Advancing MAPF towards the Real World: A Scalable Multi-Agent Realistic Testbed (SMART)*

Jingtian Yan[1], Kevin Zheng[2], Zhifei Li[1], William Kang[1], Yulun Zhang[1], Zhe Chen[2,3], Yue Zhang[2]
Daniel Harabor[2], Stephen Smith[1], Jiaoyang Li[1]

[1]Carnegie Mellon University, [2]Monash University [3]Amazon Robotics
jingtianyan@cmu.edu

Abstract

State-of-the-art algorithms for Multi-Agent Path Finding (MAPF) can plan paths for many robots in seconds. However, they often rely on simplified models, making their real-world performance unclear. Bridging the gap is difficult, as accurate evaluations require complex setups and access to large fleets of physical robots. To tackle these challenges, we present **S**calable **M**ulti-**A**gent **R**ealistic **T**estbed (SMART): a software tool for evaluating the potential of Multi-Agent Path Finding (MAPF) algorithms in realistic environments. SMART connects simplified MAPF solvers with an execution framework based on Action Dependency Graphs. The combination allows seamless integration with complex robot simulators that account for continuous time, kinodynamics, communication delays, and execution uncertainties. It lowers barriers for researchers and enables, for the first time, large-scale MAPF evaluations in physics-based simulations with up to thousands of simultaneous robots.

Video — https://youtu.be/irtFxMjyJXs
Demo — https://smart-mapf.github.io/demo/
Code — https://github.com/JingtianYan/SMART
Paper — https://arxiv.org/abs/2503.04798

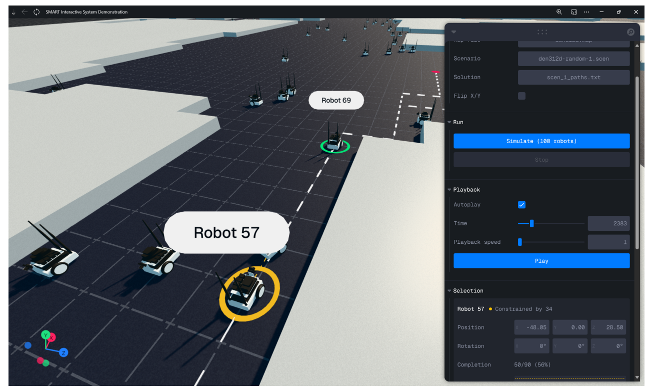

Figure 1: The SMART web interface visualizing a multi-robot simulation on a grid map. In the viewport, users interact with individual robots to inspect paths and inter-robot constraints. On the side panel, users can configure the environment, control playback, and see execution details.

Introduction

The Multi-Agent Path Finding (MAPF) problem (Stern et al. 2019) is an abstract planning problem motivated by a wide variety of applications, including automated logistics, mail sortation, traffic management, and more. State-of-the-art MAPF solvers regularly compute collision-free paths for large numbers of agents; e.g., hundreds optimally and thousands suboptimally.Unfortunately, there exists a substantial gap between the simplified agent models used by MAPF solvers and the physical robots employed in real-world applications. For example, most MAPF solvers ignore kinodynamics, which means they do not account for a robot's speed, acceleration, and motion constraints. Most MAPF solvers also assume perfect execution, which means they ignore unexpected delays (e.g., controller tracking errors) that affect robots in practice. Thus, while MAPF solvers promise high-quality solutions, their computed plans are often not achievable in practice. Closing the gap is difficult: concrete evaluation of a MAPF plan requires a fleet of physical robots, a large operating environment and complex software to program and monitor their execution.

In this paper, we present SMART, **S**calable **M**ulti-**A**gent **R**ealistic **T**estbed, a software tool used to evaluate MAPF algorithms in realistic scenarios. SMART incorporates key real-world factors, including robot kinodynamics, collision dynamics, communication delays, execution imperfections, and spatial inaccuracies caused by controller limitations. At the same time, SMART is highly scalable, capable of simulating environments with thousands of robots, thus meeting the needs of modern MAPF planners designed for large agents. Empirically, SMART supports the simulation of 2,000 robots with faster than real-time speed. SMART supports standard file formats for maps, scenario definitions, and MAPF solutions. It is available both as a standalone tool and online; the open-source nature of our code allows for easy derivations as needed.

*This work was partially supported by the National Science Foundation under grants #2328671 and #2441629, as well as a gift from Amazon.

