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Embedded multi-spectral image processing for real-time medical application☆

Chao Li*, Souleymane Balla-Arabé, Fan Yang

LE2I CNRS 6306 Laboratory, University of Burgundy, France

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ABSTRACT

The newly introduced Kubelka–Munk Genetic Algorithm (KMGA) is a promising technique for the assessment of skin lesions from multi-spectral images. Using five skin parameter maps such as concentration or epidermis/dermis thickness, this method combines the Kubelka–Munk Light–Tissue interaction model and Genetic Algorithm optimization process to produce a quantitative measure of cutaneous tissue. Up to the present, variant improved KMGA implementations have been successfully realized using the recent parallel computing techniques. However, all these achievements are based on the multi-core CPUs. This results in a quite high cost and low practicability for the hardware equipment of the clinical system. Fortunately, Embedded Systems (ES) applications have made great progress in recent years, and many highly effective image processing devices, such as DSPs (Digital Signal Processor) and FPGAs (Field Programmable Gate Array), have been made available to engineers at a very convenient price. Nevertheless, today's embedded devices have as well the advantages of high speed, high embedability, low power consumption, more flexibility, etc. Thus, we focus our researches on the embedded KMGA application development. In this paper, we realize the CPU-to-FPGA transplantation of KMGA within a special High-Level Synthesis (HLS) SW/HW Co-design framework. Moreover, several optimizations are made on the algorithm and source code to improve the performances of the final implementation. Compared with CPUs, intensive experiments demonstrate that the proposed approaches can effectively improve the performances of KMGA method both in terms of efficiency and accuracy.

1. Introduction

Medical imaging is one of the major research subjects in Computer-Aided Diagnosis (CAD). With computer-aided medical imaging, doctors use the computerized analysis results as a "second opinion" to make the final decision. This technique can improve the diagnosis by helping for the diagnostic itself or quantifying the evaluation results, and be used for monitoring the efficiency of a treatment over time as well. For example, Medical ultrasound is widely used for non-destructive diagnosis of internal body structure lesions or guiding the treatment process, while Molecular Imaging is developed to explore the changing of cells and molecular level during the disease process.

Historically, well trained dermatologists analyze the skin color and interpret the clinical pathologies depending on their knowledge and experience, which often results in the mistakes due to the subjective judgment. Recently, in order to make the diagnosis conclusions objective, computer assisted methods for cutaneous lesions assessment increasingly attracts the medical researchers. More precisely, some image processing systems are used to minimize the usages of the naked eyes and quantify the lesions zone's optimal properties.

Using the knowledge of the skin absorption and scattering properties, a novel Light–Tissue Interaction model based multi-spectral skin lesion assessment method, Kubelka–Munk Genetic Algorithm (KMGA), is proposed by Jolivot et al. [1]. This method combines the KM model [2] with Genetic Algorithm (GA) for the optimization process. It can analyze both of the most important light absorbers (blood and melanin) in the skin according to the multi-spectral images which is acquired only by a hand-held multi-spectral camera. However, KMGA is a quite resources costly algorithm. Its central unit for the data processing is the high performance multi-core CPUs in personal computers (see Fig. 3.3 in [3]). This results in a high cost for the hardware equipment and seriously narrows its advantages in terms of portability. Therefore, finding a lighter, cheaper and powerful alternative of CPUs for KMGA becomes a new challenge.

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* Corresponding author. Tel.: +33 658892280.
E-mail address: chao.li.1986@ieee.org, lichao8601@hotmail.com (C. Li).

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Our work focus on the performance improvement of KMGA skin lesion assessment system by using high performance computing technologies. In recent years, Embedded Systems (ES) have made great progress, and many highly effective Field Programmable Gate Array (FPGA) devices have been made available to engineers at a very convenient price. These achievements offer nice opportunities to obtain more performance improvements from a complex design [4–12]. For example, Colodro-Conde et al. [8] propose a FPGA architecture of area-based algorithms for calculating distance in stereoscopic vision systems, Sidiropoulos et al. [9] introduce a novel 3-D FPGA architecture for efficient implementation both of compute-bound and I/O-bound applications and Toledo-Moreo et al. [10] present a hardware architecture for the FPGA-based implementation of 2-D convolution with medium–large kernels. Furthermore, Zuo et al. [13] and Kestur et al. [14] point out that in their designs FPGAs performance much better than CPUs or GPUs in terms of power-efficient, and another comparative study made by González et al. [15] further indicates that the cost of FPGAs is significantly lower than the other computing platforms. Thus, we fix the goal of the work introduced in this paper on the FPGA implementation of KMGA.

Within the conventional development framework, the development languages of FPGA, i.e. VHDL or Verilog, usually have a low abstract level, which allows the hardware configurations in RTL (Register-Transfer Level). Therefore, the complex algorithms are difficult to be specified within such languages. Recently, Cong et al. [16] and Liang et al. [17] introduce a novel High-Level Synthesis (HLS) procedure that can automatically synthesize the specification of algorithm from C like languages into RTL. Nevertheless, its C-to-RTL synthesis process can be configured by using directives for implementation optimizations. We therefore base our work on a HLS based SW/HW Co-design framework.

