Anytime Multi-Agent Path Finding using Operation Parallelism in Large Neighborhood Search

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ABSTRACT

Multi-Agent Path Finding (MAPF) is the problem of finding a set of collision-free paths for multiple agents in a shared environment while minimizing the sum of travel times. The current state-of-the-art anytime algorithm for MAPF is based on Large Neighborhood Search (LNS), called MAPF-LNS, which is a combinatorial search algorithm that iteratively destroys and repairs a subset of collision-free paths. In this paper, we propose Destroy-Repair Operation Parallelism for LNS (DROP-LNS), a parallel framework that performs multiple destroy and repair processes simultaneously to explore a larger searching space under a limited time budget. Unlike MAPF-LNS, DROP-LNS is able to exploit parallelized hardware to improve the solution quality. We extend DROP-LNS to two alternatives and conduct experimental evaluations to compare the performance. The results show that DROP-LNS significantly outperforms the state-of-the-art.

KEYWORDS

Multi-Agent Path Finding, Anytime Algorithm, Parallelism

1 INTRODUCTION

A wide range of real-world applications can be formulated as Multi-Agent Path Finding (MAPF) problem such as autonomous warehouse [6] and unmanned aerial vehicles [1]. MAPF aims to find a set of collision-free paths, each from an assigned start location to a goal location, for multiple agents in a shared environment while minimizing the sum of travel time [5]. However, solving MAPF optimally is NP-hard, which limits the scalability of many algorithms [7]. MAPF is based on a undirected and unweighted graph, where $k$ agents navigate from their start vertices to their goal vertices. At each discretized timestep, an agent is allowed to move to an adjacent vertex or wait at its current vertex. A path for an agent is a sequence of vertices indicating where the agent is at each timestep, with the path cost being the total timesteps for the agent to move from its start vertex to its goal vertex. The objective of MAPF is to minimize the suboptimality ratio, defined as sum of path cost/sum of individual shortest paths $\sim 1$.

Anytime algorithms are promising approaches to scalable MAPF. In particular, Large Neighborhood Search (LNS) is the leading anytime algorithm in solving MAPF (MAPF-LNS) [3]. Starting with a feasible solution from any existing suboptimal MAPF algorithm, MAPF-LNS iteratively selects a subset of agents, destroys their paths, and repairs them while keeping the other paths fixed. However, the repairing operations can be time-consuming, and MAPF-LNS may struggle to improve its solution on large-scale instances. In this work, we propose Destroy-Repair Operation Parallelism for LNS (DROP-LNS), a parallel framework that performs multiple destroy and repair processes simultaneously to explore a larger searching space in a limited time budget. Unlike MAPF-LNS, DROP-LNS is able to exploit parallelized hardware to improve the solution quality. We also evaluate different parallelism variants and show that DROP-LNS trades off between productivity and synchronization to achieve better performance, where the former describes the concurrent execution of tasks, and the latter describes the access to the best-known solution to guide the search toward better quality 1.

2 DESTROY-REPAIR OPERATION PARALLELISM FOR MAPF-LNS

DROP-LNS uses a main thread and a set of worker threads to parallelize the search. The core idea is to wrap pairs of destroy and repair operations as tasks via the main thread and assign these tasks to idle worker threads. DROP-LNS maintains shared variables that can be modified by any thread, including the best-known solution with the minimum SOC found so far, the weights for each destroy heuristic, and a task queue with a fixed capacity. To avoid data racing, DROP-LNS uses two mutexes to ensure that only one thread can modify (1) the task queue and (2) any other shared variables at a time, respectively, as shown in Figure 1.

DROP-LNS first uses the main thread to initialize a feasible solution via LaCAM [4]. The main thread then fills the task queue

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with the fixed capacity of tasks until the time budget runs out. An idle worker thread tries to access the task queue and, if successful, pops a task from it. Before executing a task, the worker thread tries to access and copy the shared variables to its private memory, i.e., the best-known solution $P$ and weights for destroy heuristics. Then, it performs a pair of destroy and repair operations to the copied best-known solution based on the copied weight of each destroy heuristic, resulting in an updated solution, denoted as $P_{\text{new}}$. After the operations, the worker thread tries to access the shared variables. If the updated SOC is lower than that from the shared variables, then the best-known solution is replaced with the one in the private memory. The weight value corresponding to the destroy heuristic from the private memory is updated according to the SOC difference between $P$ and $P_{\text{new}}$. That is, the worker threads of DROP-LNS update the best-known solution asynchronously, as illustrated in Figure 2a.

**3 PARALLELISM VARIANTS OF MAPF-LNS**

We also implement two parallelism variants: SYNC-LNS and DETA-LNS. SYNC-LNS selects the same number of neighborhoods as the worker threads and performs a pair of destroy and repair operations individually on each worker thread. After all the worker threads complete their own destroy and repair operations, SYNC-LNS updates the best-known solution and the weight value by comparing the solution with the lowest SOC among all solutions generated by the worker threads. That is, DETA-LNS never synchronizes solutions and weights until the time budget runs out, as shown in Figure 2c.

**4 EMPIRICAL EVALUATION**

We use a 4-neighbor grid map of size $32 \times 32$ from the MAPF benchmark suite [5]. DROP-LNS outperforms SYNC-LNS and DETA-LNS while maintaining its performance as the number of threads increases, and outperforms the state-of-the-art algorithms for anytime MAPF, namely LaCAM* and MAPF-LNS, as shown in Figures 3 and 4 respectively. Please refer to our full paper in https://arxiv.org/abs/2402.01961 for more details.

**5 CONCLUSION**

In this work, we presented DROP-LNS, a parallel framework that performs multiple destroy and repair operations concurrently to explore more regions of the search space within a limited time budget, while the currently best-known solution is updated asynchronously to maintain the productivity of worker threads. The empirical evaluations show that DROP-LNS outperforms state-of-the-art anytime algorithms such as MAPF-LNS and LaCAM* in the MAPF benchmark. Future work includes developing more sophisticated mechanisms for synchronization and extensions to anytime bounded-suboptimal algorithms and parallel algorithms using GPU.
REFERENCES


