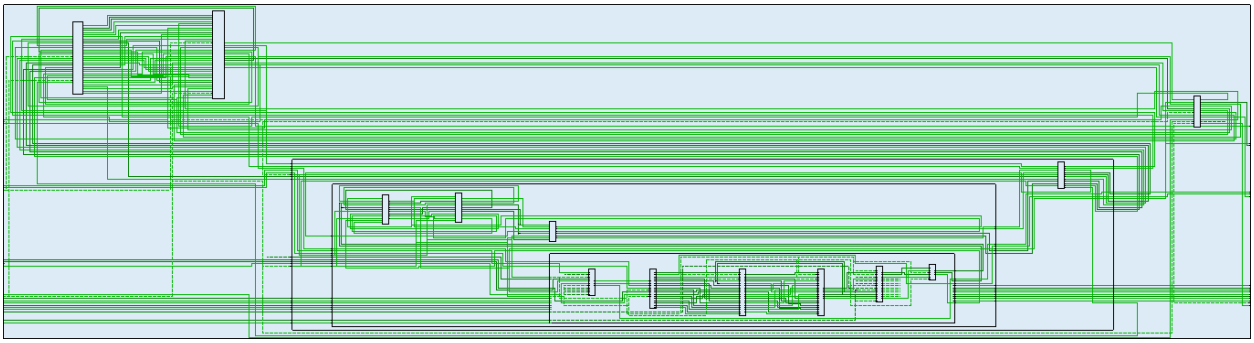
Introduction

Under Apertus Association in Google Summer of Code 2019, I worked in implementing lossless JPEG 1992 core and it's supporting software.

While raw images provide high quality, raw huge size limit FPS and cause difficulties in transition and storing.

My task was to implement lossless JPEG 1992 core to be placed in Axiom Beta and Axiom Micro FPGAs, the core will compress the sensor data (raw stream) with no loss in quality what so ever. This will enable higher FPS and/or lower bandwidth.

I have completed the main core that will compress the stream of data, I have also wrote software to control the core and the DMA and wrote several tools to manipulate, generate and analyze raw and lossless files. I have also worked in an open source DMA for the core, and tested open source library that can decode resulting files.



Mentors: a1ex, Bertl

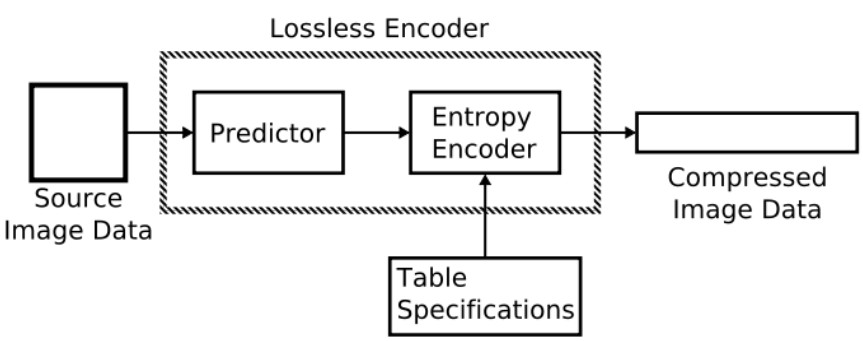
Core github link

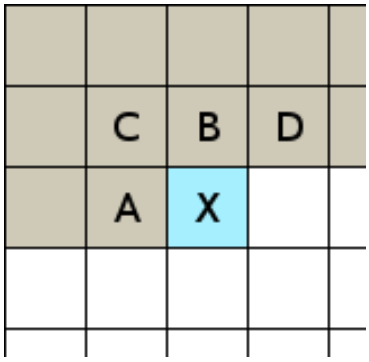
Library github link

Raw image tools github link

Lossless JPEG

Lossless JPEG was developed as a late addition to JPEG in 1993, using a completely different technique from the lossy JPEG standard. It uses a predictive scheme based on the three nearest (causal) neighbors (upper, left, and upper-left), and entropy coding is used on the prediction error.



