SUPPORTING OpenMP 5.0 Tasks in hpxMP - A study of an OpenMP implementation within Task Based Runtime Systems

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ABSTRACT

OpenMP has been the de facto standard for single node parallelism for more than a decade. Recently, asynchronous many-task runtime (AMT) systems have increased in popularity as a new programming paradigm for high performance computing applications. One of the major challenges of this new paradigm is the incompatibility of the OpenMP thread model and other AMTs. Highly optimized OpenMP-based libraries do not perform well when coupled with AMTs because the threading of both libraries will compete for resources. This paper is a follow-up paper on the fundamental implementation of hpxMP, an implementation of the OpenMP standard which utilizes the C++ standard library for Parallelism and Concurrency (HPX) to schedule and manage tasks [1]. In this paper, we present the implementation of task features, e.g. \texttt{taskgroup}, \texttt{task depend}, and \texttt{task_reduction}, of the OpenMP 5.0 standard and optimization of the \texttt{#pragma omp parallel for} pragma. We use the daxpy benchmark, the Barcelona OpenMP Tasks Suite, Parallel research kernels, and OpenBLAS benchmarks to compare the different OpenMP implementations: hpxMP, llvm-OpenMP, and GOMP. We conclude that hpxMP is one possibility to overcome the competition for resources of the different thread models by providing a subset of the OpenMP features using HPX threads. However, the overall performance of hpxMP is not yet comparable with legacy libraries, which are highly optimized for a different programming paradigm and optimized over a decade by many contributors and compiler vendors.

Keywords OpenMP, hpxMP, Asynchronous Many-task Systems, C++, clang, gcc, HPX

1 Introduction

Asynchronous many-task (AMT) systems have emerged as a new programming paradigm in the high performance computing (HPC) community [2]. Many of these applications would benefit from the highly optimized OpenMP-based linear algebra libraries currently available. e.g.\ eigen, blaze, Intel MKL. However, there is a gap between OpenMP and AMT systems, since the user level threads of the AMT systems interfere with the system threads of OpenMP preventing efficient execution of the application.

To close this gap, this paper introduces hpxMP, an implementation of the OpenMP standard, which utilizes a C++ standard library for parallelism and concurrency (HPX) [3] to schedule and manage tasks. HpxMP implements the OpenMP standard conform \texttt{#pragma omp parallel for} pragma [1]. Furthermore, the OpenMP standard has, since OpenMP 3.0 [4], begun to introduce task-based concepts such as depended tasks and task groups (OpenMP 4.0 [5]), task-loops (OpenMP 4.5 [6]), and detached tasks (OpenMP 5.0 [7]). This work extends hpxMP with the \texttt{#pragma omp task} pragma to provide the concept of task-based programming and validates its implementation against the
Barcelona OpenMP Tasks Suite. Next, hpxMP is validated against the daxpy benchmark, OpenBLAS, and Parallel Research Kernels benchmarks to compare the different OpenMP implementations: hpxMP, llvm-OpenMP, and GOMP.

This paper is structured as follows: Section 2 covers the related work. Section 3 briefly introduces the features of HPX utilized for the implementation of tasks within hpxMP. Section 4 emphasizes the implementation of OpenMP tasks within the HPX framework and shows the subset of OpenMP standard features implemented within hpxMP. Section 5 shows the comparison of the different OpenMP implementations and finally, Section 6 concludes the work.

2 Related Work

Multi-threading solutions

For the exploitation of shared memory parallelism on multi-core processors many solutions are available and have been intensively studied. The most language independent one is the POSIX thread execution model [8] which exposes fine grain parallelism. In addition, there are more abstract library solutions like Intel’s Threading Building Blocks (TBB) [9], Microsoft’s Parallel Pattern Library (PPL) [10], and Kokkos [11]. TBB provides task parallelism using a C++ template library. PPL provides in addition features like parallel algorithms and containers. Kokkos provides a common C++ interface for parallel programming models, like CUDA and pthreads. Programming languages such as Chapel [12] provide parallel data and task abstractions. Cilk [13] extends the C/C++ language with parallel loop and fork-join constructs to provide single node parallelism. For a very detailed review we refer to [2].

With the OpenMP 3.0 standard [4] the concept of task-based programming was added. The OpenMP 3.1 [14] standard introduced task optimization. Depend tasks and task groups provided by the OpenMP 4.0 standard [5] improved the synchronization of tasks. The OpenMP 4.5 [6] standard allows task-based loops and the OpenMP 5.0 [7] standard allows detaching of tasks, respectively.

