EFFICIENT IMPLEMENTATIONS OF OPERATIONS ON RUNLENGTH-REPRESENTED IMAGES

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ABSTRACT

Performance enhancements which can be obtained from processing images in runlength-represented form are demonstrated. A runlength-based image processing framework, optimised for handling bi-level images, was developed for this. The framework performs efficiently on modern computer architectures, and can apply both raster-based and runlength-based methods. Performance enhancements for runlength-based image processing in terms of memory access and cache utilization are explained.

1. INTRODUCTION

As memory capacity in modern computer architectures continues to increase, it is unlikely that all memory can be accessed efficiently. Therefore, modern computer architectures have higher level caches intended for frequently accessed data, and devices like RAM and disk for infrequently accessed data [4]. The key to high performance applications is to have frequently accessed memory resident in the higher level caches, and in general as few memory accesses as possible.

This paper aims at two goals:

1. Show that processing a number of bi-level images in runlength-represented form is highly memory- and cache-efficient, giving better performance than traditional raster-based processing.
2. Show that it is possible to develop memory efficient server-side solutions for handling many concurrent image processing tasks.

Surprisingly, most well-known APIs today use a *Raster* (a rectangular array of pixels) as the only means of referencing image data. Very often the entire raster is cached prior to any coding. This means that applications having many concurrent requests would require a lot of memory. For instance the Java Image I/O API (*http://java.sun.com/j2se/1.4.2/docs/guide/imageio/*) is based on Raster access.

In this paper, terminology for comparing raster-based and runlength-based methods will be introduced. Test images consisting of a number of bi-level layers (introduced in section 3) will be used. These are large images which are tiled. Runlength-based and raster-based processing are performed for each tile to generate test results such as figure 1. This figure will be clarified further in section 4, but it shows that runlength-based processing gives a statistical distribution for performance well below that of raster-based processing. Also, runlength-based processing scales better with the level of image detail.

The concept of *lazy evaluation* is introduced in section 2 in order to study the low-memory image processing techniques studied in this paper. Measurements in this paper show that performance and memory usage come out best when *runlength-based* lazy evaluation is performed, and underlying image data is *memory mapped*.

A set of framework components were developed in order to demonstrate that goals 1 and 2 can be achieved:

1. An XML vocabulary for expressing how to combine bi-level images. The vocabulary can control features like colours, scaling factors and inclusion order. An example for an image used in this paper can be accessed from *http://www.ifi.uio.no/∼oyvindry/rim/larvik.xml*,
2. a core component for processing input expressed by the XML vocabulary, and generating output in any format. The C++ header file for the library is located at *http://www.ifi.uio.no/∼oyvindry/rim/rim.h*.
3. a multithreaded image server component for handling concurrent image requests.

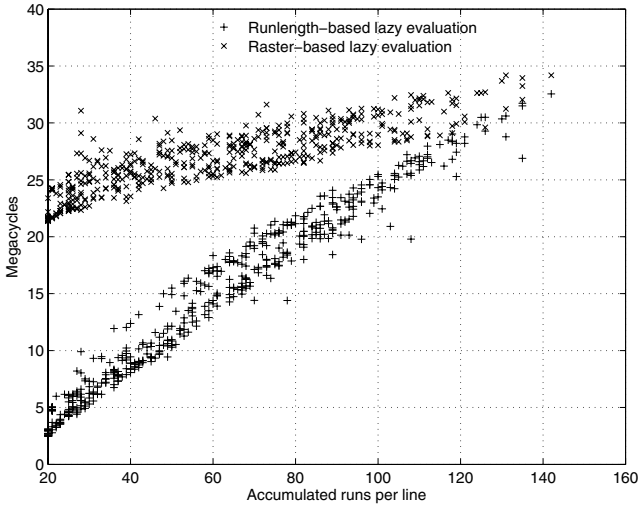


Figure 1: Comparison of times spent with raster-based and runlength-based lazy evaluation. Accumulated runs per line is used as measure for image detail

The image server was developed for hosting image requests for web servers. Figure 2 shows different components in our architecture. The type of GIS-like images assumed in this paper are perfect for thin clients with low bandwidth, like cell-phones and PDA's.

2. LAZY EVALUATION

The TIFF standard [1] expresses that lines in an image are decompressed in raster scan-order, and that only the decompressed previous line is needed to decompress the next line. This means that small amounts of memory is needed in the decompression process, since only one decompressed line is needed kept in memory at a time. The processing strategy of keeping only a few lines decompressed in memory at any time is referred to here as *lazy evaluation*. Using lazy evaluation is very handy especially for large images, since it may be too much to keep an entire image in memory.