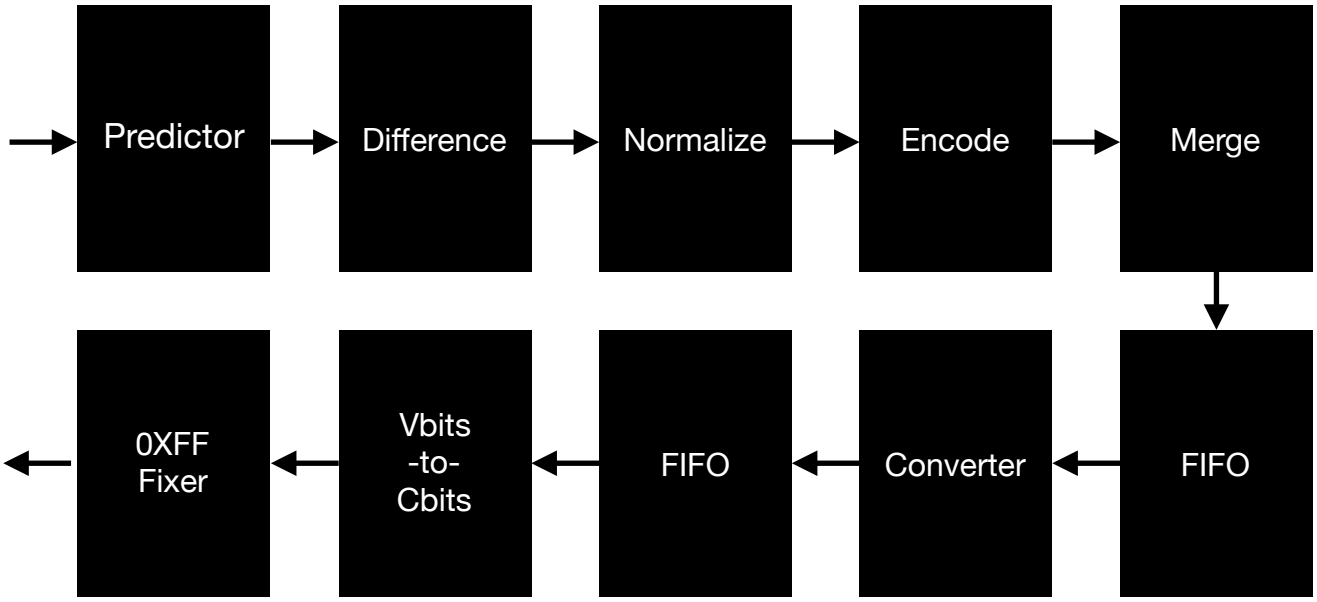


I will short it as **LJ92**.

LJ92 In Axiom Cameras

Lj92 will be placed in the USB3.0 pipeline, It will provide a typical compression of (**55%** to **75%**) which practically will provide more FPS and/or lower bandwidth with no effect on the quality what so ever.