Integration of Multi-threading solutions within distributed programming models.

Some major research in the area of MPI+X [15–18], where the Message Passing Interface (MPI) is used as the distributed programming model and OpenMP as the multi-threaded shared memory programming model has been done. However, less research has been done for AMT+X, where asynchronous many-task systems are used as the distributed programming model and OpenMP as the shared memory programming model. Charm++ integrated OpenMP’s shared memory parallelism to its distributed programming model for improving the load balancing [19]. Kstar, a research C/C++ OpenMP compiler [20], was utilized to generate code compatible with StarPU [21] and Kaapi [22]. Only Kaapi implements the full set of OpenMP specification [23], such as the capability to create task into the context of a task region. The successor XKaapi [24] provides C++ task-based interface for both multi-core and multi-GPUs and only Kaapi provides mult-cluster support.

3 C++ Standard Library for Concurrency and Parallelism (HPX)

HPX is an open source C++ standard conferment library for parallelism and concurrency for applications of any scale. One specialty of HPX is that its API offers a syntactic and semantic equivalent interface for local and remote function calls. HPX incorporates well known concepts, e.g. static and dynamic dataflows, fine-grained futures-based synchronization, and continuation-style programming [25]. For more details we refer to [25–31].

After this brief overview, let us look into the relevant parts of HPX in the context of this work. HPX is an implementation of the ParalleX execution model [32] and generates hundreds of millions of so-called light-weight HPX-threads (tasks). These light-weight threads provide fast context switching [3] and lower overheads per thread to make it feasible to schedule a large number of tasks with negligible overhead [33]. However, these light-weighted HPX threads are not compatible with the user threads utilized by the current OpenMP implementation. For more details we refer to our previous paper [1]. This work adds support of OpenMP 5.0 task features to hpxMP. With having a light-weighted HPX thread-based implementation of the OpenMP standard it enables applications that already use HPX for local and distributed computations to integrate highly optimized libraries that rely on HPX in future.

4 Implementation of hpMP

hpxMP is an implementation of the OpenMP standard, which utilizes a C++ standard library for parallelism and concurrency (HPX) [3] to schedule and manage threads and tasks. We have described the fundamental implementation of hpxMP in previous work [1]. This section addresses the implementation of few important classes in hpxMP, task
features, such as taskgroup, task depend, and task_reduction in the OpenMP 5.0 standard [7], within hpxMP and its optimization for the thread and task synchronization which are the new contribution of this work.

4.1 Class Implementation

An instance of omp_task_data class is set to be associated with each HPX thread by calling hpx::threads::set_thread_data. Instances of omp_task_data are passed by a raw pointer which is reinterpret_casted to size_t. For better memory management, a smart pointer boost::intrusive_ptr is introduced to wrap around omp_task_data. The class omp_task_data consists the information describing a thread, such as a pointer to the current team, taskLatch for synchronization and if the task is in taskgroup. The omp_task_data can be retrieved by calling hpx::threads::get_thread_data when needed, which plays an important role in hpxMP runtime.

Another important class is parallel_region, containing information in a team, such as teamTaskLatch for task synchronization, number of threads requested under the parallel region, and the depth of the current team.

4.2 Task Construct

Explicit tasks are created using the task construct in hpxMP. hpxMP has implemented the most recent OpenMP 5.0 tasking features and synchronization constructs, like task, taskyield, and taskwait. The supported clause associated with #pragma omp task are reduction, untied, private, firstprivate, shared, and depend.

 Explicit tasks are created using #pragma omp task in hpxMP. HPX threads are created with the task directives and tasks are running on these HPX threads created. __kmpc_omp_task_alloc is allocating, initializing tasks and then return the generated tasks to the runtime. __kmpc_omp_task is called with the generated taskId parameter and passed to the hpx_runtime::create_task. The tasks are then running as a normal priority HPX thread by calling function hpx::applier::register_thread_nullary, see Listing 1. Synchronization in tasking implementation of hpxMP are handled with HPX latch, which will be discussed later in Section 4.3.

Task dependency was introduced with OpenMP 4.0. The depend clause is #pragma omp task depend(in: x) depend( out: y)depend(inout: z). Certain dependency should be satisfied among tasks specified by users. In the implementation, future in HPX is employed. The functionality called hpx::future allows for the separation of the initiation of an operation and the waiting for the result. A list of tasks that current task depend on are stored in a vector<shared_future<void>> and hpx::when_all(dep_futures) are called to inform the current task when it is ready to run.

