcare facilities for the mass irrespective of the socio-economic structure. Generally, a low cost imaging system for capturing the responses of the colorimetric spots and further analysing and digitally processing the signal for a better interpretation is the most popularly used detection system in the POC colorimetric devices. Somehow, the inherent issues related to the overall bio-chemical and fluidic systems and the generic limitations of the camera systems for the use as a colorimeter affect the overall detection performance of the device highly. While, the errors arising from these two diverse systems have completely different influences on the overall device performance, still the detection as well as mitigation of the errors highly depends on the analysis and interpretation of the captured digital color images. Furthermore, the imaging systems or more broadly the Optical Detection Systems (ODS) consist of multiple sub-systems like the light source, camera system and the 3D imaging box that have either joint or individual influences on the overall detection performance. To address all of these issues in the overall quantification performance and to provide some fruitful solutions to these issues without any increase of device complexity and cost budget, this thesis work has mainly provided a generic framework for improving the quantification performance for any colorimetric analyte detection work using the Paper Microfluidic sensors.

Based on the prior knowledge of the existence of multiple sources of errors, this thesis work has mainly focused on providing generalizability, interpretability and incorporation of the specific domain knowledge within the simple Image Analytics and Machine Learning frameworks for the Paper Microfluidic Colorimetric Analysis. While the prior knowledge about the source of uncertainties from the fluidic and bio-chemical systems like the issue of non-uniform color generation have been exactly addressed within the quantification framework, the effect of the very complex surface characteristics of the Filter Paper materials has also been included within the color signal representation and attribute discovery frameworks. In contrast to the state of the art quantification approaches of the Image Analytics based POC Colorimetric devices; this thesis work has relied on characterizing the errors and signals originating from different sub-systems of the ODS utilizing the Physics as well as specific domain information. In this regard, how the Physics and domain information can be amalgamated with the specific Image Analytics and Machine Learning frameworks has become the major exploratory work of this thesis.

This thesis work relies highly on the state of the light reflection models or the generic color image formation models that provide some powerful insights of the overall ODS and its

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different constituents. In fact, the major challenges of translating the physical information into the algorithmic works of the Image Analytics and Machine Learning have been diluted mostly using the numerical and analytical studies from different light reflection models like the Dichromatic Reflection Model (DRM). Apart from the algorithmic developments, the major interpretability of the errors and the color signal of interest for any conventional Paper Microfluidic Colorimetric setups for a low cost imaging system must be treated as the pivot behind improving the generalizability of the predictive system remarkably.

This thesis work has identified that the overlook of two separate works of the Digital Image and Signal Processing domains by the Paper Microfluidic Colorimetric POC device development communities; signal estimation and signal quality enhancement are major factors behind declaring the present POC Colorimetric devices as highly 'inaccurate'. Furthermore, both of these works can actually be integrated properly with the Physics and domain information. While, the different factors of the ODS like the light source parameters, positions of the light and camera sources with respect to the Region of Interest (ROI) or in general the conventional geometric factors of the imaging systems and different camera parameters like the Exposure or White Balance parameters control the image and color signal quality, due to the presence of multiple source of errors and uncertainties within the color image generation framework, dedicated colorimetric signal estimation works are of paramount importance. Exactly, from these two realizations, this thesis work has utilized the exact understanding of the role of different constituents of the ODS on the color signal quality assessment and estimation of the colorimetric signal as a characterization work. In fact, not only the characterization of different constituents of the ODS, this thesis work has also proposed the characterization works of the complex Filter Paper Materials with the changes in the colorant strengths. Furthermore, the analytical as well as numerical works from the Physical models like the DRM and the above mentioned characterization works become the pivot behind representing the signal in such a way that robust signal estimation becomes a simpler task. Apart from different kind of image representations and their suitability in handling multiple estimation related issues, this thesis work has also proposed generic algorithmic development works relevant for Paper Microfluidic Colorimetry.

This thesis work addresses the major loopholes within the state of the art Paper Microfluidic Colorimetric Quantification techniques and proposes a novel Physics-informed Image Analytics framework that aims to solve multiple well-known issues in the conventional POC devices. From a Machine Learning outlook, it emphasises more on the generalizability and interpretability and hence Physics and domain knowledge have emerged as a spontaneous source of information for devising a novel framework that is able to improve the device performance remarkably without increasing the complexity of the device and the cost budget. The incorporation of further physical details that have not been yet addressed within the thesis work and translating this into exact algorithmic works of Image Analytics and ML have been considered as the major future works of this thesis. Specifically, the exact understanding of the complex interaction among the light, camera and material has been considered as the game changer for the objective of this thesis work.

Keywords: Paper Microfluidics, Colorimetric Detection, Analyte Detection, Computer Vision for Colorimetric Analysis, Color Image Representation, Physics-informed Machine Learning, Light Reflection Models.