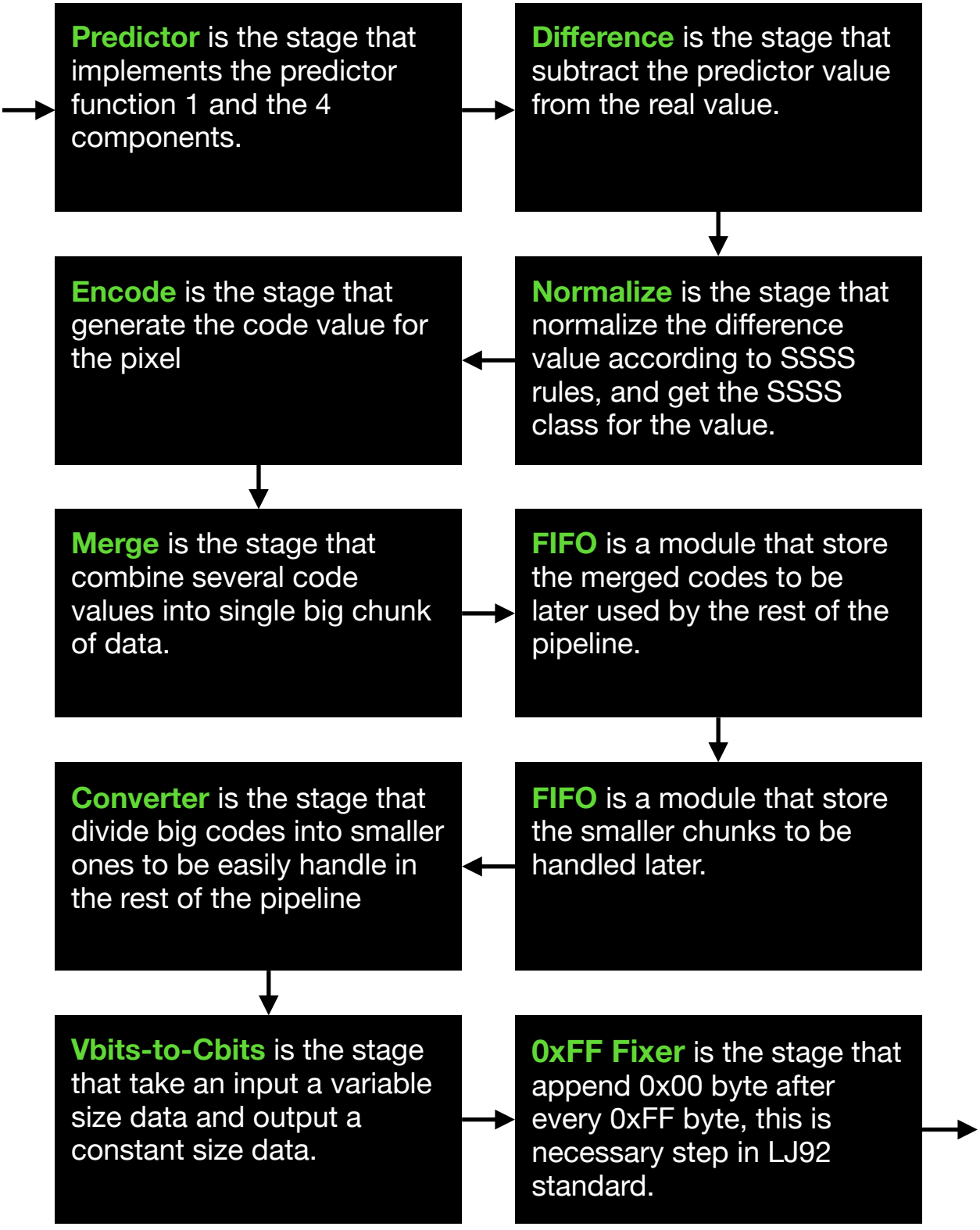
LJ92 Pipeline



LJ92 Beta/Micro Technical Details

- Input: 2 pixels per cycle for Axiom Beta and 1 pixel per cycle for Axiom Micro.
- Output: 16bits of data.
- **LJ92** uses predictor function 1.
- **LJ92** uses 4 components.
- **LJ92** handles 12bits images.
- **LJ92** adds marker at the beginning and ending of each frame.
- **LJ92** stream is [starting_marker][compressed_frame][ending_marker]…
- starting_marker is 16bytes of 0xFF.
- ending_marker is 16bytes of 0xFF in case of complete frame. or 0xFFFE in case of incomplete frame.

LJ92 Pipeline In Details



Receiver End

In receiver end, the receiver will receive a stream from the camera, the receiver must detect and extract each frame, append the header and the tailer to every frame.

The receiver will make use of **the following information** when generating the header.

- **LJ92** uses predictor function 1.
- **LJ92** uses 4 components.
- **LJ92** bit depth is 12bits.
- **LJ92** SSSS as following unless changed via AXI-Lite interface.
  (0b1110, 4)
  (0b000, 3)
  (0b001, 3)
  (0b010, 3)
  (0b011, 3)
  (0b100, 3)
  (0b101, 3)
  (0b110, 3)
  (0b11110, 5)
  (0b111110, 6)
  (0b1111110, 7)
  (0b11111110, 8)
  (0b111111110, 9)
- **LJ92** width and height are only set via AXI-Lite interface.

Please refer to **lj92_image.cpp** to check how header and tailer are generated using those information.

