Accessible Hardware Implementation for Multi-Agent Collective Construction

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Abstract

We propose a 2D simulation system for multi-agent collective construction (MACC) based on simple line-following intelligent machines (SLIM) - small differential drive mobile robots. Our MACC-SLIM system alleviates the high upfront cost of implementing MACC on real hardware. Our system builds upon widely available resources, namely a standard LCD screen and commodity mobile robots, allowing researchers and schools easier access to MACC hardware implementation. We test the system on plans generated by an optimal state-of-the-art MACC algorithm, demonstrating there are still non-insignificant synchronization delays. The MACC-SLIM system allows us to observe bottlenecks, parallelism, and possible execution failures of plans generated by the MACC algorithms.

Introduction

The multi-agent collective construction (MACC) bridges the gap between computer science, robotics, and civil engineering. We focus on the MACC based on the TERMES agents (Lam et al. 2020; Petersen, Nagpal, and Werfel 2011), one of the most elaborate formalizations and implementations of real hardware (Singh et al. 2024; Kumar, Jung, and Koenig 2014; Srinivasan et al. 2023). In this formalization, a group of simple agents builds a user-defined structure from blocks. The blocks are the same size as the agents, an agent can carry at most one block. The building area is a 3D grid, where agents move on the ground or on top of the structure and place blocks. An agent can *enter* and *leave* the building area at the ground level from its side, optionally carrying a block. An agent can *move* to an unoccupied neighbor cell, given the height difference is at most one block. Lastly, an agent can *pick_up* or *deliver* a block from/to the neighbor cell, if it is unoccupied and at the same height (Lam et al. 2020).

While the TERMES robots are an important research tool, which inspired today's state-of-the-art MACC models (Singh et al. 2024; Srinivasan et al. 2023; Deng et al. 2019), they still rely on custom components and in-house assembly (Petersen, Nagpal, and Werfel 2011). This poses a challenge in acquiring and maintaining the system. Another challenge is represented by the considerable size of the TERMES system which requires a large laboratory space. We address these challenges with our proposed MACC-SLIM system that uses standard components: an LCD screen and small commodity mobile robots (Ozobots).

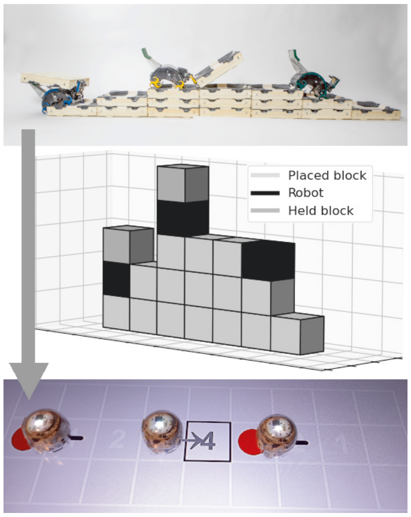

Figure 1: Progression in multi-agent collective construction (MACC). Description of images from top to bottom: (1) The TERMES robots. "Termes robot 01" by Forgemind ArchiMedia is licensed under CC BY 2.0. (2) MACC discretization of the problem. (3) Execution of the MACC plan by our MACC-SLIM system (using Ozobots on a screen).

Proposed Implementation

The main idea of our proposed Simple Line-following Intelligent Machines (SLIM) system is to use widely available, small robotic agents with only a few required sensors (so alternative products can be found) and a flat-laid LCD screen. Inspired by previous work (Chudý and Surynek 2021; Barták, Švancara, and Krasičenko 2020), our system uses the screen to send simple commands to the agents via animated colored circles and lines – the robot decodes the next instruction from the circle color, using the lines for course correction. These actions are in our case high-level instructions *move forward one block*, *turn left by 90°*, and *turn right by 90°* (matching the first three high-level instructions of the TERMES robots). The remaining TERMES

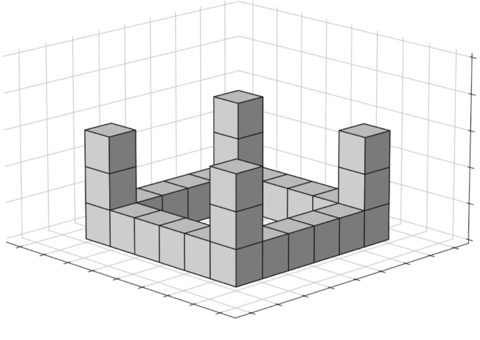

Figure 2: MACC benchmark instance 1

high-level instructions (*pick up block* and *attach block*) are displayed on the screen but not acted out by the agents.

