

**parallel Computing 2025**

**M.Sc. Embedded Systems**



**Report Part 1**

**Group Members:**

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| **Mehdi Moallemkolaei** | **153010947** | [**mehdi.moallemkolaei@tuni.fi**](mailto:mehdi.moallemkolaei@tuni.fi) |
| **Md Ashfak Haider Nehal** | **153045077** | [**mdashfakhaider.nehal@tuni.fi**](mailto:mdashfakhaider.nehal@tuni.fi) |

# **Part 1.**

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## **6.1. Benchmarking the original Code and Improving Performance via Compiler Settings**

### **6.1.1 & 6.1.2: Original code in Debug mode Vs. Release mode**

It was tested on TC303 Lab PC:

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | Delays/Versions | Physics  (moving sat) | Graphics  (space coloring) | Total |
| 1 | **Original C – Debug Mode** | **~ 170 ms** | **~ 1257 ms** | **~ 1429 ms** |
|  | | | | **~ 1461 ms** |
| **~ 1407 ms** |
| **~ 1399 ms** |
| **~ 1433 ms** |
| **~ 1465 ms** |
| 2 | **Original C – Release Mode** | **~ 119 ms** | **~ 560 ms** | **~ 681 ms** |
|  | | | | **~ 676 ms** |
| **~ 693 ms** |
| **~ 694 ms** |
| **~ 670 ms** |
| **~ 684 ms** |

The Release build improves performance by ~52% overall versus Debug, mainly due to compiler optimizations.

First line in the table, shows the average over all frames after 10 first frames, and the other lines are sample frames randomly picked from 10 frames.

To run in the terminal (like for using seed):

.\out\build\x64-Release\parallel.exe

or

.\out\build\x64-Debug\parallel.exe

### **6.1.3. Auto Vectorization Report:**

**Did the compiler tell it managed to vectorize any of the loops in physics Engine or graphics Engine-functions?**No.

Enabling the flags in the CMake text file:

* target\_compile\_options(parallel PRIVATE "/Qvec-report:2")

The “Debug mode” Log does not contain any vectorization report.

The “Release mode” Log only shows:

* info C5002: loop not vectorized due to reason 'xxxx'

So, it means that no vectorization is done.

It reports like “C5002: loop not vectorized due to reason '1106/1203/1300/…'”.

For **ParallelPhysicsEngine**:

\Project\Satellites\parallel.c(129) : info C5002: loop not vectorized due to reason '1300'  
\Project\Satellites\parallel.c(142) : info C5002: loop not vectorized due to reason '1203'  
\Project\Satellites\parallel.c(138) : info C5002: loop not vectorized due to reason '1106'  
\Project\Satellites\parallel.c(177) : info C5002: loop not vectorized due to reason '1300'

For **ParallelGraphicsEngine**:

\Project\Satellites\parallel.c(226) : info C5002: loop not vectorized due to reason '500'  
\Project\Satellites\parallel.c(251) : info C5002: loop not vectorized due to reason '1104'  
\Project\Satellites\parallel.c(196) : info C5002: loop not vectorized due to reason '1106'

### **6.1.4. Best Flags:**

**Experiment with the SIMD instruction set and FP relaxation-related optimization flags. Which compilation flags did you find to give the best performance?**

We went through multiple scenarios to find the best flags:

