Homework 3 Report

Student Name: 施閔智
Student ID: 112062109

Inplementation

For the whole program

1. `load_image_color` and `save_image` loads the image in RGB form.
2. Search Algorithms implement at `full_search`, `log_search`, `three_step_search`.
   - A higher SAD means a poorer match between the target and predicted blocks, meaning the motion estimation is less accurate.
   - A higher PSNR means better prediction quality, with fewer differences between the target and predicted images.
3. `draw_motion_vectors` visualize the motion vectors with `cv2.arrowedLine`.
4. `compute_residual` compute the residual images.
5. `compute_SAD`, `compute_PSNR` do the performance calculation.
6. Tasks is precessed in `taskX` function, where X = 1,2,3,4.

Search Algorithms

Full Search

1. For each macroblock in the target image:
   - Extract the macroblock.
   - Search all possible displacements within the range [-p, p] in both horizontal and vertical directions.
   - Compute the SAD for each candidate macroblock in the reference image.
   - Select the displacement with the minimum SAD as the motion vector.
2. Update the predicted image using the best matching macroblocks.

2D Logarithmic Search

1. For each macroblock in the target image:
   - Start at the center of the search range.
   - Iteratively reduce the search step size by half.

   - At each step, evaluate the SAD for the center and four neighboring positions (up, down, left, right).
   - Move to the position with the minimum SAD and repeat until the step size is 1.
2. Update the predicted image using the best matching macroblocks.

Three-Step Search

1. For each macroblock in the target image:
   - Start at the center of the search range.
   - Use a fixed step size (p/2) for the first step and evaluate SAD for the center and eight surrounding positions.
   - Move to the position with the minimum SAD and reduce the step size by half.
   - Repeat for three steps, refining the motion vector at each step.
2. Update the predicted image using the best matching macroblocks.

Experimental Results

Task 1: Block Matching on 008-009

1.d

We evaluated Full Search and 2D Logarithmic Search under four configurations:
Search range `p ∈ {8,16}`, block size ∈ {8×8,16×16}

Method	Block Size	Search Range (p)	Total SAD	PSNR (dB)	Time (sec)
Full	8×8	8	9580644	29.08	22.799
Full	8×8	16	8529009	31.09	83.322
Full	16×16	8	11039398	27.93	7.284
Full	16×16	16	10102414	29.47	24.237
Log	8×8	8	10979841	28.22	1.701
Log	8×8	16	10373679	29.45	2.104
Log	16×16	8	11879352	27.51	0.487
Log	16×16	16	11284933	28.59	0.608

1.e : Discussion

Effect of Block Size

1. For Smaller Block Size, it have

   - Higher Accuracy: lower Total SAD and higher PSNR values.
   - Higher Computation Time: increase the number of blocks to process, leading to longer computation times.
2. For Larger Block Size, it have
   - Lower Accuracy: Larger blocks reduce motion estimation accuracy due to less flexibility, resulting in higher Total SAD and lower PSNR.
   - Faster Computation: Larger blocks reduce the number of blocks to process, improving computation time.

Effect of Search Range

1. For Smaller Search Range (p=8):

   - Faster Computation: A smaller search range reduces the number of candidate blocks to compare, leading to faster execution times.
   - Lower Accuracy for Large Motion: A smaller search range may fail to capture large displacements, resulting in higher Total SAD and lower PSNR.

2. Larger Search Range (p=16):

   - Higher Accuracy: A larger search range allows for better motion estimation, reducing Total SAD and improving PSNR.
   - Higher Computation Time: A larger search range significantly increases computation time, especially for Full Search.

Comparison of Full Search and Log Search

- Accuracy:

  - Full Search consistently achieves lower Total SAD and higher PSNR compared to Log Search across all settings. This is because Full Search exhaustively evaluates all possible displacements within the search range, ensuring the best match.
  - Log Search sacrifices some accuracy, trade for the speed, makes it a neutral option.