The TIFF standard also expresses how to decode runlengths, rather than pixel values in order. This opens up for entirely runlength-based processing, rather than raster-based processing.

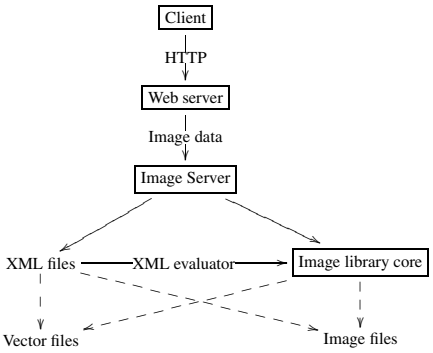


Figure 2: Workflow in the Image Server architecture.

One can thus differ between *raster-based lazy evaluation* and *runlength-based lazy evaluation*. These strategies are compared in this paper. Comparisons with no lazy evaluation at all is also done.

The TIFF standard motivates the following runlength-representation of the part of a bi-level image with upper left coordinates (x,y) and lower right coordinates $(x+wdt, y+lth)$:

- Each line is represented as a strictly increasing sequence of numbers. The numbers are the points where background/foreground changes occur, measured relative to the left side (x) of the image.
- A background/foreground change at wdt is added as a terminator for the runlength representation.

To elaborate, if $x = 0$, $wdt = 100$ and the pixels between 20 and 80 is foreground with the rest being background, runlength-representation of the line would be $\{20, 80, 100\}$. It is seen that only 3 values are needed to represent 100 pixels in this case, making the runlength representation superior in cases with few foreground/background changes.

This paper is primarily interested in images comprising of a limited number of bi-level layers. With raster-based lazy evaluation, operations are performed on raster scanlines, and merging layers is simply a copy operation into a raster. With runlength-based lazy evaluation, this is different: Runlength-represented lines need to be merged, and in this case this is not a simple copy operation. Layer merge needs to be done by traversing many runlength-represented lines in parallel. This presents an additional algorithm step, which is called the *layer merge algorithm*. This algorithm takes an ordered series of runlength-represented input lines, and produces a merged runlength-represented output line. Much time is spent in this algorithm if many images are combined, so it must be subject to much optimisation.

3. PERFORMANCE ISSUES FOR LAZY EVALUATION

The image processing library we use contains implementations of several image standards from scratch. Implementation from scratch had to be done in order to optimise for lazy evaluation. It would have been nice to use image format plugins from other parties, but this is impossible as long as most image processing libraries are entirely raster-based. The image processing library was a big task to develop, it contains about 80000 lines of code. C++ was used as programming language due to high performance demands. Performing lazy evaluation on runlength-represented images produces a string of efficiency issues. Particularly two issues will be of concern:

A runlength-representation may work well only up to a certain level of image detail. With much detail in the image comes a very time-consuming layer merge procedure. The term used to quantify image detail in this paper is *accumulated runs per line*. This is measured by calculating the total number of runs (background AND foreground) for all layers, adding them, and finally taking a line average. It is not taken into account that runs from one layer shadow for runs in other layers. Consequently, accumulated runs is not the same as the actual number of runs in the layered image, it is somewhat higher. This is not a problem for our purposes, since accumulated runs per line still gives a good indication of image detail. Intuitively, a raster-based representation would work best at high numbers for accumulated runs per line. Map data normally have low numbers for accumulated runs per line.

There is also a limit to how many layers which could be involved before the layer merge procedure becomes slow.