Sender End

Axiom cameras are generally the senders end, The **LJ92** will be placed between the memory reader and the USB3.0 module.

The **LJ92** core will be in IDLE state until the first valid input, and the core will terminate after all pixels are inputted and processed.

The core must be reseted in FPGA before every frame.

Here is the steps needed to run the core:

- Reset the core or load the bit file.
- Set the wanted height and width.
- Set the wanted maximum allowed cycle before force end the frame.
- Change the SSSS information if needed - default in previous slide.
- Setting or changing the data happens via AXI-Lite Interface with no particular order.
- Only after setting all the data correctly you may start the recording.
- Between every frame and the other you must reset the core and wait one cycle until the height, width and allowed_cycles are set again.
- After resetting, The SSSS data will stay the same, the height, width and allowed_cycles will get erased and set in the next cycle since all the core is reseted but not the core_axi_lite module.

Information about reset/clk signals:

- **clk** and **rst** signals do connect to all the core but not the core_axi_lite module.
- **axi_lite_clk** and **axi_lite_rst** do connect to the core_axi_lite only.
- **rst** and **axi_lite_rst** are both active high signals.
- Before every frame, you must only reset the “**rst**” signal but not the “**axi_lite_rst**” signal.
- **clk** and **axi_lite_clk** MUST connect to the same **clk** source.

Receiver Recording Options

Axiom cameras will be connected to recorder devices through USB3.0 modules.

The recorder devices responsibility to extract the frames from the stream and encapsulate it with suitable container like DNG or MLV.

For uncompressed raw, the receiver end can easily extract every frame as every frame is the same size, that is not the case with lossless stream since every frame is different size.

To be able to extract every lossless frame, there is a marker preceding and following every frame.

For now the receiver end should look for the starting marker and ending marker to extract every frame. then add this frame to the container.

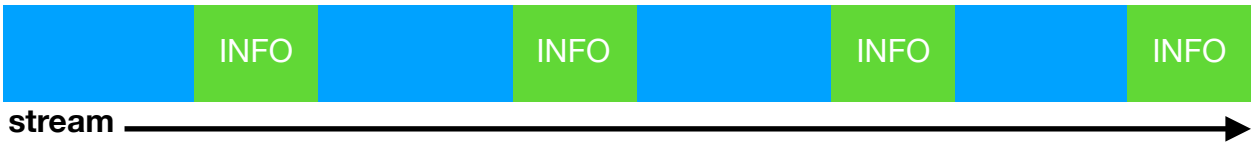
While this method is very simple, it is processing consuming for the receiver and it may limit the FPS in low end recorders.

Future work:

As mentioned, the marker method is simple but it may limit FPS, to overcome this problem I propose a way that may be implemented in the future.

The proposed method is to put information about the stream in known offsets in the stream.

using this way, the receiver will know where to look to find information about the stream like where every frame start and end.



LJ92 FPGA Core Software

In normal mode of operation where the core is placed between the memory reader and the USB3.0 module, the only software interface is AXI-Lite interface.

AXI-Lite interface propertise:

- Read and write to SSSS values.
- Read and write the height and width of the frame.
- Read and write the allowed cycle before force ending the frame.
- Read 8 debugging register - only if the core synthesized with the debugging module enable.

The core also implements the AXI4-Stream interface which allow it to be used with any DMA that handle AXI4-Stream components.

In the Github repository there is a software directory that contains code and instructions to describe how to use the core with DMA in ZYNQ. This intended only for testing purposes.

LJ92 Software:

- Uses Xilinx DMA, or open source DMA (soon).
- Write the necessary data via AXI-Lite to test RAW12 images.
- Read and display all the data in registers (height, width, allowed cycles, SSSS values, debug registers)
- Set needed info for DMA and start the DMA.
- Validate the LJ92 result against pre computer LJ92 file.
- Validate the markers.
- Accurately Calculate time consumed in every step.

Please refer to **LJ92-software** to get the software and read the instructions to test the core.

