CLOSED-LOOP VIDEO PROCESSING FOR OBJECTIVE QUALITY OPTIMIZATION

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ABSTRACT

Based on the use of no-reference quality metrics, video chain optimization practices, and video processing requirements, in this paper we formulate and discuss the principles of closed-loop video processing for picture quality optimization. Most no-reference metrics are based on a set of submetrics related to key quality factors, i.e. the minimum set of desirable and undesirable picture attributes. The video processing chain of consumer systems usually integrates a dozen or more algorithms which are designed mainly independent of each other. The video chain is mostly an open loop system, where the best operating point is chosen experimentally. In order to turn a video processing chain or pipeline into a closed-loop video processing system, we discuss the quality requirements of consumer video systems, the type of no-reference metrics suitable for a control system, and the control principles which will allow implementation of future generations of closed-loop video processing systems.

1. INTRODUCTION

The video processing chain of consumer systems includes a dozen or more components (e.g. MPEG artifact detection-correction, noise reduction, motion estimation, sharpness enhancement, deinterlacing, scaling, and color/contrast enhancement). Typically, algorithms for each module are designed separately; some may be integrated into clusters, and finally put together in the video processing chain.

The objective of a video processing chain is to deliver, for any input, the best perceived quality to the end user. In practice, this is mainly an open-loop control system, where the best operating point is chosen experimentally and then left untouched or just slightly customized. Some automatic control subsystems do exist for hardware involving the physical display parameters (e.g. brightness/contrast adaptation to local lighting), but the real time monitoring and control of the overall video chain still remains a challenge.

The main reason for this situation is that practical and effective quality metrics are presently under development; and in order to be widely accepted they need standardization [10]. Work by the Video Quality Experts Group (VQEG) has started to address this issue after some years of work aimed at quality metrics for the broadcast industry (mainly dealing with signal fidelity) [9]. Intrinsic quality which is affected by picture enhancement (e.g. resolution, sharpness), corrective processing (e.g. artifact reduction), and conditioning (e.g. format conversion) is as important as, or even more critical than, fidelity and cannot be assessed using error-based metrics.

In this paper, we will discuss the quality requirements of consumer video systems, the type of quality metrics involved, and the control principles that will allow implementation of future generation closed-loop video processing systems.

Perceived quality (related to fidelity and intrinsic quality) is influenced by digital video processing (which may modify pixel-depth, picture size, resolution, and introduce compression/transmission artifacts, etc) and the different display types (e.g. LCD, DLP, CRT) and sizes used. In previous work we have proposed that a small set of key quality factors can be identified and incorporated into a metric that can account for overall quality and correlates well with subjective scores [6].

Different control systems are possible, depending on the performance and components of the overall quality metric. Although the best metric is not yet available, the optimum set of quality factors, and the model for global and local quality. However, we can already envision a standardized quality metric that works in no-reference and reduced-reference modes, accounts for the key quality features, and allows local and global control in a closed-loop control system.

2. QUALITY REQUIREMENTS

In this section, we discuss the consumer video requirements that must be addressed by a quality metric, and the properties that will make it usable as a real time control signal.

The first requirement is the ability to predict perceptual ratings obtained in a reliable subjective test [7]. This means that based on subjective testing data (obtained on a representative sample of the consumer video population), the metric must have been trained to emulate such results within the range of interest, and with a precision equal to or better than the human visual system just noticeable difference or JND [2].

The second requirement covers the usability of the metric as a control signal, which includes:

Computational complexity must allow real-time implementation.

Quality must be a function of the values of a small set of key factors (e.g. sharpness, contrast, noise, artifact level, resolution/size).

Any key factor can be measured independently with a sub-metric, or with the overall metric if all other factors remain constant.
The key factor values at the input can be included so that quality can be measured as a function of the input and the change in key factors (thus accounting for fidelity and intrinsic quality).
The above requirements are necessary so that specific effects of consumer video processing on key factors such as resolution enhancement, sharpness enhancement, and scaling among others can be taken into account.
Another requirement that is likely to emerge in the long term is to develop a notion of global and local quality, e.g. scene vs. object/region, and a model compatible with both. This is important given that video processing is not just a single filter applied with equal strength to the entire image, but selective processing that deals with specific pixels in regions and objects that affect local and global characteristics. Figure 1 summarizes the concepts and requirements associated with the control metric.

