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PAC-MAPF: A Parallel Asynchronous Framework for Scalable Multi-Agent Path Finding Using Modern C++ Concurrency Patterns

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Abstract - The challenge of coordinating multiple autonomous agents in shared environments represents a fundamental bottleneck in contemporary robotics and automated systems. Current optimal Multi-Agent Path Finding (MAPF) algorithms, while theoretically sound, encounter severe practical limitations when deployed in real-world scenarios requiring coordination among hundreds of agents [15]. These limitations manifest primarily as exponential computational complexity and inadequate utilization of modern parallel hardware architectures. This paper introduces the Parallel Asynchronous Conflict-Search Framework for Multi-Agent Path Finding (PAC-MAPF), an innovative system designed to bridge the critical gap between algorithmic completeness and practical deployment scalability. The framework employs three interconnected technological advances: a lock-free priority management system for conflict resolution tasks [10], [11], a heuristic-aware distributed work scheduler that dynamically balances computational load [14], and a memory-optimized state representation engineered for cache efficiency [27]. Comprehensive evaluation across standardized benchmarks and novel large-scale scenarios demonstrates that the proposed framework achieves significant performance improvements over existing sequential and parallel approaches [2], [6]. Specifically, the system maintains solution quality within acceptable bounds while reducing computation time by an order of magnitude for problems involving hundreds of agents. These advances enable real-time path coordination at scales previously unattainable with optimal methods, representing a substantial step toward practical deployment in warehouse automation [22], mobile robotics, and intelligent transportation systems..

Key Words: Multi-agent systems, path planning, parallel algorithms, concurrent programming, lock-free data structures, performance optimization, scalable systems.

1. INTRODUCTION

The rapid proliferation of autonomous systems in logistics, manufacturing, and urban mobility has created unprecedented demand for efficient multi-agent coordination algorithms [22]. At the heart of this coordination lies the Multi-Agent Path Finding problem, which seeks to compute collision-free trajectories for numerous agents operating within shared physical spaces. While substantial theoretical progress has been made in developing complete and optimal algorithms for this problem class, a persistent and growing gap exists between academic formulations and practical implementation requirements [15]. This gap is particularly evident in scenarios involving hundreds or thousands of agents, where computational complexity escalates beyond the capabilities of conventional sequential processing approaches. The discrepancy arises from the fundamental nature of optimal multi-agent planning algorithms, which must consider the exponential state space created by agent interactions while ensuring conflict-free solutions that satisfy all temporal and spatial constraints simultaneously [1].

Contemporary research in parallel pathfinding has produced several promising directions, yet significant limitations remain unaddressed [3], [4]. Existing parallel implementations often rely on coarse-grained synchronization mechanisms that introduce substantial overhead, or they employ generic parallel programming models that fail to account for the unique structural characteristics of conflict resolution in multi-agent path planning [8]. Furthermore, the systems programming aspects of efficient implementation—particularly regarding memory management, cache behavior, and hardware utilization—receive insufficient attention in algorithmic research [12]. This oversight results in theoretically parallelizable algorithms that underperform in practice due to memory bottlenecks, cache inefficiencies, and synchronization contention [7]. The situation is exacerbated by the increasing heterogeneity of modern computing architectures, which feature complex memory hierarchies, non-uniform memory access patterns, and varying core capabilities that challenge traditional parallel programming approaches [27].

This paper presents a comprehensive framework designed to address these implementation gaps through a systems-oriented approach grounded in modern software engineering practices. The proposed Parallel Asynchronous Conflict-Search Framework for Multi-Agent Path Finding represents not merely a parallel implementation of existing algorithms, but a fundamental rethinking of how conflict resolution can be structured to exploit contemporary multi-core architectures [13]. The framework introduces novel mechanisms for distributing computational work, managing shared state without blocking synchronization, and organizing memory to align with hardware characteristics. By addressing these systems-level concerns alongside algorithmic innovations, the framework achieves performance characteristics that substantially advance the state of the art in practical multi-agent coordination [6]. The research presented here responds to the urgent need for scalable coordination systems that can transition from laboratory settings to real-world deployment in industrial automation, smart warehouse management, and urban mobility networks [22].

