

Integrating Project Final Documentation

CEPARCO S11 G6

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Implementing CUDA to the LMS Daltonization Algorithm.

Introduction

In this project, we explored the implementation of the LMS Daltonization algorithm using PyCUDA, utilizing the parallel computing capabilities of NVIDIA GPUs. Our goal was to simulate color vision deficiencies and compensate for them in real-time. This method is especially useful for colorblind individuals, enabling them to distinguish colors more effectively. The first step of the LMS Daltonization Algorithm is to convert the image from an RGB color space(Red Green Blue) into LMS (Long Medium Short) color space by performing matrix multiplication. It then simulates color blindness of a human with a specific type of colorblindness (e.g., protanopia, deuteranopia, or tritanopia) by modifying the LMS values through a Daltonization matrix. The values were acquired from a research study by Doliotis, P., Tsekouras, G., Anagnostopoulos, C. N., & Athitsos, V. (2009). Then the values are compensated for better color visibility after which the values are converted back into RGB.

Python Algorithm

```
def daltonize(img, intensity, deficiency):  
  
    # Image RGB  
    RGB = np.asarray(img, dtype=float)  
  
    # Deficiency matrices  
    daltonization_matrices = {  
        'd': np.array([ [1, 0, 0],  
                        [0.4942, 0, 1.2483],  
                        [0, 0, 1]]),  
        'p': np.array([ [0, 2.0234, -2.5258],  
                        [0, 1, 0],
```

```

        [0, 0, 1]]),
    't': np.array([ [1,0,0],
                    [0,1,0],
                    [-0.395913,0.801109,0]])
}

daltonization_matrix = daltonization_matrices.get(deficiency, None)
if daltonization_matrix is None:
    raise ValueError("Invalid deficiency type. Supported types are:
Deuteranomaly(d), Protanomaly(p), Tritanomaly(t)")

# RGB to LMS
LMS = np.tensordot(RGB[...,:3], RGB_to_LMS.T, axes=1)

# LMS to simul LMS
_LMS = np.tensordot(LMS[...,:3], daltonization_matrix.T, axes=1)

# simul LMS to compensated LMS
error = (LMS - _LMS) * intensity
cLMS = np.tensordot(error[...,:3], shift.T, axes=1)

# compensated LMS to compensated RGB
_RGB = np.tensordot(cLMS[...,:3], LMS_to_RGB.T, axes=1)
cRGB = _RGB + RGB

# Clip the values to be within [0, 255]
result = np.clip(cRGB, 0, 255).astype('uint8')

return result

```

Code Snippet 1: Python Daltonize function

This snippet shows the full python function of the LMS Daltonization algorithm. The program uses the OpenCV library for images and videos and uses the NumPy library to handle matrix operations. This function takes an Image or Video as input via the 'RGB' variable and determines the type of colorblindness correction to perform from the 'deficiency' function parameter.

The following is the main process of the algorithm:

```
# RGB to LMS
LMS = np.tensordot(RGB[...,:3], RGB_to_LMS.T, axes=1)

# LMS to simul LMS
_LMS = np.tensordot(LMS[...,:3], daltonization_matrix.T, axes=1)

# simul LMS to compensated LMS
error = (LMS - _LMS) * intensity
cLMS = np.tensordot(error[...,:3], shift.T, axes=1)

# compensated LMS to compensated RGB
_RGB = np.tensordot(cLMS[...,:3], LMS_to_RGB.T, axes=1)
cRGB = _RGB + RGB

# Clip the values to be within [0, 255]
result = np.clip(cRGB, 0, 255).astype('uint8')
```

Code Snippet 2: Python main algorithm process

The process primarily uses the numpy tensordot function which performs a dot product on each row of a given 3D array like the 'RGB_to_LMS' variable. The algorithm starts by converting the RGB image to its LMS color space. The Daltonization matrix is then applied to the LMS values to simulate the desired color blindness. The compensated LMS is then calculated by subtracting the simulated LMS to the LMS color space and performing dot product with the shift matrix. It is then converted back to RGB to be added to the RGB color space to apply the correction.