|  |  |  |  |
| --- | --- | --- | --- |
| Instructions used | Time spent on moving satellites | Time spent on space coloring | Total time in ms between frames |
| Ash PC | | | |
| /fp:fast | 110 ms | 574 ms | 688 ms |
| /arch:AVX2 | 154 ms | 983 ms | 1142 ms |
| /fp:fast /arch:AVX2 | 97 ms | 567 ms | 668 ms |
| /fp:fast /arch:AVX | 108 ms | 567 ms | 679 ms |
| /arch:AVX | 153 ms | 981 ms | 1138 ms |
| /arch:sse4 | 154 ms | 988 ms | 1147 ms |
| /arch:avx512 | 153 ms | 977 ms | 1133 ms |
| /arch:sse4 /arch:avx512 | 153 ms | 976 ms | 1132 ms |
| /fp:fast /arch:avx512 | 110 ms | 573 ms | 686 ms |
| /fp:fast /arch:sse4 | 111 ms | 574 ms | 689 ms |
| /arch:AVX2 /arch:sse4 | 152 ms | 984 ms | 1141 ms |
| /arch:AVX2 /arch:avx512 | 154 ms | 980 ms | 1139 ms |
| Mehdi PC | | | |
| /fp:fast | 87 ms | 375 ms | 465 ms |
| /arch:AVX2 | 131 ms | 631 ms | 765 ms |
| /fp:fast /arch:AVX2 | 86 ms | 405 ms | 493 ms |
| /fp:fast /arch:AVX | 87 ms | 355 ms | 449 ms |
| /arch:AVX | 131 ms | 611 ms | 744 ms |
| /arch:sse4 | 132 ms | 615 ms | 750 ms |
| /arch:avx512 | 127 ms | 607 ms | 736 ms |
| /arch:sse4 /arch:avx512 | 129 ms | 610 ms | 746 ms |
| /fp:fast /arch:avx512 | 86 ms | 364 ms | 458 ms |
| /fp:fast /arch:sse4 | 86 ms | 364 ms | 452 ms |
| /arch:AVX2 /arch:sse4 | 129 ms | 602 ms | 733 ms |
| /arch:AVX2 /arch:avx512 | 127 ms | 601 ms | 731 ms |
| Lab PC | | | |
| /fp:fast | 83 ms | 334 ms | 420 ms |
| /arch:AVX2 | 118 ms | 548 ms | 668 ms |
| /fp:fast /arch:AVX2 | 81 ms | 368 ms | 450 ms |
| /fp:fast /arch:AVX | 78 ms | 324 ms | 404 ms |
| /arch:AVX | 122 ms | 561 ms | 685 ms |
| /arch:sse4 | 121 ms | 548 ms | 670 ms |
| /arch:avx512 | 118 ms | 555 ms | 676 ms |
| /arch:sse4 /arch:avx512 | 122 ms | 556 ms | 680 ms |
| /fp:fast /arch:avx512 | 78 ms | 331 ms | 411 ms |
| /fp:fast /arch:sse4 | 81 ms | 331 ms | 413 ms |
| /arch:AVX2 /arch:sse4 | 122 ms | 547 ms | 671 ms |
| /arch:AVX2 /arch:avx512 | 123 ms | 545 ms | 669 ms |

flags “**/fp:fast /arch:AVX**” gave the best results on 2/3 of tested PC setups. So, we choose this combo for the rest of our project.

However, this combo “/fp:fast /arch:AVX2” also showed a great result and we will also use this combo to compare with the first chosen combo to see which will give the best final result.  
  
\* Update: both combinations are tested on the final code and they both have the exact same final result.

### **6.1.5. Each Flag’s Performance**

**Can you explain what each of the optimization flags you found to give the best performance does?**

* **/fp:fast** - Relaxes strict IEEE-754 rules so the compiler can reorder and "contract" FP ops (e.g., form FMAs), use approximate recip/rsqrt, assume no NaNs/Infs, and reassociate expressions. This often unlocks SIMD for sqrt/div heavy code and reduces dependencies. Result: faster but slightly different numerics.
* **/arch:AVX** - Allows the autovectorizer to target AVX (256-bit YMM registers) for float/double SIMD. Wider vectors than SSE, but no integer AVX2 ops.
* **/arch:AVX2** - Enables AVX2 (still 256-bit, but with rich integer/vector ops and gathers). On FP workloads, also lets the compiler use FMA3 where profitable when contraction is allowed (e.g., with /fp:fast). Often the sweet spot-on modern CPUs.
* **/arch:AVX512** - Permits 512-bit vectors, mask registers, and wide loads/stores. Only used if the CPU/OS support it; many consumer CPUs don't, or the compiler may avoid it due to potential down-clocking. If unsupported, the compiler falls back to a lower ISA.
* **/arch:SSE4** - Targets 128-bit SSE4.x. Narrower vectors; useful for older CPUs, typically slower than AVX/AVX2 on modern chips.

### **6.1.6. Code Breaker Flags:**

**Did you find some compiler flags which cause broken code to be generated, and if so, can you think why?**

No breakage occurred.

## **6.2 Generic algorithm optimization**

**Can you find any ways to change the code to either get rid of unnecessary calculations, or allow the compiler to vectorize it better, to make it faster? If yes, what did you do and what is the performance with your optimized version?**

1. **Inside parallelGraphicsEngine(), replacing the sqrt and merging two satellite loops**

**Why it’s faster**

* Removes 2× sqrtf per pixel (black hole & first satellite loop).
* Eliminates the second satellite loop entirely (we accumulate numerator+weights on the first pass and normalize once).
* Replaces divisions by using the reciprocal once (invW) and squared-distance comparisons (SIMD-friendly).
* Keeps byte-for-byte semantics vs your current sequential engine (we preserved the “nearest baseline + 3·weighted average” behavior and the inside-radius early white).