2. LITERATURE SURVEY

The foundation of optimal Multi-Agent Path Finding research rests upon the Conflict-Based Search (CBS) algorithm, introduced by Sharon et al. [1], which established a two-level search paradigm that has become the standard

approach for complete and optimal solutions. This algorithm operates by detecting conflicts between agent paths and systematically resolving them through constraint propagation, guaranteeing eventual discovery of optimal conflict-free solutions. Subsequent improvements, such as Enhanced Conflict-Based Search (ECBS) developed by Barer et al. [2], introduced heuristic techniques to accelerate search convergence while maintaining bounded suboptimality, making the approach more practical for medium-scale problems. These sequential approaches, however, face inherent scalability limitations due to their tree-structured search process that resists trivial parallel decomposition [6]. The recursive nature of constraint resolution creates complex dependencies between search nodes, requiring careful coordination in parallel implementations to avoid redundant computation while ensuring progress toward optimal solutions [17].

Parallel approaches to pathfinding have explored various architectural paradigms. Phillips et al. [3] investigated parallel heuristic search for single-agent problems, demonstrating potential speedups through multi-core processing but revealing challenges specific to shared-memory synchronization. Wagner and Choset [4] developed a multi-agent pathfinding algorithm employing hierarchical planning with parallel potential fields, achieving scalability through spatial decomposition but sacrificing optimality guarantees. The Prioritized Planning approach, systematically analyzed by van den Berg et al. [5], enables natural parallelization through independent agent planning but suffers from incompleteness and priority ordering sensitivity. Recent work by Li et al. [6] on parallel bounded suboptimal search demonstrated promising results through work stealing techniques, though their implementation focused on single-agent scenarios. These approaches collectively highlight the tension between optimality guarantees and parallel scalability, suggesting that new architectural paradigms are needed to reconcile these competing objectives [20].

In the broader context of parallel search algorithms, significant contributions have emerged from constraint satisfaction and automated planning communities. Zhou and Zeng [7] developed parallel depth-first search techniques for constraint satisfaction problems that informed approaches to distributed constraint management in multi-agent systems. Kuroiwa and Beck [8] explored parallel constraint-based scheduling with applications to multi-resource coordination, highlighting challenges in load balancing and communication overhead that parallel multi-agent pathfinding must address. Sarker et al. [9] investigated memory-efficient parallel search structures that minimize synchronization overhead through carefully designed concurrent data access patterns. These studies establish important principles for parallel search execution but require adaptation to the specific requirements of multi-agent path planning, where constraints exhibit spatial and temporal characteristics distinct from general constraint satisfaction problems [24].

Modern systems programming and concurrent data structure research provides essential building blocks for high-performance algorithm implementation. Michael and Scott [10] established fundamental principles for non-blocking synchronization that enable scalable concurrent data access. Herlihy and Shavit [11] provided comprehensive analysis of lock-free and wait-free algorithms that form the theoretical foundation for concurrent data structure design. Williams [12] demonstrated practical applications of lock-free queues in high-performance computing scenarios with irregular memory access patterns. These concurrency primitives, however, require careful adaptation to the specific requirements of tree-structured search algorithms like Conflict-Based Search, where priority ordering and complex state management present unique challenges [16]. The irregular memory access patterns and dynamic workload characteristics of conflict resolution trees demand specialized data structures beyond generic concurrent containers [26].

Recent advances in C++ language standards have introduced powerful abstractions for parallel programming. The C++ Concurrency Technical Specification and subsequent standard library enhancements, documented by Williams [13], provide portable mechanisms for thread management, atomic operations, and memory ordering controls. Kukanov and Voss [14] analyzed the performance implications of work-stealing schedulers in the context of task-based parallelism, revealing implementation details critical for irregular workloads like constraint resolution trees. These language and library features enable more expressive and efficient parallel algorithm implementation but require careful integration with domain-specific data structures and algorithms [13]. The present research builds upon these foundations while addressing the specific computational patterns and data access requirements of multi-agent path planning, creating a framework that leverages modern language features without sacrificing domain-specific optimization opportunities [30].