How CUDA is implemented

Since the LMS Daltonization Algorithm utilizes a lot of matrix multiplication, CUDA is implemented using the process to perform matrix multiplication. Doing this reduces the runtime, thus reducing latency and improving algorithm performance. The simultaneous nature of CUDA allows multiple pixels to be altered at the same time.

```
if (deficiency == 'd') { // Deuteranomaly
    daltonization_matrices[0][0] = 1; daltonization_matrices[0][1] =
0; daltonization_matrices[0][2] = 0;
    daltonization_matrices[1][0] = 0.4942;
daltonization_matrices[1][1] = 0; daltonization_matrices[1][2] = 1.2483;
    daltonization_matrices[2][0] = 0; daltonization_matrices[2][1] =
0; daltonization_matrices[2][2] = 1;
} else if (deficiency == 'p') { // Protanomaly
    daltonization_matrices[0][0] = 0; daltonization_matrices[0][1] =
2.0234; daltonization_matrices[0][2] = -2.5258;
    daltonization_matrices[1][0] = 0; daltonization_matrices[1][1] =
1; daltonization_matrices[1][2] = 0;
    daltonization_matrices[2][0] = 0; daltonization_matrices[2][1] =
0; daltonization_matrices[2][2] = 1;
} else if (deficiency == 't') { // Tritanomaly
    daltonization_matrices[0][0] = 1; daltonization_matrices[0][1] =
0; daltonization_matrices[0][2] = 0;
    daltonization_matrices[1][0] = 0; daltonization_matrices[1][1] =
1; daltonization_matrices[1][2] = 0;
    daltonization_matrices[2][0] = -0.395913;
daltonization_matrices[2][1] = 0.801109; daltonization_matrices[2][2] =
0;
} else {
    printf("Invalid deficiency type. Supported types are:
Deuteranomaly(d), Protanomaly(p), Tritanomaly(t)");
    return;
}
```

Code Snippet 3: PyCUDA Daltonization Matrices

The LMS Daltonization matrices for Deuteranomaly, Protanomaly, and Tritanomaly are stored in device memory. Depending on the user's selection, a different matrix is used.

```
// RGB to LMS
float R = img[idx];
float G = img[idx + 1];
float B = img[idx + 2];

float L = RGB_to_LMS[0] * R + RGB_to_LMS[1] * G + RGB_to_LMS[2] * B;
float M = RGB_to_LMS[3] * R + RGB_to_LMS[4] * G + RGB_to_LMS[5] * B;
float S = RGB_to_LMS[6] * R + RGB_to_LMS[7] * G + RGB_to_LMS[8] * B;
```

Code Snippet 4: PyCUDA RGB to LMS Image Conversion

The RGB to LMS image conversion is handled by matrix multiplication. This conversion is performed on each pixel in the image to transform the entire image from RGB to LMS color space.

```
// LMS to simul LMS
float _L = daltonization_matrices[0][0] * L +
daltonization_matrices[0][1] * M + daltonization_matrices[0][2] * S;
float _M = daltonization_matrices[1][0] * L +
daltonization_matrices[1][1] * M + daltonization_matrices[1][2] * S;
float _S = daltonization_matrices[2][0] * L +
daltonization_matrices[2][1] * M + daltonization_matrices[2][2] * S;

// Error calculation
float eL = (L - _L) * intensity;
float eM = (M - _M) * intensity;
float eS = (S - _S) * intensity;
```

Code Snippet 5: PyCUDA LMS to Simulated LMS Image Conversion

This transforms the original LMS values to simulate a color vision deficiency and calculates the error for correction.

```
// Compensated LMS
float cL = eL * shift[0] + eM * shift[1] + eS * shift[2];
float cM = eL * shift[3] + eM * shift[4] + eS * shift[5];
float cS = eL * shift[6] + eM * shift[7] + eS * shift[8];
```

Code Snippet 6: PyCUDA Simulated LMS to Corrected LMS Image Conversion

Using the values from the shift matrix and error calculations, the image is corrected.

```
// Compensated LMS to compensated RGB
float _R = LMS_to_RGB[0] * cL + LMS_to_RGB[1] * cM + LMS_to_RGB[2] *
cS;
float _G = LMS_to_RGB[3] * cL + LMS_to_RGB[4] * cM + LMS_to_RGB[5] *
cS;
float _B = LMS_to_RGB[6] * cL + LMS_to_RGB[7] * cM + LMS_to_RGB[8] *
cS;

// Final RGB
result[idx] = min(max(R + _R, 0.0), 255.0);
result[idx + 1] = min(max(G + _G, 0.0), 255.0);
result[idx + 2] = min(max(B + _B, 0.0), 255.0);
```

Code Snippet 7: PyCUDA Corrected LMS to Corrected RGB Image Conversion

The final compensated LMS image is then converted to RGB then checking is done to ensure that the RGB values remain within the valid range [0, 255].

