Accurate color imaging in embedded computing for volcano hazard monitoring appliances

Reproducción precisa de color en computo embebido para aplicaciones de monitoreo de riesgos del volcán

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PALABRAS CLAVE:

Computacion embebida, monitoreo de riesgos, espacios de color, volcan popocatepetl, precision perceptual

RESUMEN

Los dispositivos y computadoras embebidas con bajo consumo de energía se han vuelto una alternativa de bajo costo para aplicaciones de monitoreo de riesgos naturales, donde los datos son recolectados en tiempo real y son guardados, o transmitidos para procesamiento, como en el caso de volcán Popocatepetl. La precisión en colores sigue siendo un problema por la velocidad de procesamiento limitada en equipo embebido, tal como esta ilustrado en los experimentos de este trabajo, donde los espacios de color clásicos y precisos en forma perceptual, típicamente usados en equipos de escritorio, no son aptos para tales tareas. Sin embargo, las alternativas recientemente introducidas muestran potencial, proveyendo balance entre desempeño en tiempo real y precisión. Resultados experimentales con pruebas de desempeño corriendo en aparatos embebidos están descritos en este trabajo, proveyendo fundamentos fuertes para las alternativas propuestas.

KEYWORDS:

Embedded computing, hazard monitoring, color spaces, volcano popocatepetl, perceptual accuracy

ABSTRACT

Embedded single-board computers with extremely low power consumption have become a cost-saving alternative for natural hazard monitoring appliances, where the data is collected in real-time and stored or relayed for processing, such as in case of volcano Popocatepetl. Color accuracy still remains a problem due to limited computational speed of embedded hardware as illustrated by experiments in this work, where classical perceptually accurate color spaces typically used in desktop computing appear to be unsuitable. However, recently introduced alternatives provide a promising balance between real-time performance and accuracy. Experimental results with performance benchmarks running on actual embedded hardware are described in this work, providing a strong foundation for the proposed alternatives.

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1 INTRODUCCIÓN

Mobile computing has been the center of attention during last few years because of an increasing number of smartphones and tablets, which already play an indispensable role in today's life. If personal desktop computers were driving technological innovation just a couple of years ago, now they are being replaced by portable and wearable lightweight devices. Few years back, when first versions of Raspberry PI, appeared on the market (which was already dominated by Arduino controllers at that time), they became widely popular and now many such micro-computers exist, including BeagleBone, Intel Galileo, Nvidia Jetson, OlinuXino, Seco UDOO, VIA Embedded and many others, commonly referred to as single-board computers. These tiny devices, although being unique in one way or another, share some common attributes such as low weight, small dimensions, very low power consumption and affordable cost, making them ideal candidates for self-sufficient, autonomous, data gathering and monitoring stations.

One such station can use monitoring equipment composed of single-board computer powered by rechargeable Lithium-Polymer batteries and simple low-wattage solar cell, with sensors providing real-time data on current temperature, atmospheric pressure, variations in electromagnetic fields, gravitation changes, trace amounts of ionizing radiation, infrared and visual information, with the purpose of hazard monitoring and prediction of potential risky outcomes.

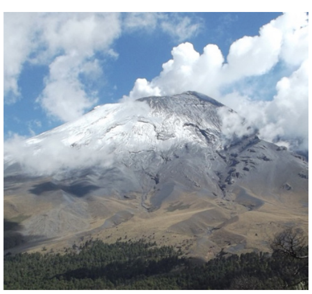

Figure 1. Volcano Popocatepetl when viewed from one of the stations.

Specifically, in one such case, an active volcano Popocatepetl (see Figure 1) is being constantly monitored by multiple agencies due to increased recent emissions of dust, eruptive explosions, and radioactive emissions, affecting several nearby cities with very high population density [1-2]. In addition to any other type of monitoring that is achieved on the volcano [3], visual analysis of real-time imagery is able to capture subtle changes of the overall situation over long distances.

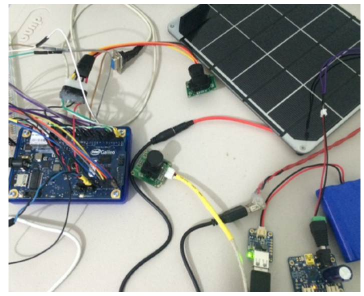

Figure 2. Parts of experimental data capture prototype before final assembly showing Galileo board, regular and IR camera, solar cell, battery and power units.