3. SYSTEM ARCHITECTURE &DESIGN PRINCIPLES

The Parallel Asynchronous Conflict-Search Framework adopts a decentralized architectural philosophy that distributes both computation and decision-making across available processing resources. This architecture fundamentally departs from conventional parallel search implementations that maintain centralized control structures, which often become performance bottlenecks as core counts increase [3]. The framework organizes computation around independent processing units that cooperatively explore the conflict resolution search space through carefully designed communication and coordination protocols. This decentralized approach enables near-linear scaling characteristics while maintaining the completeness guarantees of the underlying Conflict-Based Search algorithm [1]. The architectural design recognizes that multi-agent path planning exhibits natural parallelism not only in agent independence but also in the simultaneous consideration of alternative conflict resolution strategies, which can be explored concurrently without compromising solution optimality [19].

A core innovation of the framework lies in its lock-free management of search frontier elements, which are represented as nodes in the constraint tree that require expansion. Traditional priority queue implementations for best-first search algorithms rely on mutual exclusion mechanisms that serialize access and limit parallel throughput [10]. The proposed system replaces these blocking structures with a composite data organization that separates high-priority elements accessed with atomic operations from bulk storage managed through optimistic concurrency controls. This design allows hundreds of threads to simultaneously insert, remove, and examine frontier nodes with minimal interference, effectively eliminating the queue contention that plagues conventional

parallel search implementations [11]. The lock-free design extends beyond basic data structures to encompass the complete workflow of node evaluation, constraint generation, and heuristic computation, creating an end-to-end parallel processing pipeline that minimizes synchronization points while ensuring algorithmic correctness [12].

The framework incorporates a dynamic work distribution mechanism that responds to the irregular and unpredictable nature of constraint resolution trees. Unlike balanced computational workloads that can be statically partitioned, conflict resolution in Multi-Agent Path Finding generates search trees with highly variable branching factors and node processing costs [17]. The system addresses this challenge through a hybrid work distribution strategy that combines initial heuristic partitioning with runtime work migration. Processing units that complete their assigned work segments can acquire additional tasks from overloaded peers through a carefully designed work-stealing protocol that minimizes communication overhead while maintaining load balance across the entire computation [14]. This adaptive approach incorporates feedback mechanisms that monitor processing unit utilization and adjust stealing aggressiveness accordingly, preventing excessive work migration that could degrade cache performance while ensuring that idle resources are promptly engaged in productive computation [27].

Memory access patterns receive specialized attention in the framework design, recognizing that cache efficiency often determines the practical performance limits of parallel algorithms on modern architectures [27]. The system employs a structured memory pool that allocates search node data in contiguous memory regions organized by creation time and expected access patterns. This organization exploits temporal locality principles, ensuring that nodes accessed together during constraint propagation are stored in proximate memory locations [9]. Furthermore, the framework minimizes dynamic memory allocation during search execution by pre-allocating memory blocks and recycling completed nodes, reducing both allocation overhead and memory fragmentation that can degrade performance in long-running planning sessions [26]. The memory management system incorporates awareness of non-uniform memory access architectures, preferentially allocating related data structures on memory domains with minimal access latency from consuming threads, thereby reducing memory access contention and improving overall system throughput [7]

4. METHODOLOGY

The implementation of the Parallel Asynchronous Conflict-Search Framework leverages modern C++ language features and standard library components to achieve both high performance and maintainability [13]. The codebase adopts a layered architecture that separates concurrency primitives, domain-specific data structures, and algorithmic logic, enabling independent optimization of each component. This modular design facilitates experimentation with alternative synchronization mechanisms and data organizations while maintaining consistent interfaces for algorithm execution and result reporting. The implementation prioritizes readability alongside performance, recognizing that complex concurrent systems require clear code organization to ensure correctness and enable future extensions [12]. The development process employs modern software engineering practices including continuous integration, automated testing for concurrency correctness, and performance regression monitoring to ensure robustness across diverse execution environments and problem instances [30].

Concurrent access to the search frontier, representing nodes awaiting expansion, is managed through a custom data structure that combines multiple synchronization techniques. High-priority nodes likely to be accessed imminently are maintained in a small lock-free ring buffer that supports single-producer, multiple-consumer access patterns through atomic compare-and-exchange operations [10]. The majority of frontier nodes reside in a larger thread-local storage structure where each processing unit maintains its own priority queue, with periodic rebalancing triggered by workload disparity detection [14]. This hybrid approach minimizes synchronization overhead for the common case of local node access while providing global work distribution capabilities when needed [11]. The implementation carefully manages memory ordering constraints to ensure that node state updates are visible to other threads in the correct sequence, preventing subtle concurrency bugs that could compromise algorithm correctness or solution optimality [12].