The kernel is executed via the following python function:

```
def daltonize_gpu(img, intensity, deficiency):
    height, width, channels = img.shape
    img = img.astype(np.float32).flatten()
    result = np.zeros_like(img)

    img_gpu = cuda.mem_alloc(img.nbytes)
    result_gpu = cuda.mem_alloc(result.nbytes)

    cuda.memcpy_htod(img_gpu, img)

    block = (16, 16, 1)
    grid = (int(np.ceil(width / block[0])), int(np.ceil(height /
block[1])), 1)

    daltonize_kernel(img_gpu, np.float32(intensity),
np.int8(ord(deficiency)), result_gpu, np.int32(width), np.int32(height),
block=block, grid=grid)
    cuda.Context.synchronize()

    cuda.memcpy_dtoh(result, result_gpu)
```

```

    result = result.reshape((height, width, channels)).astype(np.uint8)

    img_gpu.free()
    result_gpu.free()

    return result

```

Code Snippet 8: Kernel execution function

The function prepares the variables needed before the kernel is executed. It prepares the image/video input by flattening the array. It then allocates memory on the GPU for the input and output and memory copies the function input to the newly allocated input variable in the GPU. The blocks and grid size are then defined, with this snippet initializing 256 threads (16x16x1) and the grid size adjusting to the amount of threads to properly fit the input. The kernel is then executed and is waited on via the `synchronize()` function to ensure every element is altered before proceeding to move the output back to the CPU. Once the output is back to the host, it is converted back to the input format and is returned.

Python vs. PyCUDA performance

The computer used on collecting the execution times has the following hardware specifications:

- CPU: Intel i7-8750H
- GPU: Nvidia GTX 1050 ti
- RAM: 16GB

Trying the program on newer hardware may produce better non-cuda program results

Video Results

The following code snippet makes up the *'main'* of the python program. It includes the GUI code which has been slightly modified to include an FPS counter for the video output:

```

# Default parameters
correction_level = 100
correction_types = ["d", "p", "t"]
default_correction_type = "d"

# Input video
vid = cv.VideoCapture(0)

# GUI
window_name = 'Daltonization for Color Deficiency Correction'
cv.namedWindow(window_name, cv.WINDOW_AUTOSIZE)

```

```

cv.createTrackbar("Correction Level (%)", window_name, correction_level,
500, lambda x: x)
cv.createTrackbar("Correction Type", window_name, 0,
len(correction_types) - 1, lambda x: x)

# FPS variables
fps = 0
frame_count = 0
start_time = timer()

while True:
    ret, frame = vid.read()

    level = cv.getTrackbarPos("Correction Level (%)", window_name) /
100.0
    correction_type_index = cv.getTrackbarPos("Correction Type",
window_name)
    default_correction_type = correction_types[correction_type_index]
    corrected = daltonize(frame, level, default_correction_type)

    # Calculate FPS
    frame_count += 1
    elapsed_time = timer() - start_time
    if elapsed_time > 1:
        fps = frame_count / elapsed_time
        frame_count = 0
        start_time = timer()

    # Display the FPS on the frame
    cv.putText(corrected, f'FPS: {fps:.2f}', (10, 30),
cv.FONT_HERSHEY_SIMPLEX, 1, (255, 0, 0), 2, cv.LINE_AA)
    cv.putText(frame, "Original", (10, 30),
cv.FONT_HERSHEY_SIMPLEX, 0.4, (255, 0, 0), 2)
    cv.imshow(window_name, np.hstack([frame, corrected]))

    if cv.waitKey(1) & 0xFF == ord('q'):
        break
vid.release()
cv.destroyAllWindows()