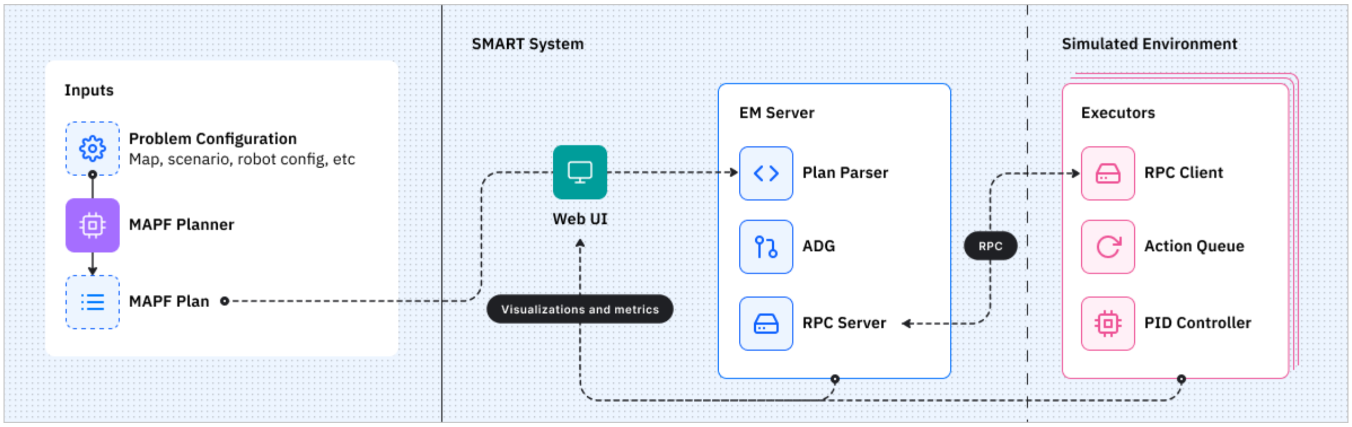

Figure 2: Combined user interaction and architecture diagram. Users provide MAPF plans via a web UI; SMART orchestrates a physically-accurate simulation and lets users visually analyse how their algorithms may perform in the real-world.

System Description

SMART comprises of an execution monitoring (EM) server and robot-specific executors running on a physics-engine-based simulated environment (Pinciroli et al. 2012) (Fig. 2). The simulator creates realistic environments and supports differential drive robots with in-place rotation, based on user-defined configurations. The EM server parses the user-provided MAPF paths, tracks the execution progress, and communicates with the executors. It leverages the Action Dependency Graph (ADG) (Hönig et al. 2019), a MAPF execution framework, to ensure robust execution of the paths generated using various simplified robot models. Each robot is assigned an individual executor that receives actions from the EM server. Specifically, the executor maintains an action queue to buffer incoming actions, executes them progressively using a controller, and synchronizes execution status with the server.

SMART Web UI

SMART provides an intuitive web app for running and inspecting MAPF simulations, allowing researchers to better understand how algorithms perform with physical robots (Fig. 1). Users configure the environment by specifying a map and scenario file in the MovingAI Benchmark (Stern et al. 2019) format. The map file specifies the grid layout by identifying obstacle and free locations, while the scenario file defines the start and goal positions for each robot. Users may apply any existing MAPF planner or develop their own, as long as the generated paths for each robot conform to the required format. The map file, scenario file, and MAPF solution can then be used as input to the standalone tool or uploaded to the online interface. The SMART online interface is a powerful, web-based visualization and interaction tool, allowing anyone to run SMART instantly from any modern browser – no installation required. Within the online interface – after the user uploads and starts the simulation – the user can control the simulation time step and adjust the playback speed. Users may select robots to view complete paths, execution status, and inter-robot constraints.

Performance Metrics

SMART provides several built-in performance metrics, including (1) *Average execution time (AET):* The sum of the simulation times required by all robots to complete their assigned paths, divided by the number of robots, (2) *Maximum execution time:* The longest simulation time taken by any single robot to complete its path, and (3) *Robot state over time:* Robots' current position, execution progress, and relationship with other robots.

Results

We evaluate SMART across six simulation environments (Yan et al. 2025). On the largest map (500 × 140 m), SMART sustains simulation speeds faster than real time for up to 2,000 robots. Replicability across 10 runs shows low variance in completion times, and CPU and memory profiling indicates modest resource usage on both a high-end server and a low-end laptop. Finally, we deploy SMART on real-world robots to validate its robustness in the real world, achieving a 100% success rate under physical execution.

References

Hönig, W.; Kiesel, S.; Tinka, A.; Durham, J. W.; and Ayanian, N. 2019. Persistent and Robust Execution of MAPF Schedules in Warehouses. *IEEE RA-L*, 4(2): 1125–1131.

Pinciroli, C.; Trianni, V.; O'Grady, R.; Pini, G.; Brutschy, A.; Brambilla, M.; Mathews, N.; Ferrante, E.; Caro, D.; ...; and Dorigo, M. 2012. ARGoS: a modular, parallel, multi-engine simulator for multi-robot systems. *Swarm Intelligence*, 6: 271–295.

Stern, R.; Sturtevant, N. R.; Felner, A.; Koenig, S.; Ma, H.; Walker, T. T.; Li, J.; Atzmon, D.; Cohen, L.; Kumar, T. K. S.; Boyarski, E.; and Barták, R. 2019. Multi-Agent Pathfinding: Definitions, Variants, and Benchmarks. In *SoCS*, 151–159.

Yan, J.; Zheng, K.; Li, Z.; Kang, W.; Zhang, Y.; Chen, Z.; Zhang, Y.; Harabor, D.; Smith, S.; and Li, J. 2025. Advancing MAPF towards the Real World: A Scalable Multi-Agent Realistic Testbed (SMART). arXiv:2503.04798.