**Vectorization angle**

* Squared distance + branch consolidation turns the inner loop into straight-line, division-light code. Compilers are far more willing to autovectorize dx\*dx + dy\*dy, reciprocal, FMAs, and min-tracking than a path with sqrt + break + two passes.

1. **Inside parallelGraphicsEngine(), removing % and /**

**Why is it faster**

* Eliminates one integer division and one modulo per pixel (both costly).
* Access patterns become perfectly linear, which the compiler and CPU prefetcher love.

**Vectorization angle**

Regular 2D loops + linear idx often trigger better auto vectorization and improved cache behavior.

**Performance**:

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  |  | moving satellites | space coloring | Total time |
| Ash PC | Before | 97 ms | 567 ms | 668 ms |
| After | 97 ms | 544 ms | 643 ms |
| Mehdi PC | Before | 87 ms | 355 ms | 449 ms |
| After | 85 ms | 354 ms | 444 ms |
| Lab PC | Before | 78 ms | 324 ms | 404 ms |
| After | 76 ms | 321 ms | 400 ms |

## **6.3. Multi-Thread Parallelization**

### **6.3.1. loops are allowed to be parallelized?**

**Which of the loops are allowed to be parallelized to multiple threads?**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| No. | Loop | Legal? | Worth doing? | Reasoning |
| 1 | Physics iteration | No | — | Loop-carried time dependence  (step t feeds step t+1). |
| 2 | Physics satellite | Yes | Yes | Independent per-satellite within a time step. |
| 3 | Graphics pixel | Yes | Definitely! | Massive, independent work per pixel. Ideal scaling. |
| 4 | Graphics satellite | Yes | Almost No | The trip count is small. Expensive to thread. Prefer SIMD inside each pixel. |

### **6.3.2. Legal Loops but not beneficial?**

**Are there loops which are allowed to be parallelized to multiple threads, but which do not benefit from parallelization to multiple threads? If yes, which and why?**

**Physics satellite** - Allowed, but not beneficial: putting #pragma omp for inside the time-step loop causes PHYSICSUPDATESPERFRAME (=100 000) barriers per frame; overhead kills scaling.

**Graphics satellite** - Allowed, but not beneficial: only 64 iterations, branchy (break) and reduction-like pattern → threads add overhead; better target is SIMD.

### **6.3.3. Code Transformations**

**Can you transform the code in some way (change the code without affecting the end results) which either allows parallelization of a loop which originally was not parallelizable, or makes a loop which originally was not initially beneficial to parallelize with OpenMP beneficial to parallelize with OpenMP? If yes, explain your code transformation?**

**Transformation 1** - Physics: loop interchange + register temporaries

What changed: Swapped the loop order so each thread owns a block of satellites and advances each one through all-time steps; kept x,y,vx,vy in registers and wrote back once at the end; used schedule(static).

Why it helps: Removes the 100,000 per-step barriers and avoids false sharing from repeatedly writing adjacent tmpPosition[i]/tmpVelocity[i]. Coarse grains per thread ⇒ good scaling.

Side math cleanup: Hoisted dt = DELTATIME/PHYSICSUPDATESPERFRAME, replaced two divides by |r| with one sqrt plus multiplies (invd, invd2).

**Transformation 2** - Graphics: parallelize rows, keep one-pass inner loop (no sqrt)

What changed: Parallelized the Graphics pixel loop by rows (#pragma omp parallel for schedule(static) over y); turned the pixel loop into a 2-D sweep (no %// per pixel); fused the two satellite passes into one pass that (a) early-outs to white if inside radius, (b) accumulates the weighted sums and weights, and (c) tracks the nearest using squared distance; normalized once.

Why it helps: Big, cache-friendly chunks (rows) minimize scheduling overhead and keep writes linear; removing sqrtf and extra pass slashes scalar cost and makes the inner loop SIMD-friendlier.

### **6.3.4. Transformation Effect**

**Does your code transformation have any effect on vectorization performed by the compiler?**

Yes, replacing sqrtf/two-pass logic with squared-distance + one pass reduces divisions and branches, which helps the compiler's autovectorizer (and at least improves instruction-level parallelism even if SIMD is limited). The physics inner loop still has a time dependency, so SIMD across steps is not expected; the cleaned math reduces stalls.