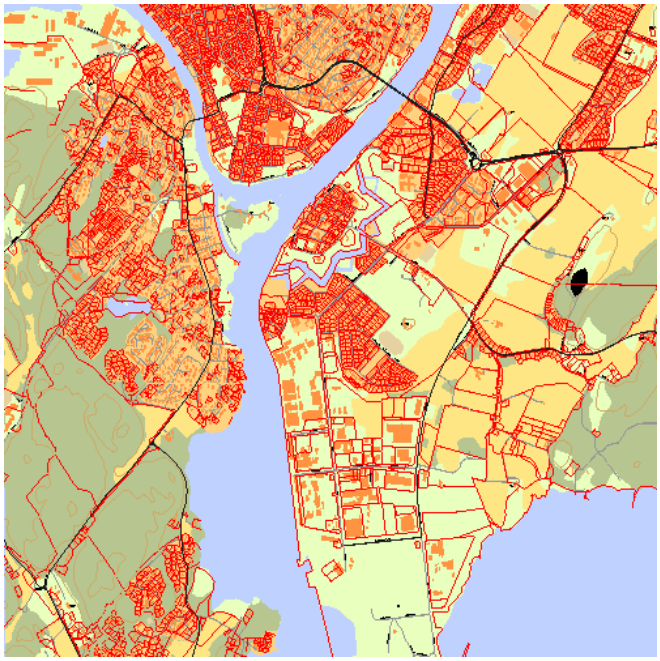


Figure 3: Layered image of Larvik, one of the test images used in this paper

3.1 Measurements in this paper

The Intel VTune Performance Analyser on win32 systems has been used in the process of hunting down performance bottlenecks for software used in this paper. Measurements have been done with *hot disk cache*, i.e. the disk cache is already filled with relevant data prior to measurements to prevent I/O from obscuring measurements. The disk cache is "warmed up" through a previous run of the program. Similarly, measurements performed do not include time used to write data TO disk.

All measurements are done on a set of two test images comprising of a high number of TIFF G4 bi-level layers. They show different parts of Norway, the first one being a Norwegian city map shown in figure 3. This image is 8000×8000 pixels in size. Both have 19 layers, and have tile dimensions of 512×512. In the measurements, the set of included layers is varied. Different plots for performance for different coding strategies are shown in this paper. The terms gigacycles ($= 10^9$ clock cycles) and megacycles ($= 10^6$ clock cycles) are used for performance measurements where applicable (gigacycles for large images requiring much from the CPU, megacycles for smaller images). All figures in this paper measuring performance show numbers for clock cycles for a single request. The performance plots also have an indication for standard deviation for each measurement. The means of the measurements are plotted, while a bar above and below them indicate the standard deviation where applicable. In this paper, measurements were performed 20 times to achieve a "low enough" standard deviation.

This paper limits itself to TIFF input and GIF [5] output, as

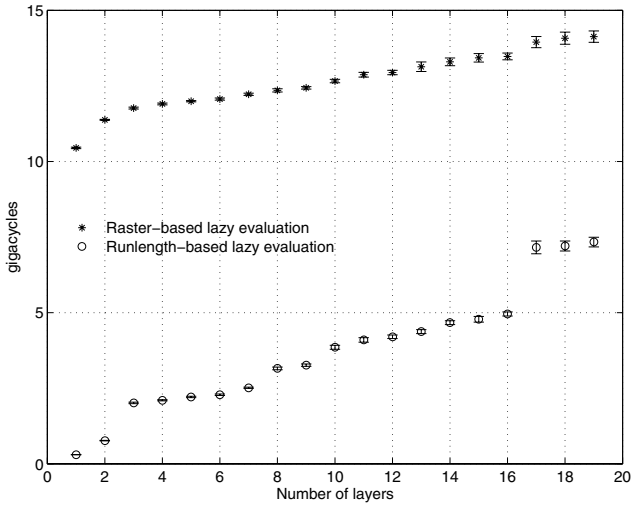


Figure 4: Total transcoding times for different coding strategies

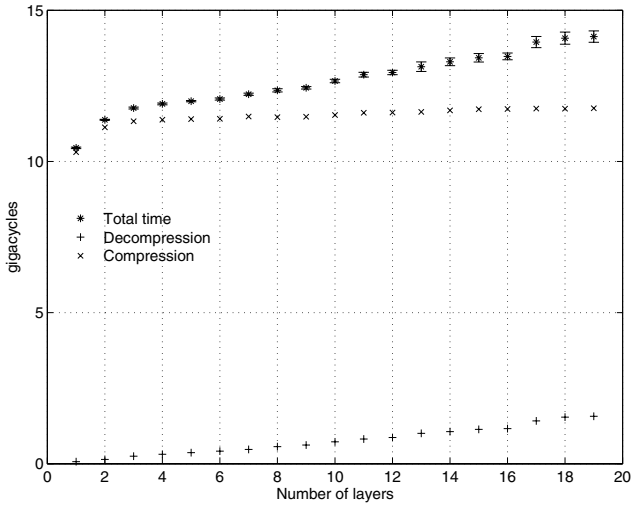


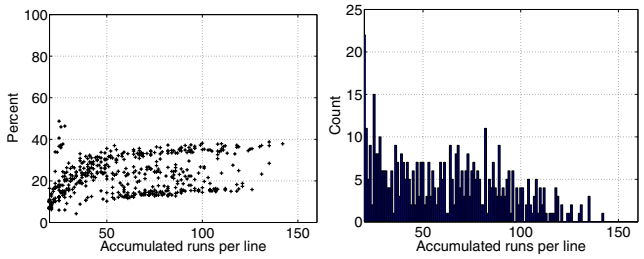
Figure 5: Time used for raster-based lazy evaluation