LJ92 Tools and Utilities

LibLJ92 Library:

- Written by Andrew Baldwin and maintained by Magic Lantern community to encode and decode LJ92 files.
- Support decoding of a single scan with single/multiple components.
- Support decoding of all predictor functions.
- Support decoding of 2 to 16 bits color depth and height and width up to 65535.
- Support encoding in predictor function 6 only.
- Support encoding in single scan with single component only.
- Support encoding of 2 to 16 bits color depth and height and width up to 65535.
- Auto generate optimal Huffman tree in encoding.

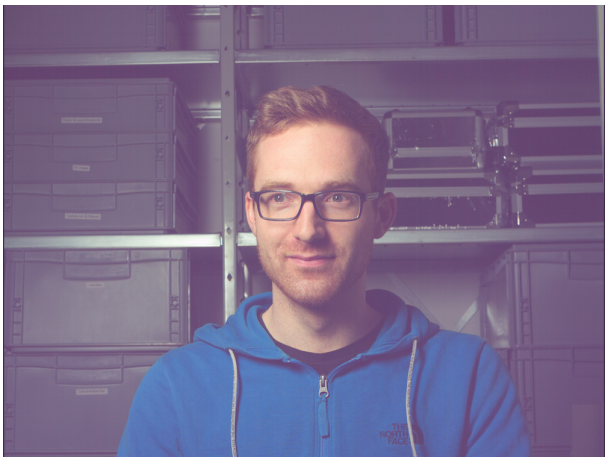
Raw Image Tools:

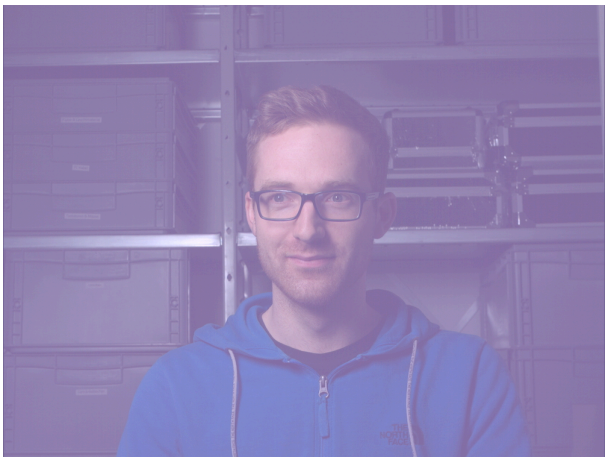
- Tools written to manipulate Raw images, Including LJ92 encoding with different options to generate LJ92 files to test the core against.
- Don’t support decoding.
- Support encoding in all predictor functions.
- Support encoding in single scan with single/multiple components.
- Support encoding of 2 to 16 bits color depth and height and width up to 65535.
- Huffman tree is inputted manually, not generated.
- The tool support several other things like generating DNG or PNM and displaying analysis of LJ92 images.

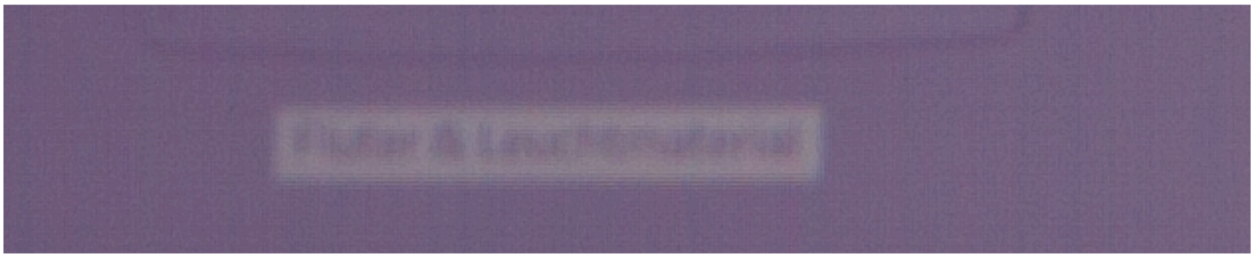
Liblj92 github link

Raw image tools github link

Test Case 1







This test case represent a simple image with average details, and relatively clean with low gain and low brightness.

The left image is 12-bits raw image and the right one is 8-bits log encoded image with optimal LUT, the bottom one is a close up to notice the noise level.