OpenMP 5.0 added great extension to the tasking structure in OpenMP task_reduction along with in_reduction gives users a way to tell the compiler reduction relations among tasks and specify the tasks in taskgroup which are participating the reduction. The implementation of taskgroup can be found in Listing 2. Reduction data is handled in kmpc_task_reduction_init, by assigning them to the taskgroups, and return the taskgroup data back to the runtime. #pragma omp task in_reduction ( operator : list ) tells the runtime which task is participating the reduction, and retrieves the reduction data by calling __kmpc_task_reduction_get_th_data. kmpc_task_reduction_fin is called by kmpc_end_taskgroup, cleaning memory allocated and finish the task reduction properly.

4.3 Thread and Task Synchronization

In this work we improved the performance of hpxMP over previous versions [1] by optimizing the control structures used for thread synchronization. Previously, an exponential back-off is used for thread synchronization. Now, HPX latch, see Listing 3, provides an easier to use and more efficient way to manage thread and task synchronization originally proposed in the draft C++ library Concurrency Technical specification[1]. Latch in HPX is implemented with mutex, condition variable, and locks however is well-designed and higher level. An internal counter is initialized in a latch to keep track of a calling thread needs to be blocked. The latch blocks one or more threads from executing until the counter reaches 0. Several member functions such as wait(), count_up(), count_down(), count_down_and_wait() of the Latch class is provided. The difference between count_down() and count_down_and_wait() is if the thread will be blocked if the data member inside Latch is not equal to 0 after decreasing the counter by 1. In parallel regions, when one thread is spawning a team of threads, an HPX latch called threadLatch will be initialized to threads_requested+1 and member function threadLatch. count_down_and_wait() is called by the parent thread after threads are spawned, making parent threads wait for child threads to finish their work. The Latch is passed as a reference to each child thread and the member function

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[1] https://github.com/cplusplus/concurrency-ts/blob/master/latch_barrier.html
Listing 1: Implementation of task scheduling in hpxMP

```c
1 void __kmpc_omp_task_alloc(...)
2 {
3     kmp_task_t *task = (kmp_task_t*)new char [task_size + sizeof_shareds];
4     // lots of initialization goes on here
5     return task;
6 }
7 }
8 void hpx_runtime::create_task(kmp_routine_entry_t task_func, int gtid, intrusive_ptr<kmp_task_t> kmp_task_ptr)
9 {
10     auto current_task_ptr = get_task_data();
11     // this is waited in taskwait, wait for all tasks before taskwait created to be done
12     current_task_ptr->taskLatch.count_up(1);
13     // count up number of tasks in this team
14     current_task_ptr->team->teamTaskLatch.count_up(1);
15     // count up number of task in taskgroup if we are under taskgroup construct
16     if(current_task_ptr->in_taskgroup)
17         current_task_ptr->taskgroupLatch->count_up(1);
18     // Create a normal priority HPX thread with the allocated task as argument.
19     hpx::applier::register_thread_nullary(.....)
20     return 1;
```

Listing 2: Implementation of __kmpc_taskgroup and __kmpc_end_taskgroup in hpxMP

```c
1 void __kmpc_taskgroup(ident_t *loc, int gtid)
2 {
3     auto task = get_task_data();
4     intrusive_ptr<kmp_taskgroup_t> tg_new(new kmp_taskgroup_t());
5     tg_new->reduce_num_data = 0;
6     task->td_taskgroup = tg_new;
7     task->in_taskgroup = true;
8     task->taskgroupLatch.reset(new latch(1));
9 }
10 void __kmpc_end_taskgroup(ident_t *loc, int gtid)
11 {
12     auto task = get_task_data();
13     task->tg_exec.reset();
14     task->taskgroupLatch->count_down_and_wait();
15     task->in_taskgroup = false;
16     auto taskgroup = task->td_taskgroup;
17     if (taskgroup->reduce_data != NULL)
18         __kmp_task_reduction_fini(nullptr, taskgroup);
19 }
```