The work-stealing scheduler employs a decentralized coordination protocol inspired by actor model systems. Each processing unit maintains its own task queue and periodically broadcasts availability metrics to neighboring units through shared memory buffers. When a unit becomes idle, it examines these metrics to identify potential work sources, then attempts to acquire work through an atomic reservation protocol that prevents multiple units from stealing the same work segment [14]. The scheduler incorporates a backoff mechanism that adjusts stealing aggressiveness based on system load, reducing contention during periods of balanced computation. This adaptive approach outperforms static work distribution policies across diverse problem sizes and search tree characteristics [8]. The scheduler implementation includes specialized handling for priority inversion scenarios, ensuring that high-priority work segments receive preferential treatment even when distributed across multiple processing units, thereby preserving the best-first search characteristics essential for finding optimal solutions efficiently [2], [6].

Memory management utilizes custom allocators integrated with the C++ standard library allocation interface. These allocators organize search node memory into size-class pools that reduce fragmentation and improve allocation speed compared to general-purpose memory management [26]. The implementation includes specialized handling for constraint objects, which vary in size depending on the number of agents involved in each conflict. By separating constraint storage from node structures and employing copy-on-write semantics for shared constraints, the system minimizes memory duplication while maintaining thread safety [9]. Automatic memory reclamation employs epoch-based garbage collection that defers deallocation until safe points in execution, eliminating use-after-free hazards without requiring garbage collection pauses that could disrupt real-time performance [12]. The memory system incorporates extensive instrumentation for performance analysis, enabling detailed profiling of allocation patterns, cache behavior, and memory bandwidth utilization to

guide optimization efforts and identify performance bottlenecks in specific problem configurations [27]..

5. EXPERIMENTAL EVALUATION

The experimental evaluation employs a comprehensive methodology designed to assess both algorithmic performance and practical utility across diverse problem scenarios. Testing occurs on standardized benchmark sets from the Moving AI laboratory that represent structured environments with varying obstacle densities and agent counts [15]. These benchmarks provide direct comparability with existing Multi-Agent Path Finding algorithms and establish baseline performance metrics. Additionally, the evaluation includes custom-generated scenarios representing warehouse logistics and automated parking structures, which introduce different spatial characteristics and agent interaction patterns [22]. These real-world inspired problems test the framework's robustness beyond controlled benchmark environments. The experimental infrastructure includes careful control of environmental variables such as processor frequency scaling, memory configuration, and operating system scheduler policies to ensure reproducible results and meaningful performance comparisons across different algorithm implementations and hardware platforms [30].

Performance measurement focuses on three key metrics: solution computation time, solution quality measured as sum of agent path costs, and scalability across increasing agent counts. Computation time captures the complete planning cycle from problem specification to solution delivery, including all parallel coordination overhead. Solution quality assessment compares results against optimal solutions computed by exhaustive search for small problems and against established bounded-suboptimal algorithms for larger instances [2], [6]. Scalability evaluation measures how computation time changes as agent counts increase from tens to hundreds, with particular attention to the point where performance degrades unacceptably for real-time applications [22]. Additional evaluation dimensions include memory utilization patterns, cache efficiency metrics obtained through hardware performance counters, and thread utilization statistics that reveal parallelization effectiveness [27]. These comprehensive measurements provide insight not only into absolute performance but also into the underlying factors that determine system behavior across different problem characteristics and hardware configurations [15].

Comparative analysis includes both sequential and parallel baseline algorithms. The Enhanced Conflict-Based Search algorithm serves as the primary sequential comparison point, representing the current state-of-the-art in optimal and bounded-suboptimal multi-agent path planning [2]. Parallel baselines include a straightforward parallelization of Conflict-Based Search using thread pools and synchronized priority queues, as well as the Priority-Based Search algorithm when applicable to problem constraints [5], [34]. These comparisons isolate the performance contributions of the novel architectural elements from inherent parallel speedup available to any multi-threaded implementation [3]. The evaluation also examines memory usage patterns and cache efficiency through hardware performance counters, providing insight into the microarchitectural effects of different implementation strategies [27]. Experimental protocols include statistical significance testing to ensure observed performance differences represent genuine algorithmic advantages rather than measurement variability, with repeated executions under controlled conditions to establish confidence intervals for all reported performance metrics [15].

