

# Experiment Design for Stochastic Three-Dimensional Reconfiguration of Modular Robots

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**Two important trends of modern modular robotics research are module size reduction and the increase of the total number of modules in a robotic system. Smaller and simpler modules are expected to be cheaper if fabricated in bulk and easier to selectively replace in a modular system in case of failures. Stochastic methods of modular robots assembly and reconfiguration enable individual module simplification and miniaturization because modules can be constructed without on-board power supplies, locomotion controllers, or actuators [1, 2]. However, stochastic reconfiguration is in many respects dependent upon the properties and operation of the environment where the modules reconfigure [3-5]. This paper discusses the challenges in design and control of the artificial environment constructed for experiments in three-dimensional stochastic reconfiguration of modular robots.**

## Introduction

While planar controlled reconfiguration of stochastic modular robots has been successfully demonstrated by several studies [4, 1, 3], volumetric stochastic reconfiguration of multiple robotic modules is yet to be achieved. There are several technical challenges along the way to achieving this goal. First, whereas in planar experiments modules require sufficient freedom of motion in a plane, three-dimensional reconfiguration necessitates providing modules with a physical ability to freely move in 3D. There are only few conceivable options of realizing this without the use of tethers and manipulators: By carrying out experiments in either microgravity or neutral buoyancy. Second, three-dimensional modules require more sophistication in connector design, as they do not have any common alignment plane, which all 2D system naturally have. The support plane acts as an external alignment mechanism for all 2D stochastic systems, effectively reducing their connector dimensionality by one

degree of freedom compared to the 3D systems. Finally, actuation of planar stochastic system is facilitated by the availability of the third dimension: for example, in case of reconfiguration on an air table, the air moves orthogonally to the surface of the table, and its flow determines the mobility of the modules. In a three dimensional system, this type of mobility control is not readily available.

This paper describes one approach to experiment design in controlled three-dimensional stochastic reconfiguration of modular robots that addresses the above stated challenges. The following sections present the structure of the experimental installation, the mechanism of assembly and reconfiguration, as well as the modular robots control organization and the user interface.

## Three-dimensional module flotation through neutral buoyancy and global system actuation

In order to provide the robotic modules with sufficient freedom of motion in three dimensions, we have constructed a neutral buoyancy environment as shown in Fig. 1. Neutral buoyancy is achieved by placing the modular robots inside of a tank filled with mineral oil (Fig. 1a) after adjusting the density of the modular robot so that it nearly equals the density of the supporting fluid. Similar to all other stochastic systems, we use a single global actuator instead of many individual actuators for every robot. In our case, this is a 1hp fluid pump (Fig. 1b) that drives the oil and, consequently, the suspended modular robots inside of the reconfiguration chamber. The fluid flow recirculation system (Fig. 1c) is also equipped with two 3-way ball valves (Fig. 1d) for fluid flow control and reversing. These valves are necessary for additional fluid agitation, as well as for the robotic structure disassembly, as will be described below. The ball valves are driven with electrical actuators (Fig. 1e), controlled from by user interface software via a USB mechanical relay switch (Fig. 1f). Fig. 2 shows the fluid flow recirculation paths for the forward and reversed flow directions.