```

Code Snippet 9: 'main' of python program

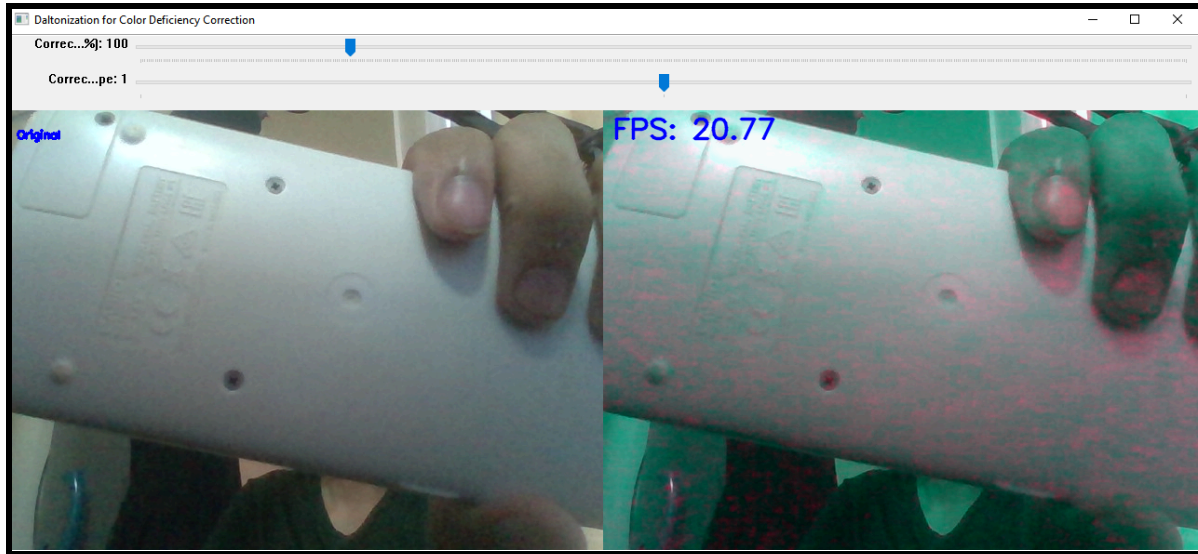


Figure 1: Non-PyCuda program FPS

Using the standard version of the program, the test machine video output is getting around 20 FPS. The FPS is not stable however, sometimes having a frame drop randomly. The FPS also shortly drops to around 15 FPS or less when the program window is significantly moved, though it goes back to its normal frame rate



.Figure 2: PyCuda program FPS

Using the PyCuda version of the program, the test machine has a stable framerate of around 30 FPS. The FPS still drops when the window is moved although it goes back up quickly and normally does not drop to below 20 FPS. The frame rate seems to be capped at the mentioned 30 FPS, possibly due to hardware limitations. Therefore it is possible that the actual performance of this program version is better than it seems.

Image Results

A modified version of the program has been used to calculate the execution times using images. The algorithm and its related functions were not changed but the GUI portion of the code was removed and replaced with the following:

```
exec_time = 0
for i in range(0,10):
    start = timer()
    daltonize_gpu(frame, 1, 'd')
    end = timer()
    # Function execution time
    print(f"[{i}]Execution Time: {end - start}")
    exec_time = exec_time + end - start

exec_time = exec_time / 10
print(f"Avg Execution Time: {exec_time}")
```

Code Snippet 10: Average Execution Time

The code shown runs the Daltonization function 10 times with the same image and calculates the average execution time after the loop. The timer() function used is from the *timeit* python library. The images used in collecting the execution times vary in size, ranging from 1080p up to 8K. When running the PyCuda version of the program, it is executed with the 'nvprof' command to also profile the GPU and API call execution times. 'nvprof' only works on Nvidia GPUs with a Compute version below 8.0. The 1050 ti from the test computer is part of the Pascal architecture which has a Compute version of 6.0 which is why it can be used. The raw results can be found in the "Timing results" folder of this repository.

Avg times (ms)	Resolution				
	1k	2k	4k	6k	8k
Python timer	240.5099	472.1305	965.0093	2791.4165	4335.1546
Pycuda timer	45.3671	78.4444	175.7644	429.6371	755.7763
Nvprof GPU total	10.1109	17.9784	39.9971	101.7457	174.5130
nvprof HtoD	4.2252	7.2217	16.2030	53.4690	70.6590
nvprof DtoH	4.9876	9.1612	20.2250	40.1960	90.4840
nvprof func	0.8981	1.5955	3.5691	8.0807	13.3700