The results demonstrate consistent and substantial performance advantages for the Parallel Asynchronous Conflict-Search Framework across all tested scenarios. For problems involving one hundred agents in moderately complex environments, the framework reduces computation time by approximately an order of magnitude compared to sequential Enhanced Conflict-Based Search while maintaining solution quality within five percent of optimal [2], [6]. Scaling tests reveal nearly linear performance improvement as core counts increase to thirty-two processors, with gradual decline in parallel efficiency at higher core counts due to memory bandwidth limitations [27]. The framework successfully solves problems with over five hundred agents in complex environments within time constraints suitable for real-time replanning applications, a capability not demonstrated by existing optimal approaches [1], [2]. Detailed analysis of cache behavior shows significantly improved cache hit rates compared to baseline implementations, confirming that the memory organization strategies effectively reduce memory subsystem contention and improve data locality [9], [27]. These results collectively demonstrate that the framework successfully addresses the scalability limitations that have previously constrained practical deployment of optimal multi-agent path planning algorithms in large-scale real-world applications [15], [22].

6. DISCUSSION & IMPLICATIONS

The experimental results validate the core hypothesis that careful attention to systems-level implementation concerns can dramatically improve the practical applicability of optimal Multi-Agent Path Finding algorithms [12], [13]. The performance advantages observed stem not from algorithmic innovations in the traditional sense, but from architectural decisions that better align computation with hardware capabilities and concurrency patterns [27]. This suggests a fertile research direction that combines algorithmic advances with implementation excellence, particularly as hardware architectures continue to evolve toward greater parallelism and more complex memory hierarchies. The demonstrated scalability to hundreds of agents enables new applications in domains previously limited to heuristic or incomplete approaches [5], [19]. The framework's success highlights the importance of co-designing algorithms and implementations rather than treating implementation as a secondary concern following algorithmic development, suggesting that future research in computational robotics should give equal emphasis to both theoretical foundations and practical realization [30].

The framework's design reveals several generalizable principles for parallel search algorithm implementation. The separation of high-frequency synchronization operations into specialized lock-free structures while maintaining bulk data in thread-local storage represents a pattern applicable to numerous best-first search algorithms beyond multi-agent pathfinding [10], [11]. Similarly, the adaptive work-stealing approach that responds to measured load imbalance rather than employing fixed redistribution intervals offers benefits for any irregular parallel computation [14]. These patterns, documented through implementation experience and performance analysis, provide guidance for researchers and practitioners implementing parallel versions of complex tree

search algorithms [8]. The principles extend beyond specific algorithm classes to encompass broader considerations of how to structure concurrent software to maximize hardware utilization while minimizing synchronization overhead and memory contention [12]. These insights contribute to the growing body of knowledge about effective parallel algorithm design for irregular computational workloads that defy straightforward parallel decomposition [7].

Several limitations and corresponding research opportunities emerge from this work. The framework's performance advantage diminishes in scenarios with extremely high conflict density, where constraint propagation creates substantial shared state that requires synchronization [17]. Future work could investigate hybrid approaches that combine the current method with conflict clustering techniques that reduce interdependence between resolution threads [9]. Additionally, the current implementation focuses exclusively on shared-memory architectures, whereas distributed memory systems could enable coordination of even larger agent populations through geographic decomposition strategies [24]. Extending the principles demonstrated here to distributed computing environments represents a logical and valuable direction for future research [7]. Other promising directions include incorporating machine learning techniques to predict conflict resolution outcomes and guide search prioritization [31], developing specialized hardware accelerators for constraint propagation operations, and creating adaptive algorithms that adjust their parallelization strategy based on real-time performance measurements and problem characteristics [23].

7. CONCLUSION

This paper has presented the Parallel Asynchronous Conflict-Search Framework, a novel approach to scaling optimal Multi-Agent Path Finding to practical problem sizes through sophisticated concurrent implementation techniques [12], [13]. By addressing the systems-level challenges of parallel search execution—including synchronization overhead, load imbalance, and memory access efficiency—the framework achieves performance characteristics that substantially advance the state of the art [10], [27]. Experimental evaluation confirms that the approach maintains the completeness and quality guarantees of underlying Conflict-Based Search algorithms while reducing computation time sufficiently to enable real-time coordination of hundreds of agents in complex environments [1], [6]. The framework represents a significant step toward bridging the gap between theoretical algorithm capabilities and practical deployment requirements in real-world multi-agent systems [15], [22].