these formats are easily demonstrated with runlength-based lazy evaluation. The focus in the measurements is the time to transcode the TIFF input layers to a single GIF output image. The TIFF standard ([1], [6] chapter 6.8) has high focus on bi-level images. It is in much use, although newer standards like JBIG2 [2] also exist. The library we use contains support for TIFF G4 with optimizations for lazy evaluation.

GIF can employ ways to utilize runlength-representations. During GIF compression, a hash table is consulted to maintain codes for different combinations of pixels. Runlength-representations can be used to reduce the number of hash table lookups by in addition administering arrays with codes for runs of different lengths for different layers.

4. COMPARING DIFFERENT CODING STRATEGIES

Runlength-based and raster-based lazy evaluation transcoding strategies are first compared. Figure 4 shows total transcoding times for these strategies. Figure 5 shows details for the raster-based strategy. The compression process is here seen to take most time. The entire test images are generated by gradually increasing the number of layers involved. Performance does not increase linearly with number of layers, this is due to the fact that layers have varying complexity. It is clear from the figures that runlength-based lazy evaluation works better at all number of layers, but that the difference from raster-based lazy evaluation is smaller when more layers are involved. It is to expect that, if the number of layers is high enough, raster-based lazy evaluation would work better. There is overhead with the layer merge algorithm. For the images used here, it is seen that this overhead pays off since total transcoding time can be decreased due to runlength optimizations. Raster-based lazy evaluation saves time by dropping layer merge, but spends more time by traversing an entire raster when coding.



(a) Time percentage spent with the layer merge algorithm

(b) Distribution of accumulated runs per line in the test images

Figure 6: Distribution of accumulated runs per line in the test images

An ideal image processing framework should switch to raster-based lazy evaluation at some point. This is reflected in figure 1, where the two test images are used as input, and different tiles are traversed to get various accumulated runs per line. It is seen from the figure that raster-based lazy evaluation performs just as well (or even better) as runlength-based lazy evaluation at high values for accumulated runs per line, but that runlength-based lazy evaluation performs better at lower values for accumulated runs per line. It is also seen that both strategies have a close-to-linear relationship with the level of image detail. The first plot in figure 6 shows the time percentage spent with the layer merge algorithm. Points are scattered, this tells us that the layer merge algorithm is highly input dependent. The second plot in figure 6 shows the distribution of accumulated runs per line in the test images.

The overhead of decoding is small when compared to compression, as is seen from figure 5. This motivates us to work with data in compressed form, which has become increasingly popular due to gains which can be achieved due to fitting smaller data into caches. Database indices are often traversed in compressed form due to little extra decompression overhead.

5. MEMORY MAPPING

Memory mapping([4] chapter 5.10) is used by operating systems to administer much used resources efficiently. The point is to have data paged only upon request, and avoid *dirty pages*. Surprisingly, memory mapping is not well known everywhere. Consequently, many programmers read data directly into RAM. With much data accessed frequently, this leads to extensive paging and swapping.

Memory mapping is very attractive to combine with lazy evaluation: While memory mapping accounts for making data available in RAM in a lazy manner, lazy evaluation accounts for decompressing these data in a lazy manner. When the two are combined, the entire handling of image data will be performed upon request only. To measure the effects of memory mapping, a *working set* analysis is performed when image files are read directly into RAM, and when memory mapping is used.

The *working set* of information $W(t,\tau)$ of a process at time t is defined as the collection of information referenced by the process during the process time interval $(t-\tau,t)$ [3]. The working set was introduced as a characteristic for the operating system to monitor

