CS677-Parallel Distributed Axis-aligned Volume Rendering using MPI: Group 10

1 Introduction

This report presents the implementation and analysis of **Parallel Distributed Axis-aligned Volume Rendering** using the **MPI (Message Passing Interface)**. The program performs volume rendering by decomposing a 3D scalar dataset across multiple processes, which then execute the ray-casting algorithm concurrently.

2 Code Explanation

The program takes a 3D scalar dataset as input and divides the domain either along a single dimension (1D) or both X and Y dimensions (2D). The main task is to perform ray-casting to generate volume-rendered images and allow for early ray termination, improving the computational efficiency. The final output is a stitched image from the bounding box given as input.

2.1 Main Function

- **MPI Initialization:** Initializes the MPI environment using `MPI_Init`, retrieves rank and size information, and parses command-line arguments.
- **Dataset Loading and Distribution:** On rank 0, the dataset is read using `readDataset`, which extracts the dimensions from the filename. The dataset is broadcasted to all ranks using `MPI_Bcast`.
- **Volume Rendering:** The program performs ray casting with the provided dataset. It utilizes domain decomposition, where each process handles a portion of the domain. The rendering is performed using the function `volumeRendering`.

2.2 Key Functions

2.2.1 `readDataset`

Reads a binary dataset file and reshapes it into a 3D array. The filename is used to extract dimensions using regular expressions, and the dataset is then read and stored in a vector for further processing.

2.2.2 `rayCasting`

Performs ray casting on a subdomain by stepping through the Z-direction of the dataset. For each voxel encountered, it uses transfer functions to assign opacity and color (RGB) values based on the data's intensity. The algorithm supports early ray termination by halting further ray processing if the accumulated opacity reaches a threshold.

2.2.3 `saveImageFromVector`

Saves the rendered sub-image from each process in PNG format. The function takes a 2D slice of the volume and normalizes the data to save it as an 8-bit image.

2.2.4 `volumeRendering`

The core function responsible for performing the ray-casting algorithm across multiple MPI processes. It handles both 1D and 2D domain decomposition:

- **1D decomposition:** Divides the X-dimension of the data across processes.
- **2D decomposition:** Divides both X and Y dimensions, ensuring the number of processes in the X-direction is greater than in the Y-direction.

2.2.5 `transposeImage` and `flipAndTransposeImage`

These functions manipulate the image data (for example, flipping and transposing) to correct the orientation before saving the final image.

3 Performance Observations

The performance was analyzed for four test cases with varying dataset sizes and process counts. For each test case, the fraction of rays that terminated early and the total time taken by the program were recorded. Some results are as follows:

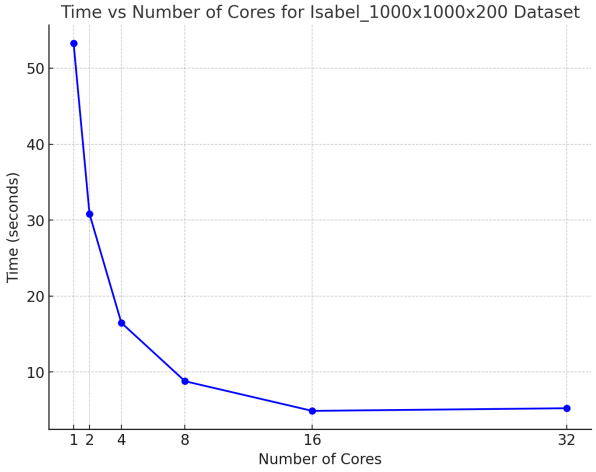

Figure 1: Runtime variation with number of cores: Smaller Dataset

We can clearly see in Figure 1. the time reduces with increase in number of cores. It saturates after core 16, and we no longer see improvement in runtime. This could be attributed to the machine maximum cores (ie. 16) and the communication time.

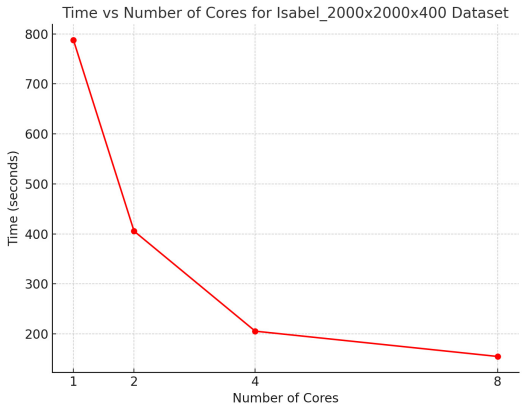

Figure 2: Runtime variation with number of cores: Larger Dataset

Figure 2. shows similar results as Figure 1. The machine ran into failure after core 8 due to large amount of data.