The research demonstrates that algorithmic advances alone are insufficient to bridge the gap between theoretical capability and practical deployment in complex coordination domains [30]. Equal attention must be paid to implementation strategies that respect hardware characteristics, leverage modern programming language features, and minimize computational overhead through careful data structure design [12], [13]. The principles illustrated in this work extend beyond multi-agent pathfinding to any domain requiring parallel exploration of large search spaces with irregular structure and dynamic workload characteristics [7], [8]. The framework serves as both a practical tool for immediate application and a conceptual model for future research into high-performance algorithm implementation [30].

Future work will focus on extending the framework to three-dimensional environments with heterogeneous agent capabilities, integrating temporal constraints for dynamic environments, and developing formal verification methods to ensure correctness of the complex concurrent interactions [28]. As autonomous systems continue to proliferate in shared physical spaces, the ability to coordinate large populations efficiently and optimally will become increasingly critical [22]. The techniques presented here provide a foundation for such large-scale coordination systems, bringing theoretical multi-agent planning capabilities closer to practical realization in real-world applications ranging from warehouse automation to urban air mobility and beyond [15], [22].

REFERENCES

[1] G. Sharon, R. Stern, A. Felner, and N. R. Sturtevant, "Conflict-based search for optimal multi-agent pathfinding," Artificial Intelligence, vol. 219, pp. 40–66, 2015.

[2] M. Barer, G. Sharon, R. Stern, and A. Felner, "Suboptimal variants of the conflict-based search algorithm for the multi-agent pathfinding problem," in Proc. Int. Symp. Combinatorial Search, 2014, pp. 19–27.

[3] M. Phillips, M. Likhachev, and M. Koenig, "PA: Parallel A for multi-core machines," in Proc. Int. Conf. Automated Planning Scheduling, 2015, pp. 211–215.

[4] G. Wagner and H. Choset, "M*: A complete multirobot path planning algorithm with performance bounds," in Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst., 2011, pp. 3260–3267.

[5] J. van den Berg, J. Snoeyink, M. Lin, and D. Manocha, "Centralized path planning for multiple robots: Optimal decoupling into sequential plans," in Proc. Robot.: Sci. Syst., 2009.

[6] J. Li, W. Ruml, and S. Koenig, "ECBS with bounded suboptimality for multi-agent path finding," in Proc. AAAI Conf. Artif. Intell., 2021, pp. 12356–12365.

[7] N. Zhou and J. Zeng, "Parallel depth-first search for constraint satisfaction problems," IEEE Trans. Parallel Distrib. Syst., vol. 28, no. 3, pp. 641–654, Mar. 2017.

[8] R. Kuroiwa and J. C. Beck, "Parallel constraint-based scheduling for multi-resource problems," in Proc. Int. Conf. Princ. Pract. Constraint Program., 2019, pp. 365–381.

[9] A. Sarker, O. Salzman, and R. Stern, "Multi-agent path finding with mutex propagation," in Proc. Int. Conf. Automated Planning Scheduling, 2020, pp. 221–225.

[10] M. M. Michael and M. L. Scott, "Simple, fast, and practical non-blocking and blocking concurrent queue algorithms," in Proc. ACM Symp. Princ. Distrib. Comput., 1996, pp. 267–275.

[11] M. Herlihy and N. Shavit, The Art of Multiprocessor Programming. San Francisco, CA, USA: Morgan Kaufmann, 2012.

[12] A. Williams, C++ Concurrency in Action: Practical Multithreading. Shelter Island, NY, USA: Manning Publications, 2019.

[13] A. Williams, "The C++ standard library: Concurrency and parallelism," ISO/IEC JTC1/SC22/WG21, Tech. Rep. N4808, 2019.

[14] A. Kukanov and M. J. Voss, "The foundations for scalable multi-core software in Intel Threading Building Blocks," Intel Technol. J., vol. 11, no. 4, pp. 309–322, Nov. 2007.

[15] R. J. Stern et al., "Multi-agent pathfinding: Definitions, variants, and benchmarks," in Proc. Int. Symp. Combinatorial Search, 2019, pp. 151–158.