In this paper, we successfully realize the FPGA implementation of a High-Convergence-Ratio KMGA (HCR-KMGA) skin lesion assessment method improved from the prototype of KMGA. During the development, several optimizations are made in order to improve the performances of the generated RTL implementation, including optical function rewriting, function optimizer improving and memory optimizing. The proposed implementations is evaluated by comparing with its CPU implementations optimized by parallel computing techniques. Intensive experiments demonstrate that our approaches can effectively accelerate the KMGA skin lesion assessment system, while improving its accuracy as well.

The remainder of this paper is organized as follows: Section 2 describes the fundamental principles of the KMGA method and its algorithm-level improvements. Section 3 presents the development process of HCR-KMGA and its hardware level optimizations. Section 4 analyzes the experimental results and evaluates our design's performances. Finally, a conclusion is given in Section 5.

2. Algorithm description

In order to retrieve the different skin physical or biological properties, several skin models have been developed [18–20]. Kubelka–Munk Genetic Algorithm is one of the latest Light–Tissue Interaction skin lesions assessment approaches. It retrieves the interested skin biological properties by inverting the KM model with the GA procedure. Firstly, the reflectance spectrum of the lesions' zone, defined as a set of total reflectance values with different wavelengths, is measured with an acquisition system. Meanwhile, a population composed of numbers of candidate solutions (called individuals) is initialized as the search space of the selection procedure. Each individual carries the information for the selection procedure, including the simulated optical properties (reflectance spectrum), the biological properties and the fitness value. In the KMGA prototype, the reflectance spectrums are performed according to the KM model, while the biological properties are randomly generated within the reasonable bounds. The fitness value refers to the spectrum similarity between the simulated spectrum and the measured spectrum. Then, the population is repeatedly selected through the selection process until a predefined number of iterations. Finally, the best candidate is selected.

KMGA could effectively retrieve the skin parameter maps via a selection process, however, this task is running-costly [18] even for a powerful processor. Thus, we propose a novel High-Convergence-Rate KMGA (HCR-KMGA) method in this section. Comparing with its prototype implemented by Jolivot et al. [3], our implementation can make more acceleration gains according to the following three approaches:

- HCR-KMGA re-specifies the KM function in order to reduce the redundant operations down to minimum.
- A Predictive Function Optimization Algorithm (PFOA) is designed to accelerate the convergence of function optimization process.
- HCR-KMGA's individuals' parameters are optimized depending on the data dependency, some unnecessary data are removed in order to save memory space.
- Multiple different termination conditions are performed in HCR-KMGA in order to avoid the redundant iterations.

2.1. Kubelka–Munk model

KMGA-based skin lesion assessment system treats the cutaneous system as an epidermis and dermis based 2-layers KM model with five principal parameters that affect the light's reflectance and transmittance: melanin concentration, epidermis thickness, blood concentration, blood oxygen saturation and dermis thickness. This algorithm consists mainly in population initialization, generation, and evolution. Experimental results show that the population initialization and generation takes up to 96% of the total execution time, population evolution takes 3% and other operations only 1%. The optical model of KM is the key technique used during the time consuming process of population initialization and generation. Thus, we use a reduced KM function previously developed for running accelerating [21].

In KM function, the total light reflectance R_{tot} and transmittance T_{tot} are expressed as:

$$R_{tot} = R_{1,2} = R_1 + \frac{T_1^2 R_2}{1 - R_1 R_2} \tag{1}$$

$$T_{tot} = T_{1,2} = \frac{T_1 T_2}{1 - R_1 R_2} \tag{2}$$

The reflectance R_n and transmittance T_n for a single layer n can be expressed as a function of the thickness of the layer d_n, the absorption coefficient $\mu_{a,n}$ and the scattering coefficient $\mu_{s,n}$. In order to simplify the computation, KM function are re-specified as follows:

$$R_n = \frac{\mu_{s.n} \times (E - 1)}{(\mu_{a+s} + K_n) \times E - (\mu_{a+s} - K_n)} \tag{3}$$

$$T_n = \frac{2K_n \epsilon}{(\mu_{a+s} + K_n) \times E - (\mu_{a+s} - K_n)} \tag{4}$$

where

$$\begin{aligned} K_n &= \sqrt{\mu_{a,n}(\mu_{a,n} + 2\mu_{s,n})} \\ \mu_{a+s} &= \mu_{a,n} + \mu_{s,n} \\ E &= \epsilon^2 = e^{2K_n d_n} \end{aligned} \tag{5}$$

The optical absorption and scattering coefficients in the epidermis and dermis layers, $\mu_{a.epidermis}$, $\mu_{a.dermis}$, $\mu_{s.epidermis}$ and $\mu_{s.dermis}$,