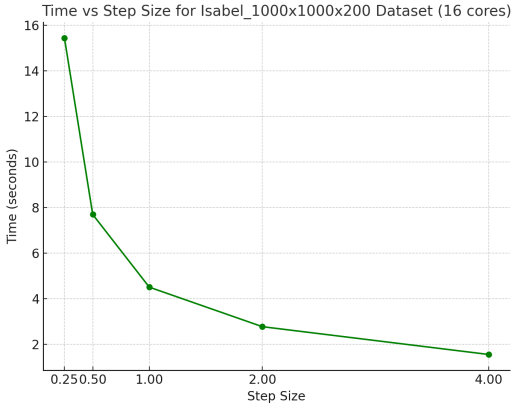

Figure 3: Runtime variation with step size

As we increase step-size the runtime also naturally reduces as shown in the Figure 3.

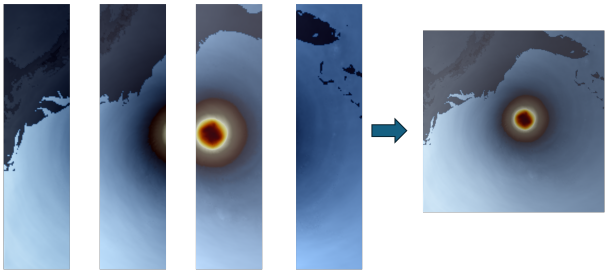

Figure 4: Final Output: Decomposition Type 1

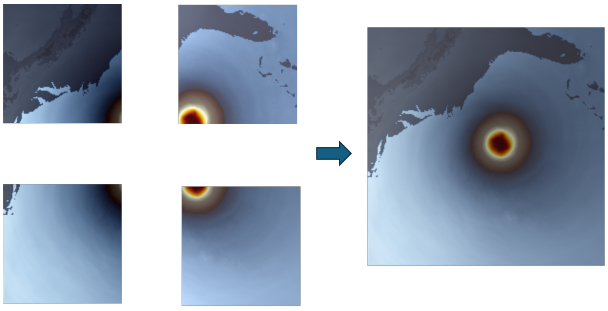

Figure 5: Final Output: Decomposition Type 2

The following test cases were also executed:

- **Test Case 1**: mpirun -np 4 ./executable Isabel_1000x1000x200_float32.raw 1 0.75 0 999 0 1000
- **Test Case 2**: mpirun -np 8 ./executable Isabel_1000x1000x200_float32.raw 2 0.25 0 500 0 999
- **Test Case 3**: mpirun -np 15 ./executable Isabel_1000x1000x200_float32.raw 1 0.5 0 999 0 700
- **Test Case 4**: mpirun -np 32 ./executable Isabel_1000x1000x200_float32.raw 2 0.35 0 500 0 999

The following tables summarize the results for each test case, including the time taken to read the dataset, render subdomains, and the fraction of rays terminated early.
Note: Threshold for the ray termination is taken as 1 for all test cases, which can be changed accordingly.

3.1 Test Case 1 Results

Metric	Value
Time taken to read the dataset	0.398647 seconds
Max time taken to render the subdomain	17.9601 seconds
Time taken to render subdomain 0	17.9601 seconds
Time taken to render subdomain 1	17.4685 seconds
Time taken to render subdomain 2	14.5604 seconds
Time taken to render subdomain 3	17.6277 seconds
Total time taken	18.3981 seconds
Rank 0: Fraction of rays terminated early	0
Rank 1: Fraction of rays terminated early	0.0122877
Rank 2: Fraction of rays terminated early	0.0962398
Rank 3: Fraction of rays terminated early	0
Avg Fraction of rays terminated early	0.0257

3.2 Test Case 2 Results

Metric	Value
Time taken to read the dataset	0.405711 seconds
Max time taken to render the subdomain	13.6457 seconds
Time taken to render subdomain 0	13.6457 seconds
Time taken to render subdomain 1	13.6385 seconds
Time taken to render subdomain 2	13.0564 seconds
Time taken to render subdomain 3	13.6217 seconds
Time taken to render subdomain 4	13.6246 seconds
Time taken to render subdomain 5	13.2385 seconds
Time taken to render subdomain 6	13.6151 seconds
Time taken to render subdomain 7	13.6364 seconds
Total time taken	13.6457 seconds
Rank 0: Fraction of rays terminated early	0
Rank 1: Fraction of rays terminated early	0
Rank 2: Fraction of rays terminated early	0.0245269
Rank 3: Fraction of rays terminated early	0
Rank 4: Fraction of rays terminated early	0
Rank 5: Fraction of rays terminated early	0.015509
Rank 6: Fraction of rays terminated early	0.000143713
Rank 7: Fraction of rays terminated early	0
Avg Fraction of rays terminated early	0.00543

3.3 Test Case 3 Results

Metric	Value
Time taken to read the dataset	0.399906 seconds
Max time taken to render the subdomain	5.53708 seconds
Time taken to render subdomain 0	4.58764 seconds
Time taken to render subdomain 1	4.57337 seconds
Time taken to render subdomain 2	4.95237 seconds
Time taken to render subdomain 3	4.56246 seconds
Time taken to render subdomain 4	4.9289 seconds
Time taken to render subdomain 5	4.85575 seconds
Time taken to render subdomain 6	4.53324 seconds
Time taken to render subdomain 7	3.78057 seconds
Time taken to render subdomain 8	3.5994 seconds