threadLatch.count_down() is called by each child thread when their works are done. When all the child threads have called the member function, the internal counter of threadLatch will be reduced to 0 and the thread will be released. For task synchronization, the implementation is trickier and needs to be carefully designed. In Listing 1, three Latches taskLatch, teamTaskLatch, and taskgroupLatch are count_up(1) when a task is created. Based on the definition of OpenMP standard, tasks are not necessarily synchronized unless a #pragma omp taskwait or #pragma omp barrier is called either explicitly or implicitly, see Listing 4. The member function of Latch count_down(1) is called when a task is done with its work. TaskLatch only matters when #pragma omp taskwait is specified, where taskLatch.wait() is called, making sure the current task is suspended until all child tasks that it generated before the taskwait region complete execution. The teamTaskLatch is used to synchronize all the tasks under a team, including all child tasks this thread created and all of their descendant tasks. An implicit barrier is always triggered at the end of parallel regions, where team->teamTaskLatch.wait() is called and the current task can be suspended. Taskgroup implementation in hpxMP is similar to a barrier, see Listing 2. All tasks under the same taskgroup are blocked until the taskgroupLatch->count_down_and_wait() function inside kmpc_end_taskgroup is called by all child tasks and their descend tasks.

4.4 Recap of the implementation

This sections summarizes the previous presented features of the OpenMP standard implemented with hpxMP. Table 1 shows the directives provided by the program layer and correspond to the main part of the presented library. Table 2 shows the runtime library functions of the OpenMP standard provided by hpxMP. Of course, the pragmas and runtime
library functions are only a subset of the OpenMP specification, but one step to bridge the compatibility gap between OpenMP and the HPX runtime system.

### 5 Comparison of the OpenMP implementations

In this paper, the Daxpy Benchmark, Parallel Research Kernels and Barcelona OpenMP Tasks Suite are used to compare the performance between three different implementations: hpxMP, llvm-OpenMP, and GOMP, which are provided by the authors, Intel, and GNU project respectively. The threads are pinned under each measurement for llvm-OpenMP and GOMP. The Blazemark benchmarks\(^2\) from the authors previous work [1] are rerun to emphasize the recent improvements of performance. The benchmarks are tested on Marvin (2 x Intel\textsuperscript{®} Xeon\textsuperscript{®} CPU E5-2450 0 @ 2.10GHz and 48 GB RAM), a node having 16 physical cores in two NUMA domains.

The versions of Clang, GCC, LLVM OpenMP and GOMP used were 8.0.0, 9.1.0, 4.5 and 4.5 respectively. We used hpxMP with commit id d9234c2, HPX with commit id 414380e, Blaze 3.4\(^3\), Boost 1.70 and gperftools 2.7. The operating system used was CentOS 7.6.1810 with kernel 3.10.

\(^2\)https://bitbucket.org/blaze-lib/blaze/wiki/Benchmarks
\(^3\)https://bitbucket.org/blaze-lib/blaze/
omp_get_dynamic  omp_get_max_threads
omp_get_num_procs omp_get_num_threads
omp_get_thread_num omp_get_wtick
omp_get_wtime  omp_in_parallel
omp_init_lock  omp_init_nest_lock
omp_set_dynamic omp_set_lock
omp_set_nest_lock omp_set_num_threads
omp_test_lock  omp_test_nest_lock
omp_unset_lock  omp_unset_nest_lock

Table 2: Directives implemented in the program layer of hpxMP. These functions correspond to the main part of the presented library.

5.1 Daxpy Benchmark

In order to compare the performance of #pragma omp parallel for, which is a fundamental pragma in OpenMP, Daxpy benchmark is used in this measurement. Daxpy is a benchmark that measures the multiplication of a float number $c$ with a dense vector $a$ consists 32 bit floating numbers, then add the result with another dense vector $b$ (32 bit float), the result is stored in the same vector $b$, where $c \in \mathbb{R}$ and $a, b \in \mathbb{R}^n$.

The Daxpy benchmark compares the performance calculated in Mega Floating Point Operations Per Second (MFLOP/s). We determine the speedup of the application by scaling our results to the single-threaded run of the benchmark using hpxMP.

Figure 1 shows the speedup ratio with different numbers of threads. Our first experiment compared the performance of the OpenMP implementations when the vector size was set to $10^3$, see Figure 1d. llvm-OpenMP runs the fastest while following with GOMP and hpxMP. Figure 1c shows that with a vector size of $10^4$, GOMP and llvm-OpenMP are still able to exhibit some scaling while hpxMP struggles to scale past 4 threads. For very large vector sizes of $10^5$ and $10^6$, the three implementations perform almost identically. hpxMP is able to scale in these scenarios because there is sufficient work in each task in order to amortize the cost of the task management overheads.

