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DISTRIBUTED PREDICTION OF MECHANICALLY UNSAFE CONFIGURATIONS BY A SYSTEM OF ROBOTIC BLOCKS

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Summary We present a computational scheme for predicting whether addition of new modules to an existing modular robotic structure will mechanically overload the system, causing it to break or lose stability. The algorithm is executed by the modular robot itself in a distributed way, and relies on the iterative solution of mechanical equilibrium equations derived from a simple Finite Element model of the robot. In the model, inter-modular connections are represented as beams and the contact between modules and external supports is accounted for by a predictor-corrector scheme. The algorithm is verified through simulations in the Programmable Matter simulator *VisibleSim* and real-life experiments on the modular robotic system *Blinky Blocks*.

MOTIVATION

This work stems from investigations into self-reconfigurable modular robots with a view towards Programmable Matter [1]. Such systems are built of simple robotic units—modules—which can compute, exchange information, join, disjoin, and move over one another. If the modules were sufficiently small, numerous and well-powered, they could potentially form a highly-versatile active metamaterial, with shape- and microstructure-changing capabilities.

Much work on self-reconfigurable robots focuses on kinematics and is devoted to reconfiguration planning—designing such module movements which allow the entire ensemble to transition from one configuration into another [2]. The present work, by contrast, focuses on mechanics of modular structures [3] and is purely static. We consider the rarely-discussed problem of mechanical safety of a modular structure, which is crucial for the structure's functionality as a physical system and reconfiguration in particular [4].

PROBLEM STATEMENT

The modular structure rests on the ground, or is otherwise in contact with external supports, loaded by its own weight. If additional modules are attached to the system, two failure scenarios may occur. Either some inter-modular connection may become overloaded and break (Fig. 1) or the center of gravity of the system may shift insecurely causing the structure to topple (Fig. 2). The task is to predict if the structure will fail or not, knowing the strength of connectors and the places where new modules will be added to the system. The prognosis should be obtained by the modular system itself using its distributed MIMD computational structure with a mesh connection topology, as it was outlined in [4].

METHODS

We focus on cubic modules attached side to side, and thus on structures arranged over a cubic Cartesian grid (Figs. 1 and 2). Despite this narrow scope, the proposed methods are general and can be used with other setups as well.

In the algorithm, the modular structure is represented as a Finite Element (FE) model whose nodal values are stored by the modules in a distributed fashion. We use a simple FE model in which each module corresponds to a single node with 6 degrees of freedom (3 displacements and 3 rotations), while connections between modules are represented as elastic beams with respective nodes as endpoints [5]. Each module only stores its own 6 nodal values. The contact with external supports is also modeled using beams, but ones having variable elastic parameters—during the iterative solution, a predictor-corrector scheme is employed to emulate unilateral connections. Further, selected modules simulate the presence of the new modules which will be added to the system.

The solution is obtained using the weighted Jacobi iterative scheme [6]. The main advantage of this procedure is that computations can be done locally—each module computes its own nodal values at step $i + 1$ using only the values at step i from its immediate neighborhood. After the iterations have converged to a desired tolerance, each module checks if any of its connections is overloaded by comparing the junction forces predicted by the beam model with the strength of connectors. This addresses the bond breakage problem. Modules also aggregate information about the active points of contact with external supports, and are able to predict if the structure will tip over or not. This addresses the stability problem.

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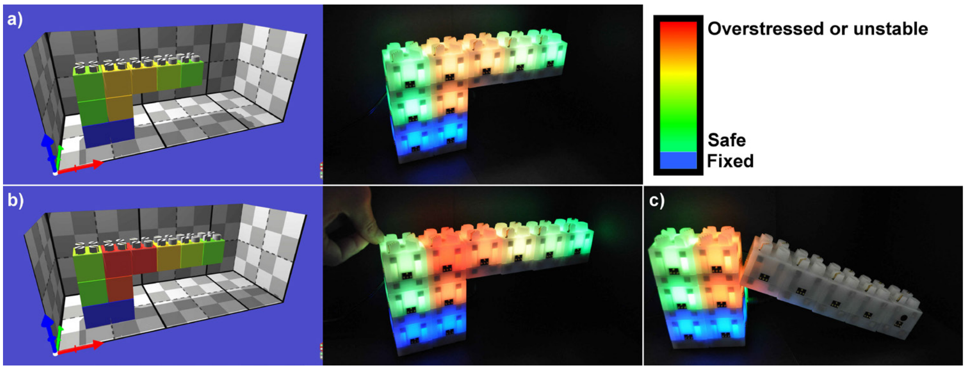

Figure 1: An example of bond breakage. Adding successive modules overloads magnetic connectors and causes the cantilever to break. The blue modules are assumed to be fixed. Left—simulations in *VisibleSim*; center and right—experiments on *Blinky Blocks*.

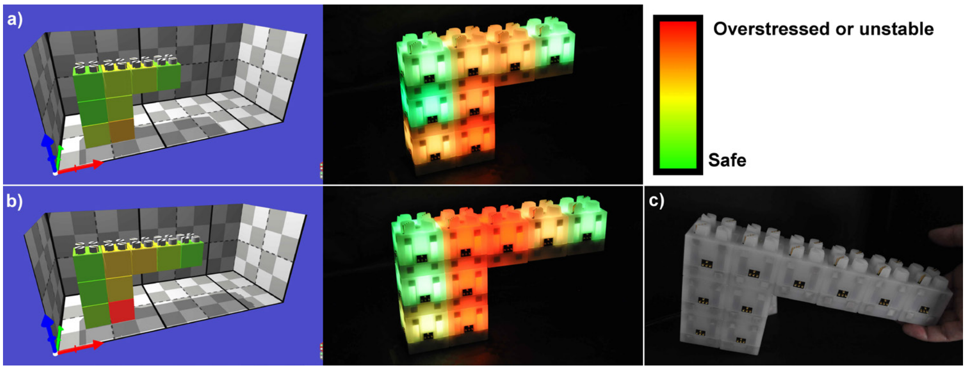

Figure 2: An example of stability loss. Adding successive modules moves the center of gravity of the cantilever beyond the supports and the structure tips over. Left—simulations in *VisibleSim*; center and right—experiments on *Blinky Blocks*.

RESULTS

Tests were performed in the dedicated simulator *VisibleSim* [7] and on the static robotic modules *Blinky Blocks* [8]. The attachment forces of Blinky Blocks were determined experimentally, while their elastic parameters assessed. Hardware experiments, like those presented in Figs. 1 and 2, revealed that the algorithm correctly predicts the mechanical behavior of small ensembles of modules, despite its crude FE representation of connected modules and the simple contact model. The weighted Jacobi solution scheme converges slowly, as expected, which will have to be addressed in the future by applying more complex alternatives like Krylov subspace methods or multigrid methods [6].

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