Tilt: The Video – Designing Worlds to Control Robot Swarms with Only Global Signals

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Abstract

We present fundamental progress on the computational universality of swarms of micro- or nano-scale robots in complex environments, controlled not by individual navigation, but by a uniform global, external force. More specifically, we consider a 2D grid world, in which all obstacles and robots are unit squares, and for each actuation, robots move maximally until they collide with an obstacle or another robot. The objective is to control robot motion within obstacles, design obstacles in order to achieve desired permutation of robots, and establish controlled interaction that is complex enough to allow arbitrary computations. In this video, we illustrate progress on all these challenges: we demonstrate NP-hardness of parallel navigation, we describe how to construct obstacles that allow arbitrary permutations, and we establish the necessary logic gates for performing arbitrary in-system computations.

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1 Introduction: Global Motion Control

One of the exciting new directions of robotics is the design and development of micro- and nanorobot systems, with the goal of letting a massive swarm of robots perform complex operations in a complicated environment. Due to scaling issues, individual control of the involved robots becomes physically impossible: while energy storage capacity drops with the third power of robot size, medium resistance decreases much slower. A possible answer lies in applying a global, external force to all particles in the swarm. This is what many current micro- and nanorobot systems with many robots do: the whole swarm is steered and directed by an external force that acts as a common control signal; see our paper [8] for detailed references. These common control signals include global magnetic or electric fields, chemical gradients, and turning a light source on and off.

Clearly, having only one global signal that uniformly affects all robots at once poses a strong restriction on the ability of the swarm to perform complex operations. The only

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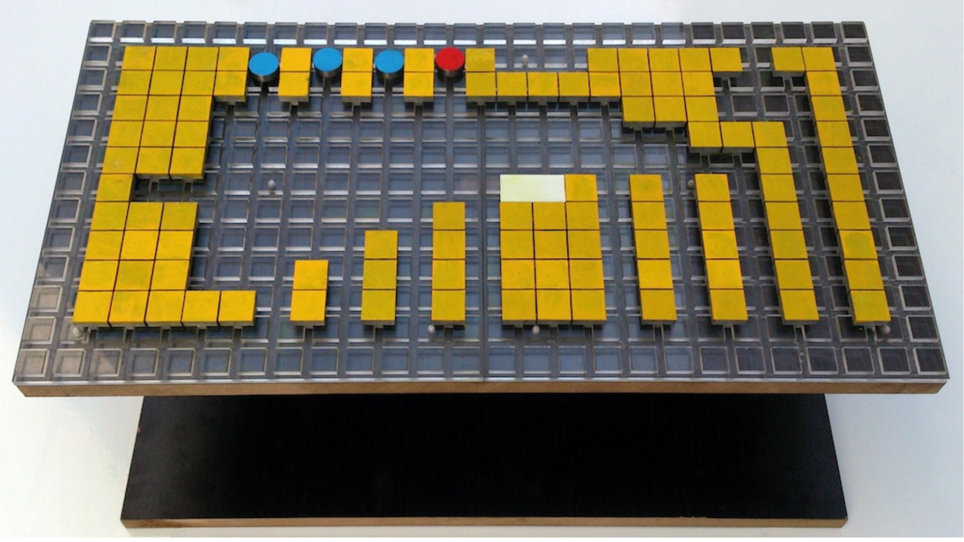

Figure 1 Gravity-fed hardware implementation of particle computation. The reconfigurable prototype is set up as a FAN-OUT gate using a 2×1 robot (white).

hope for breaking symmetry is to use interactions between the robot swarm and obstacles in the environment. The key challenge is to establish if interactions with obstacles are sufficient to perform complex operations, ideally by analyzing the complexity of possible logical operations.

This resembles the logic puzzle Tilt [9], and dexterity ball-in-a-maze puzzles such as Pigs in Clover and Labyrinth, which involve tilting a board to cause all mobile pieces to roll or slide in a desired direction. Problems of this type are also similar to sliding-block puzzles with fixed obstacles [3, 5, 6, 7], except that all particles receive the same control inputs, as in the Tilt puzzle. Another connection is Randolph's Ricochet Robots [4], a game that allows individual and independent control of the involved particles.

2 The Problems

We consider a two-dimensional grid world, with some cells occupied and others free. Initially, the planar square grid is filled with some unit-square particles (each occupying a cell of the grid) and some fixed unit-square blocks. All particles are commanded in unison: a valid command is "Go Up" (u),"Go Right" (r),"Go Down" (d), or "Go Left" (l). All particles move in the commanded direction until they hit an obstacle or another particle. A representative command sequence is $\langle u, r, d, l, d, r, u, \ldots \rangle$. We call these global commands *force-field moves.* We assume we can bound the minimum particle speed and can guarantee all particles have moved to their maximum extent.

Three of the most basic problems are as follows.

1. *Given a map of an environment, along with initial and goal positions for each particle, does there exist a sequence of inputs that will bring each particle to its goal position?*
2. *Given an initial matrix arrangement of particles, how can we design a set of obstacles, such that any permutation can be realized with a relatively simple sequence of moves?*
3. *Can we establish sets of obstacles, particles, and moves, such that the resulting motion can be used for carrying out arbitrary computation strictly within the system, i.e., without an intelligent observer?*

We have provided answers for these problems in our previous papers [2, 8, 1]. Here we present a compact visual demonstration, in part based on a real-world realization, showing that further applications and extensions are possible.

3 The Video

The video consists of a number of animation sequences, as well as several scenes demonstrating real-world model environments.

In the first part of the video, we describe the underlying model, based on a physical realization, and motivate the background from micro- and nano-robotics. We then proceed to sketch the elements and overall construction for an NP-hardness proof, resolving one aspect of the complexity of the first problem. (A separate argument shows that the problem of minimizing the number of moves for achieving a target configuration is in fact PSPACE-complete, but this is omitted.) In the third part of the video, we demonstrate how to solve the second problem: We can design relatively simple sets of obstacles that allow arbitrary matrix permutations, based on simple clockwise and counterclockwise subsequences of moves. Finally, the fourth and last part shows some of the key components for carrying out universal computation, demonstrated on a physical model for simple components, and animations for overall construction.

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