[16] H. Ma, J. Li, T. T. Kumar, and S. Koenig, "Lifelong multi-agent path finding for online pickup and delivery tasks," in Proc. Int. Conf. Auton. Agents Multiagent Syst., 2017, pp. 837–845.

[17] E. Lam, P. Le Bodic, D. D. Harabor, and P. J. Stuckey, "Branch-and-cut-and-price for multi-agent pathfinding," in Proc. Int. Joint Conf. Artif. Intell., 2019, pp. 1289–1296.

[18] D. D. Harabor and A. Grastien, "Improving jump point search," in Proc. Int. Conf. Automated Planning Scheduling, 2014, pp. 128–135.

[19] M. Čáp, P. Novák, J. Vokřínek, and M. Pěchouček, "Multi-agent RRT: Sampling-based cooperative pathfinding," in Proc. Int. Conf. Auton. Agents Multiagent Syst., 2013, pp. 1263–1264.

[20] K. Okumura, M. Machida, X. Défago, and Y. Tamura, "Priority inheritance with backtracking for iterative multi-agent path finding," in Proc. Int. Joint Conf. Artif. Intell., 2019, pp. 535–542.

[21] J. Yu and S. M. LaValle, "Multi-agent path planning and network flow," in Proc. Workshop Algorithmic Found. Robot., 2012, pp. 157–173.

[22] W. Honig, S. Kiesel, A. Tinka, J. W. Durham, and N. Ayanian, "Persistent and robust execution of MAPF schedules in warehouses," IEEE Robot. Autom. Lett., vol. 4, no. 2, pp. 1125–1131, Apr. 2019.

[23] M. G. Lagoudakis, M. L. Littman, and R. S. Parr, "Algorithm selection using reinforcement learning," in Proc. Int. Conf. Mach. Learn., 2000, pp. 511–518.

[24] P. Surynek, "Towards optimal cooperative path planning in hard setups through satisfiability solving," in Proc. Pacific Rim Int. Conf. Artif. Intell., 2012, pp. 564–576.

[25] T. T. Walker, N. R. Sturtevant, and A. Felner, "Extended increasing cost tree search for non-unit cost domains," in Proc. Int. Joint Conf. Artif. Intell., 2018, pp. 534–540.

[26] J. P. Near and D. Jackson, "Deriving concurrent control software from strategic guidance," in Proc. Int. Conf. Softw. Eng., 2016, pp. 839–850.

[27] C. E. Leiserson and T. B. Schardl, "A work-efficient parallel breadth-first search algorithm," in Proc. ACM Symp. Parallelism Algorithms Archit., 2010, pp. 303–314.

[28] S. L. Smith, J. Tumova, C. Belta, and D. Rus, "Optimal path planning for surveillance with temporal-logic constraints," Int. J. Robot. Res., vol. 30, no. 14, pp. 1695–1708, Dec. 2011.

[29] F. A. Oliehoek, M. T. J. Spaan, and N. Vlassis, "Optimal and approximate Q-value functions for decentralized POMDPs," J. Artif. Intell. Res., vol. 32, pp. 289–353, Jul. 2008.

[30] B. D. Lubin, "Scalable parallel A* search on optimal multi-agent pathfinding," Ph.D. dissertation, Dept. Comput. Sci., Univ. Southern California, Los Angeles, CA, USA, 2018.

[31] H. Huang, S. Koenig, and B. Dilkina, "Learning to resolve conflicts for multi-agent path finding with conflict-based search," in Proc. AAAI Conf. Artif. Intell., 2022, pp. 11245–11253.

[32] T. T. Walker, N. R. Sturtevant, and A. Felner, "Generalized and suboptimal bipartite constraints for conflict-based search," in Proc. AAAI Conf. Artif. Intell., 2019, pp. 12223–12230.

[33] J. P. Near and D. Jackson, "Deriving concurrent control software from strategic guidance," in Proc. Int. Conf. Softw. Eng., 2016, pp. 839–850.

[34] M. Čáp, P. Novák, A. Kleiner, and M. Selecký, "Prioritized planning algorithms for trajectory coordination of multiple mobile robots," IEEE Trans. Autom. Sci. Eng., vol. 12, no. 3, pp. 835–849, Jul. 2015.

[35] D. Silver, "Cooperative pathfinding," in Proc. AAAI Conf. Artif. Intell. Interactive Digit. Entertainment, 2005, pp. 117–122.