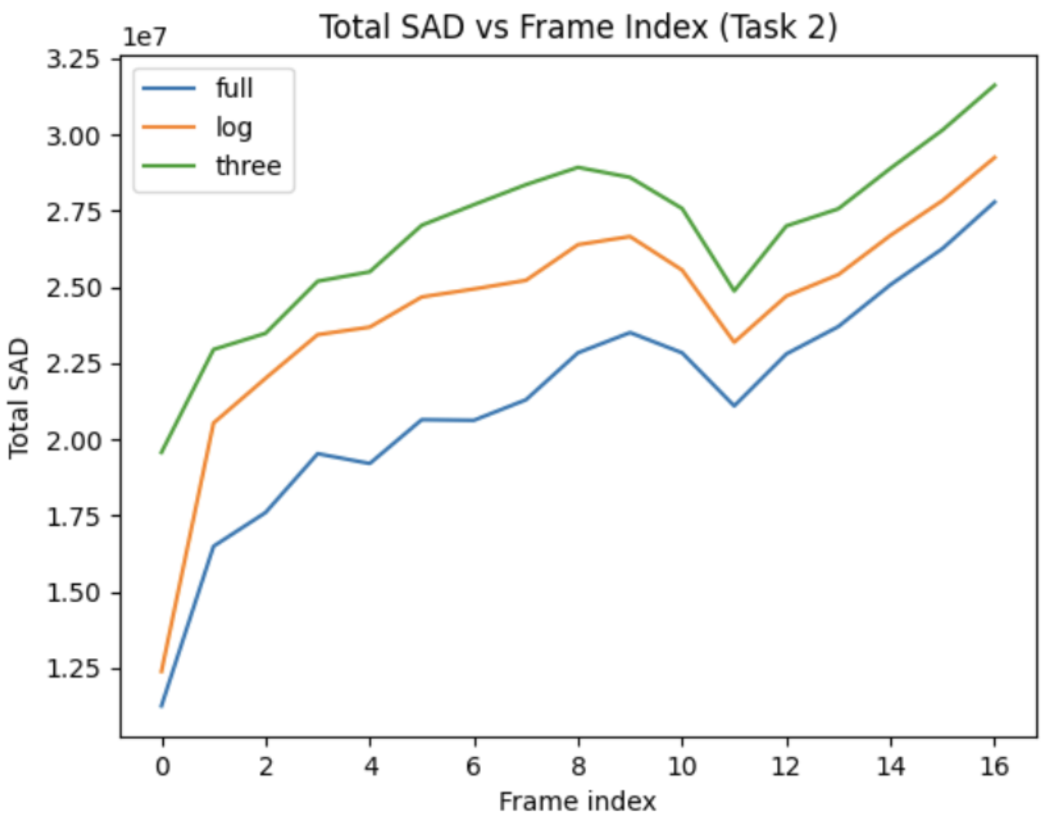
Overall

- Block Size: Smaller blocks improve accuracy but increase computation time, while larger blocks reduce accuracy but are faster.
- Search Range: Larger search ranges improve accuracy but significantly increase computation time, especially for Full Search.
- Full Search vs. Log Search: Full Search is more accurate but computationally expensive, while Log Search is faster but less accurate.

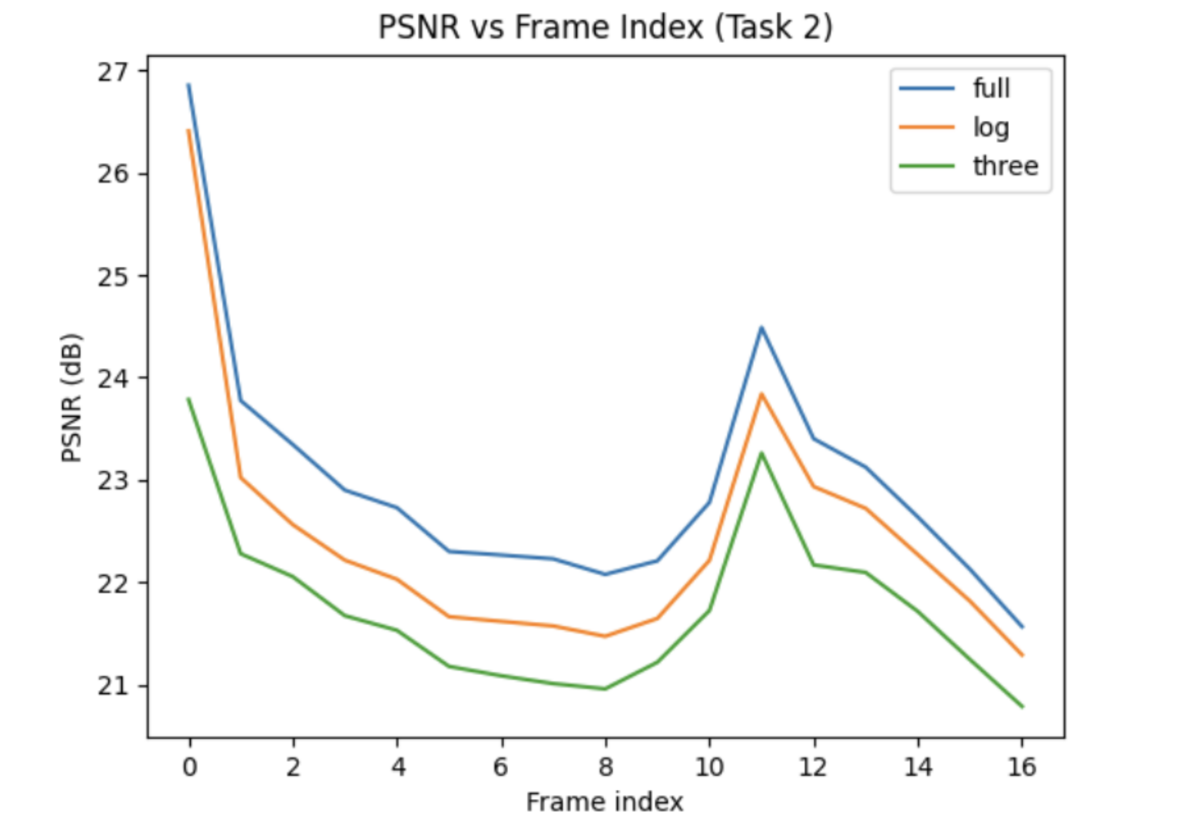
Task 2: Motion Estimation(Frames 001–017)