## **6.4. OpenMP Parallelization**

### **6.4.1. Average Frame times**

**What are the average frametimes (milliseconds) in your OpenMP-multithreaded version of the code?**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Setup used |  | Time spent on moving satellites | Time spent on space coloring | Total time in milliseconds between frames |
| Own PC Ash | **Without OpenMP** | **97 ms** | **544 ms** | **643 ms** |
| **With OpenMP** | **11 ms** | **84 ms** | **97 ms** |
| Own PC Mehdi | **Without OpenMP** | **95 ms** | **195 ms** | **293 ms** |
| **With OpenMP** | **8 ms** | **24 ms** | **34 ms** |
| Lab PC | **Without OpenMP** | **87 ms** | **170 ms** | **261 ms** |
| **With OpenMP** | **5 ms** | **16 ms** | **23 ms** |

### **6.4.2. Extra code transformations/optimizations**

**Physics (T1):** Loop interchange so that each thread owns a subset of **satellites** and advances them through **all time steps** (removes 100k step barriers). Kept x,y,vx,vy in **registers** and wrote back **once** to avoid false sharing. Hoisted dt=DELTATIME/PHYSICSUPDATESPERFRAME and replaced two divides-by-‖r‖ with one sqrt + multiplies.

**Graphics (T2):** Parallelized **rows** (outer pixel loop), changed to a **2-D sweep** (no per-pixel %//), removed sqrtf (squared-distance tests), and **fused the two satellite passes into one** (accumulate weights & nearest in one loop, then normalize once).

### **6.4.3. Which loops were parallelized?**

**Physics satellite (inner):** **Yes**, after loop interchange (OpenMP over satellites, one write-back per satellite).

**Graphics pixel (outer):** **Yes**, OpenMP over **rows** (schedule(static)).

### **6.4.4. OpenMP break?**

**Did any OpenMP parallelization break or slow things down?**

* **Naïve Physics satellite inside the time-step loop:** **Slowed down** due to **~100,000 barriers per frame**; also, more false sharing from per-step writes to adjacent tmpPosition[i]/tmpVelocity[i].  
  **Fix:** loop interchange + keep per-satellite state in registers, write back once, schedule(static).
* **Graphics pixel with collapse (2) and aggressive SIMD on MSVC:** Slight regression (scheduling overhead + conservative SIMD); the **row-parallel** version with one-pass inner loop was consistently faster.

### **6.4.5. Scaling with core/hardware threads**

**Did the performance scale with the number of CPU cores or native CPU threads (if you have an AMD Ryzen, or Intel Core i7 or i3 CPU, cores may be multi-threaded and can execute two threads simultaneously)? If not, why?**

Performance improved substantially when OpenMP was enabled and loops were coarse-grained (rows/satellites). On typical 6-16 logical-thread CPUs, **Graphics pixel** dominates scaling; **Physics** scales well after loop-interchange. If scaling plateaus, the reasons are:

1. **Graphics-bound:** once graphics time dominates, adding threads to physics yields little change.
2. **Runtime overhead:** too-fine task slicing (fixed by schedule(static) and coarse-grained).
3. **Memory bandwidth/cache effects:** especially at high thread counts.

### **6.4.6. Bonus Task**

**As a bonus question, you are now free to implement any CPU optimizations (incl. advanced multicore and vectorization optimizations) to your program as long as your algorithm produces correct results and passes the error check. How fast can you get your program on a CPU? Please, report your methods.**

The additional work on structures and mathematics to reduce latency is described in each related question in this report. like in [6.3.3](#_6.3.3._Code_Transformations), [6.4.2](#_6.4.2._Extra_code_1), or other answers.

### **6.4.7. Machine and Environment**

We did the project both on a computer at TC303 and on our own PC to test the functionality and differences.

|  |  |
| --- | --- |
| Setup | Configuration |
| Ashfak PC | Processor: Intel(R) Core (TM) i5-10400F CPU @ 2.90 GHz  RAM: 16GB  Compiler: Virtual Studio x64  Version: 4.8.09032 |
| Mehdi PC | Processor: Intel(R) Core (TM) i7-12700H CPU @ 2.30 GHz  RAM: 16GB  Compiler: Virtual Studio x64  Version: 4.8.09032 |
| Lab PC | Processor: Intel(R) Core (TM) i7-13700 CPU @ 2.10 GHz  RAM: 64GB  Compiler: Virtual Studio x64  Version: 4.8.09032 |

### **6.4.8. Hours to complete Part 1**

We spent approximately two weeks finishing part 1.

~2 hr/day, total of around 30 hrs.