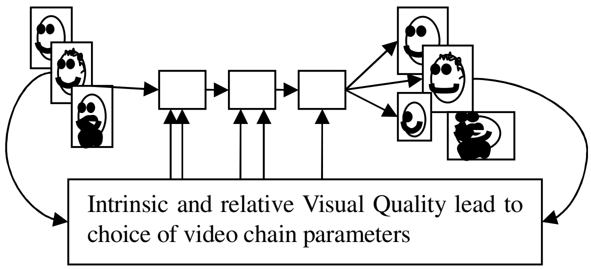

Figure 1. Generic video processing control system.

3. METRIC TYPES

In addition to working in no-reference and reduced reference modes, we address other issues which may simplify working with different types of metrics. First, we can discuss black box vs. clear box metrics. A simple black box may allow measuring quality, and sending the output to a control strategy unit which will decide what changes to the control parameters need to be tried in the next cycle. A black box would work if the response time is fast. However, with limited knowledge about what is right or wrong with quality, it is likely that a time consuming strategy is necessary. Multiple monitoring points (not just one at the output) could be used in order to increase the knowledge available to the controller.
The clear box approach, which would provide not only the overall quality measure but also the measures of the key quality factors, is more powerful but it is inherently more complex.
A clear box metric would allow using domain knowledge to build an effective controller (e.g. identify key factors which may be lacking and modify parameters of units which specifically influence those factors).
The control strategy module may receive a single metric or a set of sub-metrics. It can also receive the metric values from a measurement at the input. With access to the metric values at the input, the control strategy can make decisions using concepts such as the potential for enhancement of the quality level present at the input. It is possible that the system would not spend resources enhancing pictures that are beyond repair.

4. CURRENT APPROACH TO QUALITY OPTIMIZATION

Consumer video systems incorporate multiple processing modules, which interact together to create the desired output picture. Generally, video algorithms are developed and evaluated independently, and put together based on knowledge about their working principles and the expected interactions.
Obviously, the final quality depends on the settings and interactions of the constituent algorithms. These interactions depend on the order in which these modules are applied, as well as on the settings of each algorithm's programmable parameters. Whereas the development of individual video processing algorithms (modules) involves a lot of analysis and simulation, the development of larger chains often involves a more ad-hoc approach. However, a thorough analysis of the inter-algorithm interaction is required in order to find the optimal system architecture and the best tuning of each individual module.
Contemporary video processing system design is a challenging optimization problem. Overall image quality depends on the nonlinear interactions between multiple design parameters: variable settings for each module (or algorithm), the amount of data transferred in the video processing chain, as well as the order of the cascading modules. Unfortunately, no systematic techniques are currently available to configure the video chain without a lengthy trial and error process.

Proposals for rapid and reliable optimization methods of video processing systems based on search methods (e.g., genetic algorithm coupled with local search heuristics) have been examined where video system configuration is evolved toward the best image quality, driven by an objective video quality metric [3]. Such optimization methods rely on global quality assessment methods (a quality metric), that compiles the overall subjective preference into a quantifiable figure [1].

5. A NEW APPROACH: VIDEO PROCESSING CONTROL SYSTEM

The quality at the output of the video chain depends on the input quality and the processing that takes place along the video chain. An automated control system is the best way to make sure the output quality stays at the optimum value.

In order to automate the control process, we can apply three main schemes by themselves or in a combined fashion:

1. Use a reduced reference approach to compare input an output quality and based on the concept of quality ceiling (i.e., realistically, how much can we improve over the input quality) use an appropriate control strategy to maximize quality by setting the control parameters.
2. Use an overall, no-reference quality metric to measure quality, and use any optimum control strategy (e.g. maximum gradient search) to introduce incremental changes in the control parameters so that the system will converge to the optimum quality.
3. Use the sub-metrics that make up the overall quality metric to identify the quality profile (i.e., combination of sub-metric values). Then, choose specific control parameter(s) that will effect the desired changes to improve quality for that specific profile.

Since reduced reference case is a special case of the no-reference, we will only discuss the no-reference cases in some detail.

In the overall no-reference quality metric case, the objective is to improve quality gradually without introducing disturbing visual effects. Let us consider the time response shown in Figure 2.

