Error Correction in Collective Robotic Construction

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Collective robotic construction (CRC) involves multiple robots collaborating to build structures much larger than themselves. More specifically, a group of robots are coordinated by a centralized or decentralized control policy to modify a shared environment to achieve a high-level user-specified goal [1]. The decentralized approach is of special interest due to its scalability, high redundancy, high concurrency, and little or zero requirement for global state monitoring. These advantages enables construction of large-scale, complex structures by teams of simple, low-cost robots with limited sensing capabilities and computational power. In fact, nature has already provided ample examples of decentralized CRC systems. Social insects such as honeybees and termites build intricate nests order of magnitude larger than themselves. In robotics, few papers to date involve decentralized control for construction, for example pre-defined 3D structures using custom bricks [2], navigable slopes using amorphous materials [3], and protective barriers using compliant pocket [4].

In most of the current CRC systems, the construction relies purely on additive manufacturing, which means a modification to the structure, once done, becomes permanent. Therefore, the errors in the system could have critical and lasting impacts. These impacts have largely been overlooked and there is a lack of error mitigation methods for decentralized CRC systems due to the relatively small scale of structures and collectives being studied in the past. The majority of prior work does not incorporate errors into the simulations or prevents errors through engineering efforts [5], [6], [7]. However, for construction that involves big complex structures or large collectives, even errors with very low probability can still happen. For decentralized CRC systems, recognition and correction of these errors are especially challenging since these systems do not have access to the global state and direct controls over each agent.

In this poster, we summarize recent findings from error studies and proposed methods for decay-based error correction in the context of the TERMES system [2], a decentralized CRC system where locally-aware robots follow a reactive ruleset and a stochastic policy to build and navigate through a pre-defined 3D structure. Although our study focuses on the TERMES system, many of the findings can be applied to other CRC systems, especially systems that use environmentally-mediated coordination to guide agents with limited sensing and motion constraints to modify a shared environment.

To support our study, we developed a multi-robot simulator that incorporates realistic error profiles of the robots. We first evaluated different construction policies with the presence of errors and we showed that the policy that minimizes the longest traveling distance and maximizes the number of locations where the robot can place a brick at each time step is in general the policy that will yield the highest probability of successfully completing the structure (PoS) and the lowest construction time. We then conducted an in-depth analysis of different action failures. Based on the gained insights from the analysis, we proposed a prevention technique called predictive local checks which can enable a robot to correct the action failure immediately or prevent it from modifying the structure after a failure that cannot be corrected. This technique only requires software modifications and minimal hardware changes, and can substantially increase the PoS, in some cases by an order of magnitude.

Although the aforementioned measures can effectively reduce the likelihood of critical errors, they are not able to address existing errors which can cause deadlocks in the system and ultimately prevent any future construction. Removing these errors can effectively restore the construction process. However, it is impossible to recognize certain errors just based on the local structure information. To address these issues, we proposed a decay-based error correction mechanism which applies uniform low-probability decay to every location at every time step. The outcome is governed by a decay ruleset, which ensures that the removal will not cause additional critical errors. We demonstrated that the proposed method can significantly increase the PoS, on average by $\sim$4 times, based on the simulation results of constructing 32 randomly generated 250-brick structures in 3D. Although this performance improvement also comes with drawbacks including increased construction time and low error correction efficiency, we showed that these impacts can be alleviated by modifying the decay rate and probability. Based on our study of the spatio-temporal distribution of critical errors, we proposed a spatially and a temporally informed decay mechanism and we showed that while both mechanisms preserve the improved PoS, the former one has higher construction rate and the latter one has higher error correction efficiency compared with the uninformed decay mechanism. Critically, since all proposed methods do not require global state information, they can be executed by the same type of robots as those in the current TERMES system.

There are many potential directions for the future works, including optimization of decay parameters, combination of spatially and temporally informed decay mechanisms, and investigation of the spatial correlation of errors.

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