Evaluated all 3 methods on sequence (reference = `000.jpg`, targets = `001-017.jpg`).
Configuration: block size = 16×16, search range p = 8

- **SAD Curve:**



- **PSNR Curve:**



Discussion

1. SAD
    - Full Search
        - Full Search consistently achieves the lowest Total SAD across all frames, indicating the highest accuracy in motion estimation.
        - The Total SAD increases as the frame index increases, which is expected because the motion between the reference frame and subsequent frames becomes more significant.
    - Log Search
        - Log Search has slightly higher Total SAD compared to Full Search, as it sacrifices some accuracy for faster computation.
        - The trend of increasing Total SAD with frame index is similar to Full Search, but the gap between the two methods widens for later frames.
    - Three-Step Search:
        - Three-Step Search has the highest Total SAD among the three methods, indicating the lowest accuracy.

    - The Total SAD increases more rapidly compared to Full Search and Log Search, especially for later frames, as the method struggles to capture larger motions.

2. PSNR

    - Full Search
        - Full Search achieves the highest PSNR across all frames, reflecting its superior motion estimation accuracy.
        - The PSNR decreases as the frame index increases, which aligns with the increasing motion complexity in later frames.
    - Log Search
        - Log Search has slightly lower PSNR compared to Full Search, but the difference is not significant for earlier frames.
        - The PSNR trend follows a similar pattern to Full Search, with a gradual decline as the frame index increases.
    - Three-Step Search:
        - Three-Step Search has the lowest PSNR among the three methods, indicating the poorest motion estimation quality.
        - The PSNR decreases more steeply compared to the other methods, especially for later frames, as the method struggles with larger displacements.

3. Overall

    - Accuracy vs Speed Tradeoff:
        - Full Search provides the most accurate motion estimation (lowest Total SAD and highest PSNR) but is computationally expensive.
        - Log Search offers a good balance between accuracy and speed, making it suitable for real-time applications.
        - Three-Step Search is the fastest but sacrifices significant accuracy, especially for frames with large motion.
    - Dynamic Performance:
        - All methods show a decline in performance (higher Total SAD and lower PSNR) as the frame index increases, reflecting the increasing motion complexity in the sequence.
        - Full Search maintains the best performance across all frames, while Three-Step Search struggles the most with later frames.

Task 3: Comparison on 008-012 vs 08-009

Reference/Target	Method	Block Size	Search Range (p)	Total SAD	PSNR (dB)
8/12	Log	16×16	8	23185154	21.78
8/9	Log	16×16	8	11879352	27.51

1. Total SAD:
    - For 8/12, the Total SAD is 23185154, much higher than 11879352 for 8/9 in Question 1. This indicates larger and more complex motion between frames 8 and 12.
2. PSNR:
    - The PSNR for 8/12 is 21.78 dB, significantly lower than 27.51 dB for 8/9, reflecting poorer prediction quality due to larger motion.
3. Overall:
    - The larger temporal gap between frames 8 and 12 results in more significant motion, making it harder for Log Search to estimate accurately. This leads to higher residual errors and lower prediction quality compared to the smaller motion in 8/9.

Task 4: Time Complexity Analysis

Measured runtime for all methods at `p ∈ {8,16}` (block size = 16×16)

Method	Search Range §	Execution Time (sec)
Full	8	6.450
Full	16	23.684
Log	8	0.496
Log	16	0.836
Three	8	0.587
Three	16	0.786

Discussion

1. Theoretical Time Complexity
    - Full Search:
        - Complexity: $O(p^2 \times N)$, where p is the search range and N is the number of macroblocks.

        - Doubling the search range p increases the runtime approximately 4× due to the quadratic relationship.
    - Log Search:
        - Complexity: $O(\log(p) \times N)$, as it reduces the search space logarithmically.
        - Doubling the search range results in a small increase in runtime.
    - Three-Step Search:
        - Complexity: $O(N)$, as it performs a fixed number of steps (3) regardless of p.
        - Runtime is nearly independent of the search range.
2. Measured Execution Time
    - Full Search:
        - Execution time increases significantly with p (6.450s for $p=8$ vs. 23.684s for $p=16$), consistent with the $O(p^2)$ complexity.
    - Log Search:
        - Execution time increases slightly with p (0.496s for $p=8$ vs. 0.836s for $p=16$), matching the $O(\log(p))$ complexity.
    - Three-Step Search:
        - Execution time increases marginally with p (0.587s for $p=8$ vs. 0.786s for $p=16$), reflecting its near-constant complexity.
3. Overall

    Full Search is slow but accurate, Log Search balances speed and accuracy, and Three-Step Search is fastest but least accurate.