The actual prototype (see Figure 2) involves an autonomous self-powered unit that uses single-board computer such as Intel Galileo or Raspberry PI, or a more powerful but energy consuming variants such as Seco UDOO or VIA EPIA P910 (connected to Arduino Mega ADK), wired with analog and digital sensors, cameras, lithium-polymer battery and solar cell, capturing data to onboard storage and sending it using VHF or UHF transceivers.

The captured images have to be sent to a data relay (which can then send them over Internet) or transmitted directly over cellular network. The problem with this approach is that the majority of captured images have very subtle or insignificant changes in them, especially at night, where only explosions hot enough can be visible (due to infrared sensitivity of the camera). Sending each and every single captured frame results in excessive transmission costs, high battery usage and premature failure of multiple components due to heat cycling and deep battery discharging at night. In addition, it also requires considerable involvement of the personnel to review each and every obtained image to find relevant changes.

The solution taken to above problem is to analyze obtained imagery directly by the embedded system and transmit only those frames that have significant and important changes visible. This provides benefits of not only determining any significant visible changes, but also giving priorities (weights) to certain areas on the image, specifically those closer to the volcano. During normal daylight conditions small changes of hue and greater changes in brightness are the most significant elements when comparing images in sequence. The actual process involves solving a classical color difference problem.

2 REAL-TIME IMAGE PROCESSING

Initial color format, in which the images are received, is defined with RGB color values and can be relied upon as long as camera specification is available with the appropriate color profiles, the process described thoroughly in classical literature [4-5]. Some informal attempts have been made to do the comparison using modified Euclidean distance [6], which was tested earlier in experiments [7], but since RGB values have no implicit information about the actual hue or lightness of the color, they need to be converted into something more meaningful.

Simplest candidate would be either HSV or HSL color space, originally described by A.R. Smith back in 1978 [8], yet being used typically in their most primitive form, for instance, like in CSS web standard [9]. However, these color spaces in their well-established form are inaccurate for digital processing [10].

Several formal alternatives have been proposed by CIE authority, known as CIE XYZ, CIE Lab* and CIE Luv* color spaces [11]. The development of these color spaces had intent to have better perceptual linearity characteristic for individual color values in an attempt to accurately predict MacAdam ellipses [12] (regions on CIE chromaticity diagram, where colors are indistinguishable one from another as perceived by an average human eye). However, perceptual accuracy of these color spaces have been put on question [13] and did not produce convincing results in earlier experiments [14]. Measuring color difference using these color spaces usually involves some adjustments and fine-tuning of the distance equation to achieve reliable accuracy [15-17].

Other potential candidates include Guth's ATD95 color space [18] and DIN99-derived color spaces [19-20], which were involved in earlier experiments on mobile computing [7], although producing better visual results, were too complex and cumbersome for practical use on mobiles. Most recent refinements include CIECAM-based color spaces, that take chromatic adaptation of human eye into account [21-22].

Some improvements over HSV and HSL were also proposed in an attempt to improve visual accuracy but without significant hit on real-time performance, including HCL color space [23], HSP2 color space [24]. Recently YCHiq and YScH color spaces were proposed [25] and were shown experimentally to outperform classical variants in performance benchmarks on mobiles, while at the same time being easier to use and calculate.

3 EXPERIMENTAL RESULTS

Although data acquisition station can continue doing calculations over relatively long intervals of time (a couple of seconds or more), before sending the data, image capturing, processing and transmitting usually takes most of that time, especially with working with image sizes of 2 MP or more. Therefore, several different single-board computers have been involved in a series of experimental benchmarks while processing a single frame of 2 MP image (1600 by 1200 pixels) by reading the pixels, converting them to the appropriate color space and then calculating color differences, saving results onto destination color difference array.

Figure 3. Intel Galileo, Raspberry PI and VIA EPIA boards used in experiments (along with some other miscellaneous equipment).

The experiments were made on the hardware that was readily available and includes Intel Galileo (gen1), Raspberry PI (model B), VIA EPIA P910 and Utilite Pro. The tests were also executed on desktop computer and a couple of Android-based phones and tablets to allow a broad range of comparison. The test code was compiled to native i386, x86_x64 or arm-hf binary with full compiler optimizations enabled. The results are shown on tables 1 and 2 below.

	RGB	HSL	HCL	Lab
Desktop Board	0.02	0.10	0.20	1.79
LG/Google Nexus 5	0.12	0.53	1.30	7.71
VIA EPIA P910	0.20	1.00	1.61	9.97
Samsung Galaxy S4	0.16	0.71	1.69	9.54
Samsung Galaxy S2	0.23	1.05	2.57	12.29
Utilite Pro	0.30	1.27	3.03	13.64
Raspberry PI	0.80	3.36	7.62	36.44
Intel Galileo	1.69	8.54	19.62	92.03

Table 1. Benchmark results when processing pixels in RGB, HSL, HCL and CIE Lab* color spaces.
(Table values are given in seconds.)