The visual 2D manipulation of the blocks enables the assembly of larger structures without requiring the production of additional bricks. The simplification to 2D does not restrict the set of plans and structures – we can simulate the same set of plans and structures as the original TERMES since both platforms assume robots that do not overlap horizontally. Figure 1 shows three visualizations of the same world state. Since the TERMES robots stack blocks into columns without overhangs (Petersen, Nagpal, and Werfel 2011), we may visualize each column as a single number – its height. The column heights and the grid are shown as white on a gray background during the mission to avoid interfering with the Ozobot color sensing and line following.

Creating the MACC 4-directional move action from color instructions is simple – turn the agent in the appropriate direction and then send the move-forward command. The most challenging are enter and leave actions, since multiple agents may have to go through a single border cell. In addition, the state-of-the-art models count only the number of agents on the grid (Lam et al. 2020; Rameš. and Surynek. 2024), which would have the agents circle the construction area, moving to their next assigned border cell. To avoid this, we go through the mission plan, timestep by timestep, and count for each border cell the number of agents that entered through it, minus the amount that left the building area through it, from the start of the mission. We then compute $n_{a,(x,y)}$ as the maximum of this number for each border cell (x, y), over all timesteps. This is the number of agents we assign in a queue to the border cell. Any missing agent would have to be requested to enter at a timestep with no agents available at the border cell; but that would increase the maximum number of entries and $n_{a,(x,y)}$ as a consequence.

Demonstration

In the demonstration video[1], we showcase 24 robotic agents collaborating on building a small castle (see figure 3). The plan has been generated by an optimal MILP model, as described in (Rameš. and Surynek. 2024). We can observe parallelism and possible bottlenecks during plan execution.

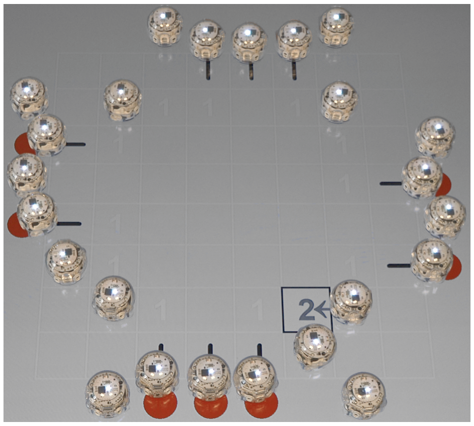

Figure 3: A group of 24 SLIM agents building the MACC benchmark instance 1

The simulation reveals that when the makespan is to be optimized it is not realistic to assume discrete time with one action per timestep (as is done in state-of-the-art optimal MACC algorithms (Lam et al. 2020)). In addition, since the MACC model does not currently include information about agent orientation or how many agents entered the grid from a given border cell, these synchronization delays cannot be sufficiently taken into account by even the action duration generalization model used for the creation of the instance 1 (see figure 2) plan for this paper (Rameš. and Surynek. 2024). This is caused by the action duration in the model being given as a function of the agent state, which does not contain the necessary information (agent orientation and how many agents on the grid entered from the same border cell) and must therefore return the same duration for movement with and without rotating the agent (Rameš. and Surynek. 2024). The time of execution of individual actions on our robots varies significantly which should be reflected in theoretical models (similar to the inclusion of turn-action in MAPF by (Barták et al. 2019)).

Conclusion and Future Work

We propose the MACC-SLIM system, an accessible hardware implementation of the multi-agent collective construction. The system uses a flat-laid consumer-grade screen to show the construction site and send instructions to the simple line-following robotic agents operating on top of it. The agents implement the high-level movement actions of the TERMES robots, the original, but not easily accessible MACC research platform. In contrast to the TERMES, our platform is compact and can fit into a small laboratory.

The system demonstration shows that the current optimal state-of-the-art models do not sufficiently address the varying duration of agent movement, causing even optimal plans to have agents waiting a noticeable time for synchronization.

In future work, our system may be used to thoroughly analyze the timing of MACC actions. Special attention may have to be directed at the non-trivial *enter* and *leave* actions, where the agent interacts with the block reservoir, and multiple agents may move through a single border cell in a single plan execution.

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[1] Available at https://youtu.be/kIv-7w2GO_8

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