5.2 DGEMM benchmark

We chose to use the DGEMM benchmark from Parallel Research Kernels\(^4\) [34] to test our implementation. The purpose of the DGEMM program is to test the performance doing a dense matrix multiplication. The DGEMM benchmark compares the performance calculated in execution time (seconds). Figure 2 shows the execution time with different numbers of threads. The performance of the OpenMP implementations when the matrix size was set to $10^3$ is shown in Figure 2a. hpxMP and llvm-OpenMP runs perform similar while both outperform GOMP; Figure 2b shows that with a matrix size of 100, GOMP and llvm-OpenMP are still able to exhibit some scaling while hpxMP struggles to scale past 4 threads and is slower that GOMP after 8 threads.

5.3 Barcelona OpenMP Task Suit

We chose to use the fast parallel sorting variation of the ordinary mergesort [35] of the Barcelona OpenMP Tasks Suite to test our implementation of tasks. We sorted a random array with $10^7$ 32-bit numbers is sorted with cut off values from $10$ to $10^7$. The cut off value determines when to perform serial quicksort instead of dividing the array into 4 portions recursively when tasks are created. Higher cut off values create larger size of tasks and, therefore, fewer tasks are created. In order to simplify the experiment, parallel merge is disabled and the threshold for insertion sort is set to 1 in this benchmark. For each cut off value, the execution time of hpxMP using 1 thread is selected as the base point to calculate speedup values. Figure 3 shows the speedup ratio when using different numbers of threads.

For the cut off value $10^7$ (Figure 3a), the array is divided into four sections and four tasks in total are created. The speed up curve rapidly increases when moving from 2 threads to 4, but no significant speedup is achieved when using more than 4 threads in all three implementations. HpxMP and llvm-OpenMP show comparable performance while GOMP is slower.

The cut off value of $10^5$ (Figure 3b) increases the number of tasks generated. In this case, llvm-OpenMP has a performance advantage while hpxMP and GOMP show comparable performance.

\(^4\)https://github.com/ParRes/Kernels
Figure 1: Scaling plots for the Daxpy benchmarks running with different vector sizes: (a) $10^6$, (b) $10^5$, (c) $10^4$, and (d) $10^3$. Larger vector sizes mean larger tasks are created. The speedup is calculated by scaling the execution time of a run by the execution time of the single threaded run of hpxMP. A larger speedup factor means a smaller execution time of the sample.

Figure 2: Scaling plots for the Parallel Research Kernels DGEMM Benchmarks ran with the vector size of: (a) 1000, (b) 100. The relation between time consumed and the number of threads using hpxMP, llvm-OpenMP, and GOMP are plotted. The time consumed is calculated by the execution time (s). A smaller time execution time means better performance of the sample.
Figure 3: Scaling plots for the Barcelona OpenMP Task suit’s Sort Benchmarks ran with the cut off values of: (a) $10^7$, (b) $10^5$, (c) $10^3$, and (d) 10. Higher cut off values indicate a smaller number of larger tasks are created. The speed up is calculated by scaling the execution time of a run by the execution time of the single threaded run of hpxMP.

For the cut off value $10^3$ (Figure 3c), llvm-OpenMP shows a distinct performance advantage over hpxMP and GOMP. Nevertheless, hpxMP still scales across all the threads while GOMP has ceased to scale past 8 threads.

For a cut off value of 10 (Figure 3d), a significant number of tasks are created and the work for each task is considerably small. Here, hpxMP does not scale due to the large amount of overheads associated with the creation of many user tasks. Because each task performs little work, the overhead that they create is not amortized by the increase in concurrency.

For a global view, the speedup ratio $r$ is shown in Figure 4, where the larger the heatmap value is, the better performance OpenMP has achieved in comparison to hpxMP. Values below 1 mean that hpxMP outperforms the OpenMP implementation. As shown in the heatmap, llvm-OpenMP works best when the task granularity is small and the number of tasks created is high. GOMP is slower than both implementations in most cases. For large task sizes, hpxMP is comparable with llvm-OpenMP (Figure 4a). This result demonstrates that when the grain size of the task is chosen well hpxMP will not incur a performance penalty. Here, some more research has to be done on how hpxMP can handle task granularity and limit the overhead in task management for small grain sizes. Some related work can be found here [23, 24, 36–38].