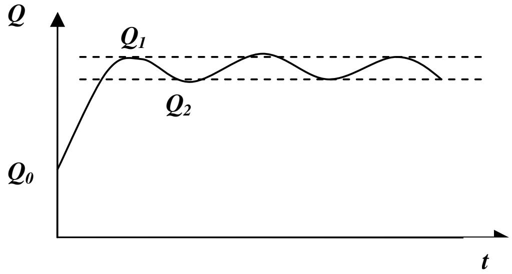

Figure 2. Convergence of the quality control process.

Outputs for quality points Q0, Q1, and Q2 are shown in Figure 3 (Q0 corresponds to sequence football coded at 2.5MBs). In this case, the sharpness control parameter (using an LTI-CTI algorithm) is increased gradually until the quality starts dropping (e.g. from Q0 to Q1 there is a quality improvement, but from Q1 to Q2 the quality drops a bit due to over-enhancement).

With sub-JND control, the size of the incremental steps will be finer than that shown in the example and will not introduce visual artifacts in the final state.

The disadvantage of this approach is that it may be inefficient or slow, as it does not know which of many parameters to modify first, and it does not guarantee global convergence.

Figure 3. Outputs for different video chain settings.

In the case of no-reference sub-metrics, we use the sub-metrics profile to make a more informed decision about settings for control parameters. Figure 4 shows quality profiles (for three sub-metrics) for the three quality cases in Figure 3. One can see that due to the blockiness level, one can improve sharpness and contrast but only to the point where blockiness itself does not become more annoying.

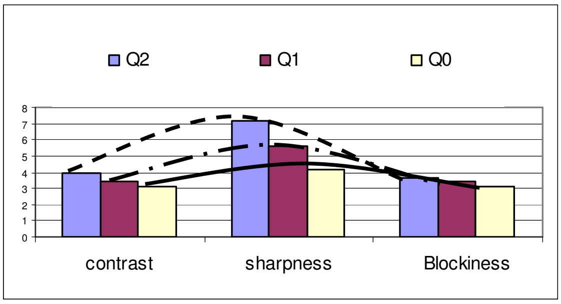

Figure 4. Quality profiles for enhancement options.

This means that sharpness, above other parameters, can be improved to match the best possible profile, and the setting is good as long as the profile does not change drastically. We have used this method before, i.e. use of case based reasoning, for the optimization of medical images [4].

Figure 5 shows the generalized block diagram of the control process in which an overall quality metric or a set of sub-metrics are used to drive the control parameters leading to an optimum quality output. The diagram also shows the possibility of locally controlling modules with specific sub-metrics as local objective functions.

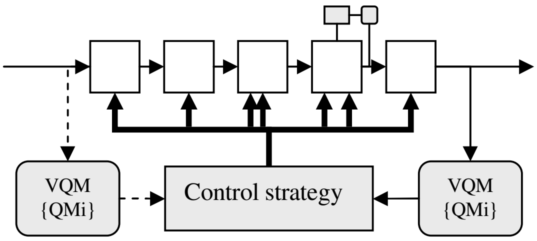

Figure 5. Generalized video processing control.

6. DISCUSSION AND PERSPECTIVES

We have proposed new research on video processing control systems to optimize picture quality in real time. We have formulated principles that make a strong case for the pursuit of this area of research and development.

In particular, the progress on no-reference quality metrics and digital video processing systems suggest a necessary technological convergence between consumer video processing and picture quality control.

Although there has been progress on no-reference sub-metrics (e.g. sharpness metric [5]), all sub-metrics will need to be high performance no-reference types. In some cases such as spatial-temporal noise, one may have to work with the best estimates possible, or with metrics for the most tractable cases, e.g. compression noise [8].

The control strategy module is the critical component of the system we propose. The best strategy is to pursue control using an overall metric (or a set of sub-metrics) that meets the requirements to a minimum degree so that the expected performance can be achieved.

The notion of global vs. local quality metrics is necessary for local control. We need to understand the effect of content (and distortions of it) on quality. Furthermore, breaking the overall quality metric down into partial values that correspond to key factors requires the use of compatible units of measurement.

Finally, the impact of the new approach on video system operation and design will need to be demonstrated on the fine grain control around the operating point as well as the overall design and broad range control process.

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