Fluidic Stochastic Modular Robotics: Revisiting the System Design

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Here we present a new design of a system for stochastic self-assembly and reconfiguration of zero d.o.f. lattice modular robots in the fluid. The Fluidic Stochastic Modular Robotics (FSMR) system is envisioned to serve as a prototype for future sub-millimeter scale implementation with all critical structural parts having analogous counterparts implemented in MEMS. New FSMR features include controlled mechanical module interconnections, active selective module rejection, mediate inactive module flow control, and individual module orientation sensing.

In scaling modular robotic systems to sub-millimeter sizes and large quantities, direct application of conventional modular robotics approaches would require using microscopic batteries, module locomotion mechanisms and planning individual transitional trajectories for increasing numbers of modules.

Unfortunately, miniaturizing conventional robotic elements is a daunting task [1]: Current advances in manufacturing of micro batteries with maximum capacities below 100 $\mu A \cdot hr/\mu m \cdot cm^2$ [2, 3] are yet to match the consumption requirements of tens to hundreds milliamperes of available MEMS actuators [4-6]. While measuring only few mm^2 in area and tens of microns in thickness [4-6], each electromagnetic MEMS actuator will require at least hundreds times its volume of highest density micro batteries for a minute of sustained operation. Electrostatic micro actuators have motion range of several microns [7, 8] or require voltages of hundreds of volts [9]. Most MEMS would require additional micro-mechanical transmission to make them applicable for micro-robot locomotion due to their kinematics [10]. Motion planning for reconfiguring large numbers of robots with considerations for module collaboration, traffic negotiation, collision avoidance, and module docking in 3D remains an area of active research [11-15].

In this paper, we propose to circumvent the challenges of matching available small scale power supplies with micro actuators, constructing the locomotion micro-mechanisms and coordinating individual locomotion patterns of modular robots. Instead, we describe a system where modular robots can self-assemble and reconfigure without on-board batteries or locomotion mechanisms.

The system consists of a set of modular robots and a substrate submerged into a fluidic medium (Figure 1). Instead of motors for individual module locomotion, the fluidic medium is used as an external global actuator. Instead of on-board batteries, the modular robots are equipped with electrical terminals that enable them to share electrical power with other robots or the substrate when attached to them; when detached from the growing structure, the modules are driven passively by the fluidic medium towards or away from the substrate.

Earlier FSMR implementations [16] showed the feasibility of two-module reconfiguration. However, the large size and inertia of individual modules necessitated using low fluid exchange rates in order to achieve sufficient cohesion between the fluid flow and the robots. This resulted in reconfiguration time of tens of minutes making extensive experimentation quite inefficient. The cohesion between the fluid flow and the modules improves with the reduction of the module size and fluid displacement due to the increase of the role of the viscous friction forces and reduction of the role of the inertial forces. This motivated us to reduce the module fluid displacement in the re-designed FSMR by 5 times compared to [16]; lattice grid size dropped from 130 to 80 mm.

Overall, in re-designing the large-scale prototype of the system, the following requirements were observed:

1. All technology used must have small-scale analogs
2. Individual modular robots (Figure 2) must:
   - be able to move freely in 3D within the fluid;
   - predictably and passively align and attach on contact [17];
   - be able to share electrical power with other modules and the substrate when attached [18];
   - have means of communication with other modules and the main controller;

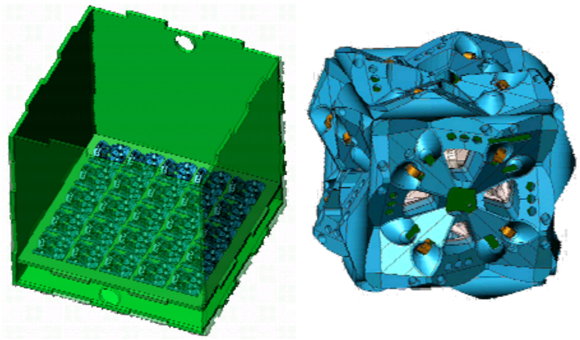

Figure 1. System components. *Left*: Fluid tank with substrate, fluid intake and outlet. *Right*: Modular robot

- identify their position and orientation once attached to the structure;
- when activated, have means to control the flow of passive modules within the fluid [19];
- be able to attach, passively bond to, and detach from the structure when commanded [20].

3. The substrate must:
- selectively attract dormant floating modules;
- be geometrically compatible with the modules;
- provide the modular robots with power…
- and communication with the main controller.

The substrate consists of an array of the bonding sites geometrically compatible with the modular robots and acts as a sieve capable of selectively allowing or restricting the flow of fluid through each of its cells. The fluid containing suspended modular robots is pumped externally through the open cells of the substrate. Upon approaching a substrate cell, the modular robot passively aligns, attaches to it, receives electrical power, identifies its location and orientation and reports to the main controller. The main controller verifies the desirability of placing a module in the reported location. If the connection is approved, the module becomes a part of the sieve and the growing structure; otherwise, the module is released back into the fluid. Thus, the task of transitional trajectory planning for modules during reconfiguration is also circumvented.

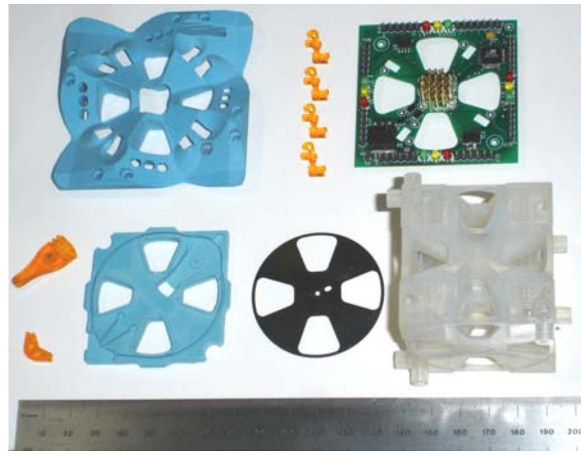

Figure 2. Robot components. *From left to right starting with top row*: robot interface, latching hooks, PCB, valve driving lever and SMA wire retainer with crimp holders, valve mechanism body, valve shutter, robot core manifold.

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[19] MEMS fluidic valve examples given in U.S. Patents 6,626,416; 6,948,799; 6,969,153.

[20] MEMS actuator examples given in U.S. Patents 6,983,594; 6,691,513; 6,454,396; 6,936,950; 6,661,617; 5,801,472.