12-bits image size : **18MB**

8-bits image size : **12MB**

12-bits lj92 size : **10.7MB**

8-bits lj92 size : **5.5MB**

12-bits lj92 / 12-bits image = **59.4%**

8-bits lj92 / 8-bits image = **45.8%**

8-bits lj92 / 12-bits image = **30.5%**

Test Case 2

This test case represent a complex image with average to high details, and relatively noisy image with high gain and middle brightness.

The left image is 12-bits raw image and the right one is 8-bits log encoded image with optimal LUT, the bottom one is a close up to notice the noise level.

12-bits image size : **18MB**

8-bits image size : **12MB**

12-bits lj92 size : **11.9MB**

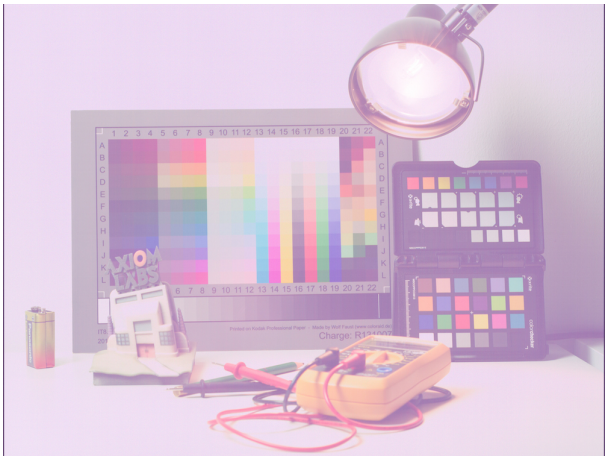
8-bits lj92 size : **6.5MB**

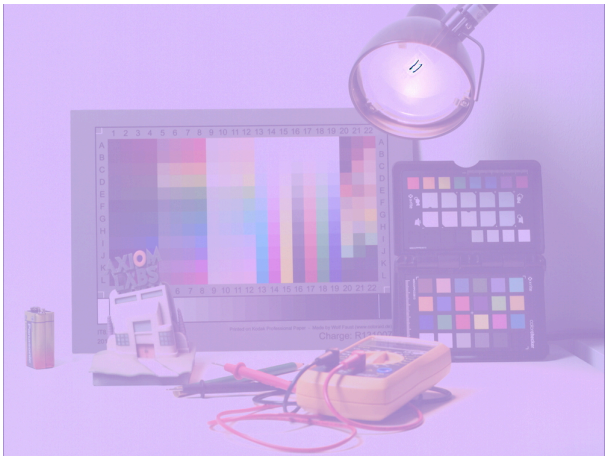
12-bits lj92 / 12-bits image = **66.3%**

8-bits lj92 / 8-bits image = **54.2%**

8-bits lj92 / 12-bits image = **36.3%**

Test Case 3





This test case represent a simple image with average details, and relatively noisy image with high gain and very high brightness, it is extreme PLR frame as well.

The left image is 12-bits raw image and the right one is 8-bits log encoded image with optimal LUT, the bottom one is a close up to notice the noise level.

12-bits image size : **18MB**

8-bits image size : **12MB**

12-bits lj92 size : **13.6MB**

8-bits lj92 size : **6.9MB**

12-bits lj92 / 12-bits image = **75.3%**

8-bits lj92 / 8-bits image = **57.5%**

8-bits lj92 / 12-bits image = **38.3%**

Test Cases Analysis

As we know LJ92 is dependent on how close every pixel to its neighbors values, so we can do the analysis based on this fact.

- **bit depth:** inversely proportional to compression ratio, since higher bit depth yields bigger Huffman codes and more difference between neighbor pixels.
- **details:** inversely proportional to compression ratio, since the higher the details in the image, the more and higher difference between every neighbor pixels.
- **noise:** inversely proportional to compression ratio, since higher noise levels will result in a lot of difference between neighbor pixels.
- **brightness:** inversely proportional to compression ratio, since in high brightness pixels, more noise is present in them and changes between neighbor pixels will be much bigger than low brightness frames.
- **PLR:** inversely proportional to compression ratio, since PLR introduce much more noise in the pixels and the difference between pixels are very common and relatively high.
- **optimal LUT:** is quite beneficial since it only throw noise pixels and compress high brightness pixels into close values to each other.
- **row & col - fixed pattern noise:** can cause very bad compression ratio as those affect close pixels and can cause very high change between them, so a fix prior to compression is essential.
- **de-noising and smoothing:** can help the compression a lot as these algorithm tend to yield a cleaner images with no subtle changes between close pixels.