Time taken to render subdomain 9	3.76022 seconds
Time taken to render subdomain 10	4.53367 seconds
Time taken to render subdomain 11	4.55299 seconds
Time taken to render subdomain 12	4.92492 seconds
Time taken to render subdomain 13	4.86277 seconds
Time taken to render subdomain 14	5.53708 seconds
Total time taken	5.88807 seconds
Rank 0: Fraction of rays terminated early	0
Rank 1: Fraction of rays terminated early	0
Rank 2: Fraction of rays terminated early	0
Rank 3: Fraction of rays terminated early	0
Rank 4: Fraction of rays terminated early	0
Rank 5: Fraction of rays terminated early	0
Rank 6: Fraction of rays terminated early	0
Rank 7: Fraction of rays terminated early	0.164397
Rank 8: Fraction of rays terminated early	0.259262
Rank 9: Fraction of rays terminated early	0.170363
Rank 10: Fraction of rays terminated early	0
Rank 11: Fraction of rays terminated early	0
Rank 12: Fraction of rays terminated early	0
Rank 13: Fraction of rays terminated early	0
Rank 14: Fraction of rays terminated early	0
Avg fraction of rays terminated early	0.148505

3.4 Test Case 4 Results

Metric	**Value**
Time taken to read the dataset	0.484728 seconds
Max time taken to render the subdomain	5.58455 seconds
Time taken to render subdomain 0	5.51523 seconds
Time taken to render subdomain 1	4.00589 seconds
Time taken to render subdomain 2	3.61874 seconds
Time taken to render subdomain 3	3.73047 seconds
Time taken to render subdomain 4	5.24405 seconds
Time taken to render subdomain 5	2.50838 seconds
Time taken to render subdomain 6	4.1608 seconds
Time taken to render subdomain 7	5.06256 seconds
Time taken to render subdomain 8	2.44245 seconds
Time taken to render subdomain 9	2.75207 seconds
Time taken to render subdomain 10	4.85032 seconds
Time taken to render subdomain 11	2.88984 seconds
Time taken to render subdomain 12	3.06973 seconds
Time taken to render subdomain 13	2.81992 seconds
Time taken to render subdomain 14	4.30542 seconds
Time taken to render subdomain 15	4.87351 seconds
Time taken to render subdomain 16	3.1882 seconds
Time taken to render subdomain 17	3.42773 seconds
Time taken to render subdomain 18	4.93916 seconds
Time taken to render subdomain 19	2.83242 seconds
Time taken to render subdomain 20	4.24881 seconds
Time taken to render subdomain 21	4.96544 seconds
Time taken to render subdomain 22	4.26463 seconds
Time taken to render subdomain 23	4.59775 seconds
Time taken to render subdomain 24	4.64949 seconds

Time taken to render subdomain 25	3.28168 seconds
Time taken to render subdomain 26	5.54181 seconds
Time taken to render subdomain 27	5.06106 seconds
Time taken to render subdomain 28	4.19519 seconds
Time taken to render subdomain 29	5.27845 seconds
Time taken to render subdomain 30	5.0328 seconds
Time taken to render subdomain 31	5.58455 seconds
Total time taken	5.58455 seconds
Rank 0: Fraction of rays terminated early	0
Rank 1: Fraction of rays terminated early	0
Rank 2: Fraction of rays terminated early	0
Rank 3: Fraction of rays terminated early	0
Rank 4: Fraction of rays terminated early	0
Rank 5: Fraction of rays terminated early	0
Rank 6: Fraction of rays terminated early	0
Rank 7: Fraction of rays terminated early	0
Rank 8: Fraction of rays terminated early	0
Rank 9: Fraction of rays terminated early	0
Rank 10: Fraction of rays terminated early	0
Rank 11: Fraction of rays terminated early	0
Rank 12: Fraction of rays terminated early	0
Rank 13: Fraction of rays terminated early	0
Rank 14: Fraction of rays terminated early	0
Rank 15: Fraction of rays terminated early	0
Rank 16: Fraction of rays terminated early	0
Rank 17: Fraction of rays terminated early	0.19407
Rank 18: Fraction of rays terminated early	0
Rank 19: Fraction of rays terminated early	0
Rank 20: Fraction of rays terminated early	0
Rank 21: Fraction of rays terminated early	0
Rank 22: Fraction of rays terminated early	0
Rank 23: Fraction of rays terminated early	0
Rank 24: Fraction of rays terminated early	0
Rank 25: Fraction of rays terminated early	0
Rank 26: Fraction of rays terminated early	0
Rank 27: Fraction of rays terminated early	0
Rank 28: Fraction of rays terminated early	0
Rank 29: Fraction of rays terminated early	0
Rank 30: Fraction of rays terminated early	0.000301205
Rank 31: Fraction of rays terminated early	0
Avg Fraction of rays terminated early	0.00607

4 Conclusion

The results highlight the performance of ray casting with parallel computing under different configurations.

- Time to render subdomains vary based on the number of processes used.
- Fraction of early termination depends on step size and the subdomains.
- Partition subdomains with the eye of black hole has higher early termination of rays (example: rank 3 in full bounds 1d decomposition)

5 Group Information

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