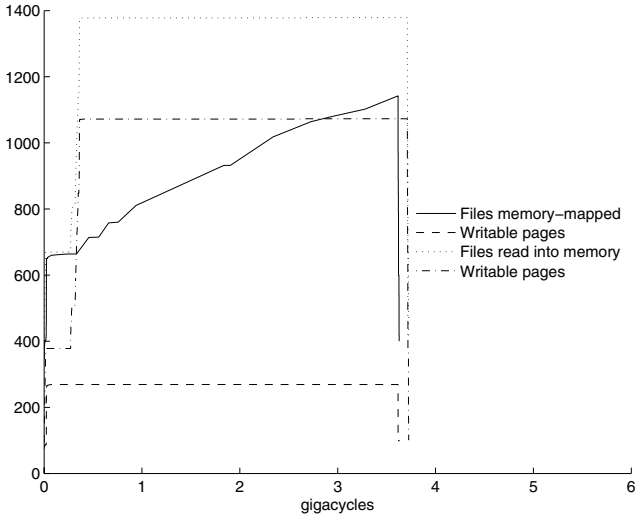


Figure 7: Process working set with and without memory mapping. 8000×8000 image

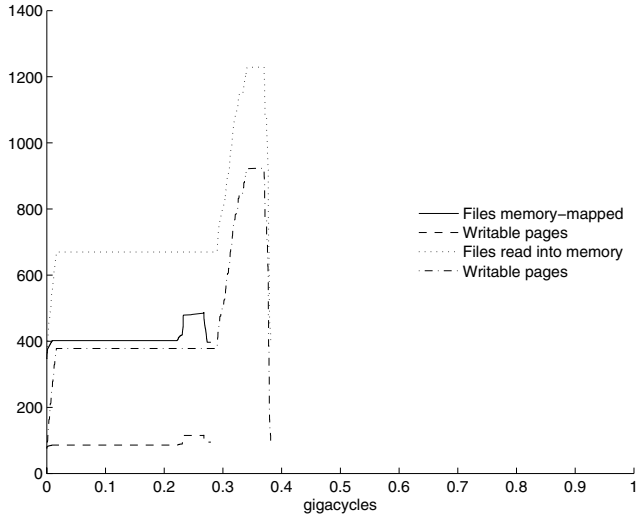


Figure 8: Process working set with and without memory mapping. 512×512 image

and base it's allocation decisions on. These thoughts appeared in the literature almost 40 years ago, and are still valid today. The working set is still, and will continue to be an important performance metric. Information is here in terms of pages.

The working set is measured with the **Psapi** library in the Visual studio 7.0 platform SDK on Windows XP. This library gives information about all the pages in the working set, including whether they are read-only, shared or writable.

Processing a whole image (8000×8000 pixels, figure 7), and one small image (512×512 pixels, figure 8) is performed. The large image serves to ensure that large amounts of data need to be memory mapped. It is noted that these are merely tests. Remarks listed here are not conclusive, but are mere observations related to the measurements.

- The process working set is seen to be highest without memory mapping. This means that performance would suffer most with this strategy when the server experiences high loads, since the working set influences paging behaviour.
- It is seen that the working set increases more gradually when memory mapping is used. This is as expected, since memory mapping gradually makes more and more data physically resident.
- One would expect that the working set would approach the same upper limit with both strategies when a whole image is processed. As is seen, the memory mapping strategy does not reach this high. An explanation for this can be found in the presence of multiple subfiles in the image file. TIFF supports having multiple subfiles embedded in the same file. The technology described in this paper uses multiple subfiles to speed up certain image processing operations. These subfiles are not processed in the measurements, hence they are not mapped into RAM.
- The working set is seen to be smaller when the image is small with the memory mapping strategy.
- The working set is seen to have a high initial number of pages. A plausible explanation for this can be shared pages originating from libraries needed by the running program. In any case, the operating system controls certain resources which may contribute to the working set.
- Pages are classified into read-only and writable pages. The number of writable pages has also been measured explicitly. The memory mapping strategy is superior when it comes to having few writable pages.

It is tempting to have the entire image decompressed in memory in a server-side solution, to avoid the overhead of decompressing data. The problem with this is that it requires a large working set. A small working set is attractive, and reduces swapping, gives better locality of reference, fewer page faults, and more cache hits.

In the next section the image server is used to generate high loads. The image server component maintains memory mappings for all images, so that as few memory mappings as needed are created.

6. IMAGE SERVER EXPERIMENTS

Here it is demonstrated that lazy evaluation is a good strategy when processor demands get higher. No lazy evaluation means that an entire raster is set prior to coding. Many requests drawing into different rasters would then pollute the cache with large amounts of memory.