Best & Worst Size Cases Analysis

As LJ92 is a variable encoding algorithm, its output can vary widely, so it is quite important to know how to calculate the worst possible case for every frame.

Every LJ92 pixel is encoded in two parts, the Huffman code and the difference value.

To get the worst and best case, we need to know the possible values for every part.

The analysis will be conducted for 12-bits frame.

- **Difference Value:** can take any value from 0-bits to 12-bits, where 12-bits represent the sensor bit depth.
- **Huffman Code:** is dependent on the table that is programmed by the user, but a reasonable assumption that it can take from 1-bits to 13-bits. The one used in compressing the test cases and the default one in the core is from 3-bits to 9-bits

So the best case scenario for the current configuration will be 4bits for every pixel which is 33.3% compression ratio.

The worst case scenario for the current configuration will be (9+12)bits for every pixel which is 175% compression ratio.

When working with 8-bits images, best and worst case scenario for (8-bits lj92 / 8-bits image) are 25% and 212.5% and that is for our current configuration.

In general, when we set the Huffman table we optimize it for the most common classes to yield best average compression. As worst and best cases are extremely hard to produce we generally ignore them. Most frames will yield 55% to 75% compression ratio, but a worse compression ratio is very possible to occur.

Performance Analysis

For the purpose of performance Analysis I will explain it using Axiom Beta configuration.

- **Input:** 2 pixels/cycle
- **Output:** 16 bits/cycle
- **CLK Freq:** 200 MHz

Also LJ92 pipeline can be represented as following.

Maximum theoretical Input pixels per second: 400 Million Pixels/sec

Maximum theoretical output pixels per second: 400 MByets/sec

Practical Issues

- In parts of the image that compress very much, it saturate the input logic very good and accept two pixels/cycle, but it under saturate the output logic which mean it will output 16bits every several cycles, not every cycle as intended.
- In Parts of the image that compress badly, it saturate the output logic very good and output 16-bits/cycle every cycle, but the input logic will have stall cycles and won't be able to accept two pixels every cycle.

Both of those issues will happen in different times in the image, and they highly dependent on the frame, so every frame may suffer more or less.

Overcome Practical Issues

As explained earlier, both problems occur as either the input or the output is under saturated, so I will propose few solution that can help.

- Increase CLK frequency for the design, This consider to be the simplest solution if the design can handle higher frequencies, this will mitigate the effect of under saturating the input/output logic.
- Increase the input pixels/cycle from 2 to 3 or 4, this will greatly improve the performance with the expense of increasing the logic footprint, this solution will need to be implemented if we need to fully utilize the 400MB/s bandwidth of the usb3.0. By implementing this solution we will guarantee to always have enough data for the output logic, but the input logic will be undersaturated most of the time as the input logic can't accept 4pixels/cycle for every cycle in the frame.

I choose to implement the first solution by increasing the CLK frequency to 215MHz since the design already accept this speed.

After actual implementation and testing with usb3.0 we may opt to increase the pixels/cycle from 2 to 3 or 4 if the increase in bandwidth worth the increase in logic footprint introduced. Also increasing the input pixels from 2 to 4 is quite easy - code related - since the "input logic" is generic and can support several configuration with no new code.

References & Useful Links

- Lossless JPEG [wikipedia.org]
- How DNG compresses raw data with lossless JPEG92 [thndl.com]
- CCITT Rec. T.81 (1992 E) - PDF [w3.org]
- aaalgo/ljpeg [github.com]
- ilia3101/MLV-App/liblj92 [github.com]
- FaresMehanna/MLV-File-Format/LJPEG-1992 [github.com]
- FaresMehanna/RAW-Image-Tools [github.com]
- FaresMehanna/JPEG-1992-lossless-encoder-core [github.com]