	Luv	ATD	DIN	YSH
Desktop Board	1.43	1.86	2.11	0.18
LG/Google Nexus 5	5.68	7.36	8.49	0.87
VIA EPIA P910	8.12	10.5	11.26	1.60
Samsung Galaxy S4	6.92	8.75	10.23	1.08
Samsung Galaxy S2	10.1	13.0	14.09	1.72
Utilite Pro	11.5	14.7	15.89	2.09
Raspberry PI	30.2	37.5	42.30	5.11
Intel Galileo	74.8	92.9	103.3	9.04

Table 2. Benchmark results when processing pixels in CIE Luv*, ATD95, DIN99 and YScH color spaces. (Table values are given in seconds.)

The equipment, where actual benchmarking experiments have been performed include desktop board with Intel Core i7 4790K processor and DDR3 2166 Ghz RAM, LG / Google Nexus 5 smartphone, VIA EPIA P910 board, Samsung Galaxy S4, Utilite Pro (quad-core version), Raspberry PI (model B) and Intel Galileo (gen1). On desktop and EPIA boards, application was compiled for x64/SSE3, on Raspberry PI and Utilite Pro for ARMv6 / VFPv2, on Intel Galileo for i386/X87 and on Nexus 5, Samsung Galaxy S2 and S4 smartphones for ARMv6 / VFPv3 targets.

Although Android-based smartphones, as can be seen from above tables, vastly outperform single-board computers, they are much more expensive and due to limited customization and power requirements are unsuitable for the data acquisition in question. Another important observation is that in most cases, several seconds are required to process a pair of 2 MP captured images, although in some cases it can be up to a minute or more. An interactive 3D graph that shows each of the values to scale in comparison with others is shown below.

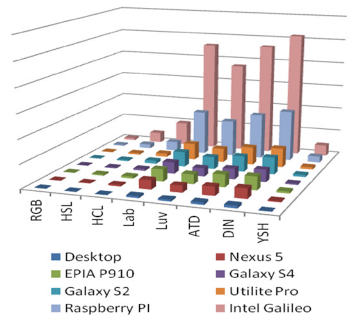

Figure 4. Time proportions of different color comparison techniques and hardware equipment in relation to others.

The results shown on Figure 4 in addition to previous data tables, indicate that attempting to measure colors in any color space that requires conversion between one or more CIE units such as CIE XYZ and CIE Lab*, is too expensive for embedded hardware as it requires significant computation effort. Calculating the differences in terms of hue and brightness can realistically be performed in HSL, HCL and YScH color spaces. For the actual experimental prototype, YScH color space was chosen because in earlier experiments it has demonstrated to be more accurate than RGB and HSL, in addition to modeling "brightness" of colors more accurately.

4 CONCLUSIONS AND FUTURE WORK

In recent years, many varieties of single-board computers have appeared, each with its own set of benefits but sharing common characteristics such as low power consumption, small size and affordable costs. These devices make ideal candidates for self-sufficient autonomous data acquisition stations that can be used for hazard monitoring of volcano Popocatepetl. Among many possible sensors that can be connected to the embedded device, images captured form camera provide important source of information of the overall situation on the volcano. However, the transmission of high resolution images is costly, so images need to be processed and only relevant ones are sent. Images are compared in sequence by calculating difference between each of the pixels, while working in one of color spaces that provide sufficient color accuracy.

The majority of classical color spaces, although can be processed by embedded system, take too long when working with high quality images of 2 MP and higher resolutions. Experiments shown in this work indicate that YScH color space proposed in earlier works remains a solid candidate for image processing and it was the one to be chosen for the final prototype. Also, it can be seen from the experiments that single-board computers lagging behind in performance to typical Android-based phones, but that comes at the price of being affordable and configurable.

There is still room for improvement, however, as the current image processing technique uses floating-point calculations, whereas it can be further optimized to use integer calculations, by using fixed-point values. This may increase performance on relatively limited embedded processors such as Intel Quark used in Galileo board. These experiments are planned to be made in the nearest future.

Other promising directions would be making dedicated hardware, or, when available, taking advantage of embedded GPUs to do the appropriate conversion and image processing, which will both free main CPU to do other work and improve real-time performance.

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