Figure 9 comes from a test program posting 10 concurrent image server requests for a single tile. It shows memory usage at different points in time, these being instants where memory allocations are performed. Some observations from figure 9 are in place:

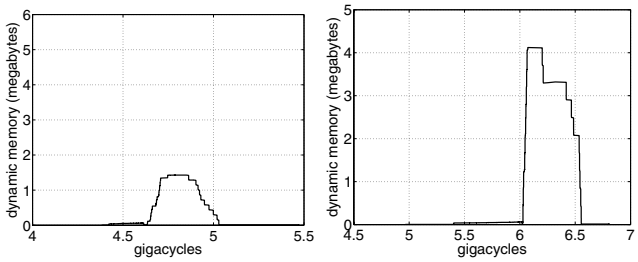
It is seen that less memory is used with lazy evaluation. These numbers can be partially deduced from table 1, where significant memory allocations for different strategies are gone through.

The difference spent in time between lazy evaluation and no lazy evaluation is not as high as is indicated by figure 4. This has to do with the fact that a tile with much detail is tested on. For such tiles, figure 1 shows that runlength-based and raster-based methods do not differ much.

It is reasonable to assume good cache utilization with lazy evaluation due to low memory usage. Measurements which confirm numbers for cache misses are not dealt with in this paper. Increasing the number of concurrent image server requests would be a good way to trigger cache misses.

7. MEMORY USAGE

Different implementation strategies use different amounts of memory. The amounts of memory used for three different strategies are compared in this section: Runlength-based lazy evaluation with and without memory mapping, and memory mapping without lazy evaluation. Each strategy is tested on different number of layers and image size, the results are displayed in table 1. Significant memory allocations are listed in the table, like runlength-represented lines and output buffer for the image data. The listed memory allocations



(a) Memory usage, runlength-based lazy evaluation (b) Memory usage, no lazy evaluation

Figure 9: Comparison of image server memory usage with and without lazy evaluation

	Strategies		
	a)	b)	c)
Image with 19 layers. Entire image is rendered			
Runlength-rep. lines	659	659	659
Output buffer	75	75	75
Raster allocation	0	62500	0
Files read into RAM	0	0	3200
Image with 10 layers. One tile only is rendered			
Runlength-rep. lines	41	41	41
Output buffer	8	8	8
Raster allocation	0	256	0
Files read into RAM	0	0	1728

Table 1: Memory (in kilobytes) three strategies: a) Memory mapping. b) No lazy evaluation. c) No memory mapping. Image with 10 layers, one tile rendered

stand for 80% of peak memory for lazy evaluation.

It is seen that memory increases with the size of the image, and that lazy evaluation is superior when it comes to memory usage. Runlength-represented lines are the major allocations for the memory mapping strategy, particularly if many layers are involved or the image is large.

8. LAZY EVALUATION FOR OTHER OUTPUT FORMATS

Lazy evaluation does not lend itself directly to all output formats, like it does to GIF in this paper. One image format which can be adapted to lazy evaluation is JPEG2000 [7].

JPEG2000 groups samples in blocks, and applies arithmetic coding to them. 4 block rows are at any point active when coding, so that one can only hope for working with 4 decompressed lines at a time. JPEG2000 uses an (optional) Discrete Wavelet Transform (DWT). The DWT can be applied in stages, depending on the desired resolution level. When applying DWT, a larger cache of transformed subband samples may be needed when coding. Many implementations of the DWT exist which buffer up all subband samples in one DWT stage before going to the next stage (*sequential* DWT). This strategy is not compatible with lazy evaluation, since it requires many image lines decompressed in memory at the same time. Fortunately, the DWT can also be implemented in a *pipelined* manner which consumes image input lines incrementally, see [7] chapter 17.4. With pipelining, DWT stages are performed in a lazy manner, i.e. when enough subband samples are available. Pipelining of DWT stages is the strategy which a JPEG2000 coder should apply to take advantage of lazy evaluation. To utilize lazy evaluation as best we can, DWT pipelining can also be paired with a fitting progression order, [7] chapter 13.1.1.

9. CONCLUSION AND FUTURE WORK

There is still much room for smart image processing applications when it comes to high demands for performance. The concept of lazy evaluation is tested here on specific images with a specifically developed library to illustrate this. Lazy evaluation has clear benefits when combined with memory mapping, leading to attractive numbers for memory usage. It was also argued that lazy evaluation is very attractive to cache utilization.

There are many follow-ups to the practical implementation and applications of runlength-based lazy evaluation. Runlength-based lazy evaluation is attractive when it comes to other operations such as rotation and computing image differences. A paper is already in progress to demonstrate thin client applications using the image server framework.

Results in this paper were obtained with an Intel Pentium M processor with 1600MHz clock speed, L2 cache size of 1MB and 512 MB RAM. All tests were run under Windows XP, and all programs were compiled with Microsoft Visual C++.NET 7.1.

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