5.4 Blazemark

In this section, the dmatdmatadd benchmark from Blaze’s benchmark suite is rerun to demonstrate the recent improvements in performance when compared to the authors previous work [1]. Blaze [39] is a high performance C++ linear algebra library which can use different backends for parallelization. It also provides a benchmark suite called Blazemark for comparing the performance of several linear algebra libraries, as well as different backends used by Blaze, for a selection of arithmetic operations. The results obtained from dmatdmatadd are presented and 4 graphs are illustrated for a specific number of cores (1, 4, 8, and 16) accordingly. The series in the graphs are obtained by running the benchmark with llvm-OpenMP, an older version of hpxMP, and the current state of hpxMP [1].

https://bitbucket.org/blaze-lib/blaze/wiki/Benchmarks
Figure 4: Speedup Ratio of Barcelona OpenMP Task suite’s Sort Benchmark ran over several threads and cut off values using the hpxMP, llvm-OpenMP, and GOMP implementations. Values greater than 1 mean that the OpenMP implementation achieved better performance when compared to hpxMP. Values below 1 indicate that hpxMP outperformed the OpenMP implementation.

Figure 5: Scaling plots for dmatmatadd Benchmarks for different number of threads, compared to llvm-OpenMP and previous work of the authors [1]: (a) 1, (b) 4, (c) 8, and (d) 16
The Dense Matrix Addition benchmark (dmatdmatadd) adds two dense matrices $A$ and $B$, where $A, B \in \mathbb{R}^{n \times n}$, and writes the result in matrix $C \in \mathbb{R}^{n \times n}$. The operation can be written as $C[i, j] = A[i, j] + B[i, j]$. Blaze uses the threshold of 36, 100 elements, which corresponds to matrix size 190 by 190, before parallelizing the operation. Matrices with less than 36, 100 elements are added sequentially. Figure 5 demonstrates the new scaling results for the dmatdmatadd benchmark using 1, 4, 8, and 16 cores. We observe notable improvement in performance between the previous version of hpxMP and the current version. The performance more closely mimic that of llvm-OpenMP.

5.5 Discussion

With the results presented above, we showed that hpxMP has similar performance to llvm-OpenMP for larger input sizes. For some specific cases hpxMP was faster than llvm-OpenMP. This occurred because the operation of joining HPX threads at the end of a parallel region introduces less overheads than the corresponding operation in llvm-OpenMP. Joining the HPX threads are now done with a latch which is executed in user space. The cost of the operation amounts to a single atomic decrement per spawned HPX thread. However, llvm-OpenMP uses kernel threads and therefore must wait for the operating system to join the participating threads.

For smaller input sizes however, the hpxMP is less performant as the overheads introduced by the HPX scheduler are more significant compared to the actual workload. HPX threads require their own stack segment as HPX threads are allowed to be suspended. OpenMP does not incur this overhead as launched tasks are not able to be suspended. In this way, the llvm-OpenMP implementation produces fewer scheduling overheads.

6 Conclusion and Outlook

This work extended hpxMP, an implementation of the OpenMP standard utilizing the light-weight user level threads of HPX, with a subset og the task features of the OpenMP 5.0 standard. This contribution is one step towards the compatibility between OpenMP and AMT systems as it demonstrates a technique that enables AMT system to leverage highly-optimized OpenMP libraries. For the Barcelona OpenMP Task benchmark, hpxMP exhibited similar performance when compared to other OpenMP runtimes for large task sizes. However, it was not able to compete with these runtimes when faced with small tasks sizes. This performance decrement arises from the more general purpose threads created in HPX. For the #pragma omp parallel for pragma, hpxMP has similar performance for larger input sizes. By using the HPX latch, the performance could be improved. These results show that hpxMP provides a way for bridging the compatibility gap between OpenMP and AMTs with acceptable performance for larger input sizes or larger task sizes.

In the future, we plan to improve performance for smaller input sizes by adding non-suspending threads to HPX, which do not require a stack, and thus reduce the overhead of thread creation and management. Additionally we plan to test the performance of HPX applications which use legacy OpenMP libraries, e.g. Intel MKL. However, more of the OpenMP specification needs to be implemented within hpxMP. These experiments will serve as further validation of the techniques introduced in this paper.

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A Source code

The source code of hpxMP [40] and HPX is available on github released under the BSL-1.0.

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