Table 1: Average execution time (ms) from 10 runs

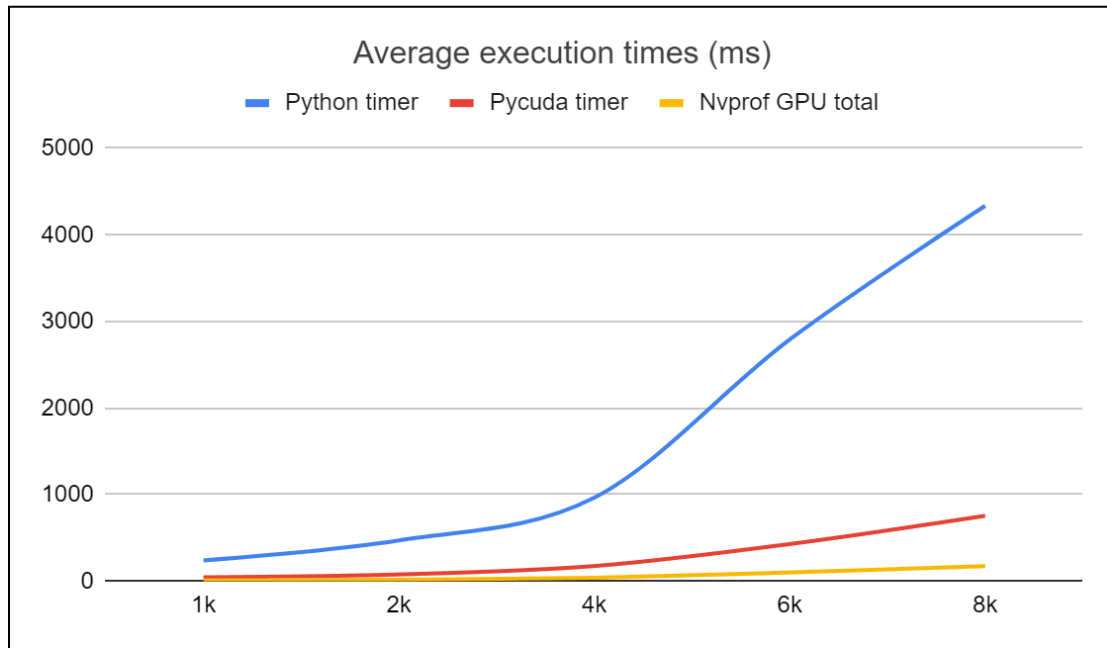


Figure 3: Execution time line graph

The results shown were performed with 256 threads (16x16x1). As shown, using CUDA significantly decreases the execution time of the Daltonization function. The Nvprof GPU total is the sum of the last 3 values in the table which are the indicated GPU activities in nvprof. It is part of the Pycuda timer and roughly makes around 20% of the function execution time.

Pycuda speedup					
1k	2k	4k	6k	8k	Avg
5.301416665	6.018664175	5.490356978	6.497149571	5.736028769	5.808723232

Table 2: Pycuda speedup values

As shown in Table 2, the PyCuda version of the program is on average 5.81 times faster than the standard Python-only version.

Threads	Resolution				
	1k	2k	4k	6k	8k
256	0.8981	1.5955	3.5691	8.0807	13.3700
512	0.8851	1.5728	3.5230	8.0495	13.3430
1024	0.9016	1.5951	3.8902	8.2968	13.5780

Table 3: GPU Daltonization function average execution time (ms)

This table shows the average execution time of the Daltonization function in the GPU. Comparing the results, the difference is at most only a few hundred microseconds. As shown in the table, using 512 threads shows the best performance consistently while using 1024 threads consistently performed the worst. This result indicates that using 512 threads is the most optimal for the test machine's GPU.

Conclusion

Our project demonstrates the substantial benefits of using CUDA for image processing tasks. The PyCUDA implementation of the LMS DALtonization algorithm not only achieves real-time performance but also maintains the accuracy and effectiveness of the sequential Python version. This highlights the potential of GPU computing in enhancing accessibility tools for individuals with color vision deficiencies, showing that there is potential for more responsive and scalable solutions in the field of assistive technology.

A possible future implementation for improving the Daltonization algorithm is to modify its adaptability. The algorithm could adjust based on the image/video contents such as changing the color scheme of specific parts of the image or video. By adding a color detection algorithm to detect specific colors or dominant colors present in the image/video, then color changes would be applied based on the detection results. Techniques such as color histograms, k-means clustering, or other image segmentation methods are possible tools to help implement the improved algorithm.

Expanding the project's platform support is another way of learning more ways to improve and optimize the algorithm. By extending compatibility to macOS and especially turning it into a mobile application, we would be able to gather more feedback on the study. Users will be able to provide feedback, allowing us to learn more about flaws or areas that need improvement.

References

Doliotis, P., Tsekouras, G., Anagnostopoulos, C. N., & Athitsos, V. (2009). Intelligent modification of colors in digitized paintings for enhancing the visual perception of color-blind viewers. In *Artificial Intelligence Applications and Innovations III* 5 (pp. 293-301). Springer US. Retrieved from https://www.researchgate.net/publication/220828504_Intelligent_Modification_of_Colors_in_Digitized_Paintings_for_Enhancing_the_Visual_Perception_of_Color-blind_Viewers