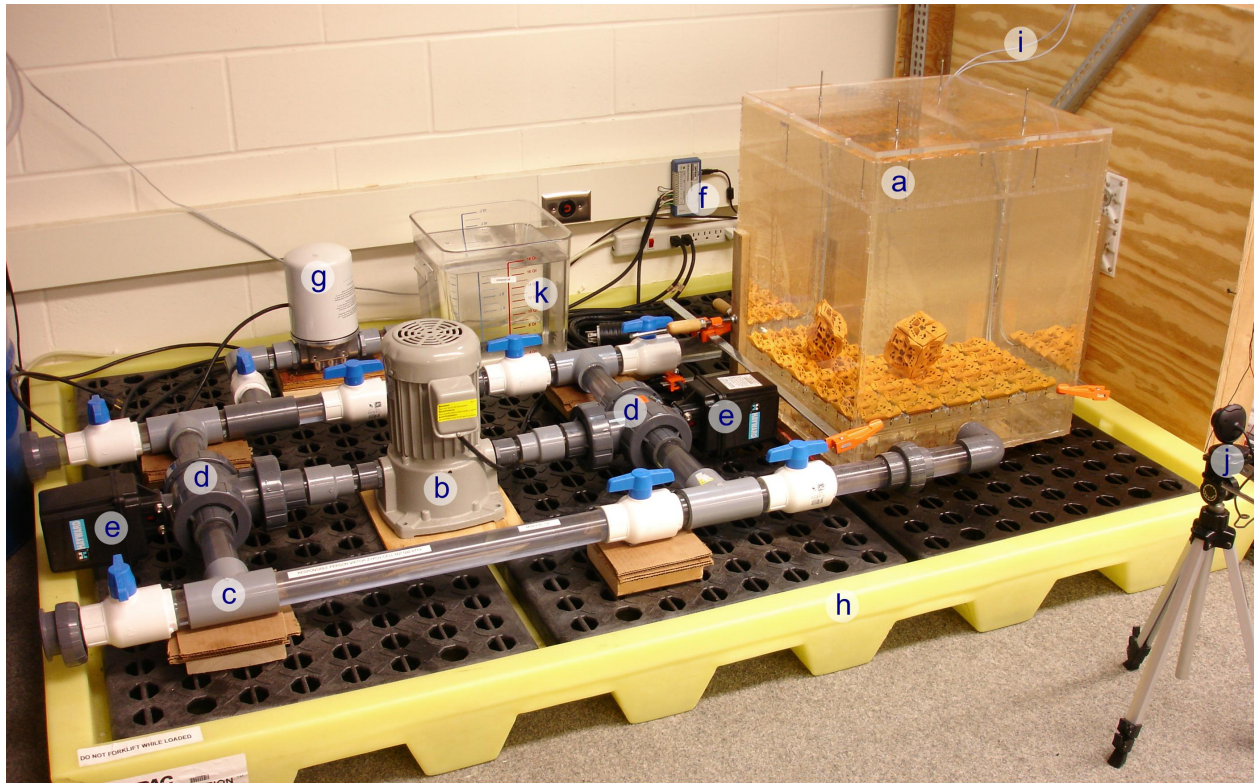


Figure 1. Fluidic experimental environment: a) fluid-filled neutral buoyancy tank, b) fluid pump, c) piping for fluid flow circulation, d) 3-way ball valves for reversible fluid flow control, e) electric ball valve actuators, f) USB-controlled valve actuator switch, g) fluid filter, h) fluid leak control platform, i) robot electrical power supply and communication interface, j) webcam, k) robot buoyancy control station.

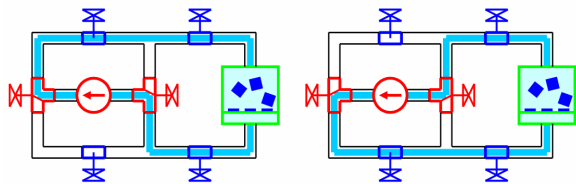


Figure 2. Fluid flow schematics: (left) forward flow, (right) reversed flow

Even though, at first glance, it appears that the problem of free motion in 3D has been solved for the stochastic modules by using a neutral buoyancy environment, there still remains a serious challenge of adjusting the weight of the module to make it exactly neutrally buoyant. After a few minutes of operation, the temperature of oil starts to increase due to fluid recirculation. This temperature change affects the robot buoyancy, presumably due to unbalanced thermal expansion of the oil and the parts of the modular robot.

### Experimental tank and reconfiguration mechanism

The fluid tank is shown in Fig. 3. It consists of three sections: the main chamber (Fig. 3a) where the robotic modules (Fig. 3b) are placed for experiments

in assembly and reconfiguration, the fluid collector (Fig. 3g) separated from the main chamber by the array of 5×5 modular robot connection ports (Fig. 3c), and the fluid inlet area (Fig. 3d) separated from the main chamber by the diffuser plate (Fig. 3f). The array of robot connection ports serves as a substrate for the “growth” of modular structures. It provides the attached modules with both the electrical power supply and the instructions for further structure modification through the electrical and communications interface (Fig. 3i).

The fluid flow is normally directed from the top of the tank to its bottom. By selectively opening the fluid valves of the substrate sockets, the flow can be redirected towards the locations on the substrate plate, where the placement of a modular robot is desired. As long as the neutrally buoyant modules move along with the fluid in which they are suspended, the flow of the carrying fluid will drive them to the selected substrate sockets. This method of actuation gives some degree of control over the speed of the reconfiguration process, similarly to the use of an air table for the 2D stochastic robots. In fact, we expect that using a pump to drive the fluid towards the selected substrate locations should accelerate the assembly process, compared to the case when such directional driving force is absent.

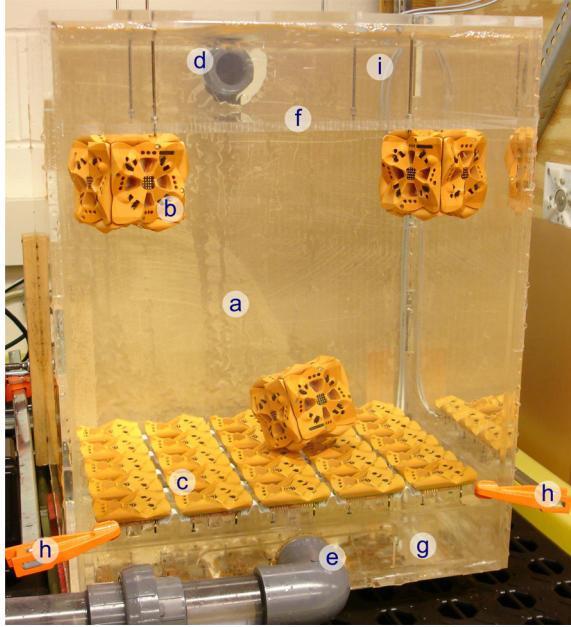


Figure 3. Experimental chamber: a) robot assembly and reconfiguration area, b) stochastic modules, c) substrate plate, d) fluid inlet, e) fluid outlet, f) diffuser, g) collector area, h) safety clamps, i) robot electrical power supply and communication interface.

As shown in Fig. 3 and Fig. 4, the robotic substrate sockets and the modular robots are equipped with geometrically compliant interfaces and mechanical latches. The surfaces of the robot shells and the substrate sockets are designed with 4-way symmetry enabling the freely floating robots to align themselves passively under the influence of driving fluid flow onto the substrate or another robot's socket along both unrestricted degrees of freedom.

Once the robots are aligned and pressed towards each other by the pressure of the fluid, their latches (see Fig. 4) engage and they become mechanically and electrically connected. The electrical and communications interface of the robots is also a 4-way symmetrical hermaphroditic spring loaded pin-to-pin contact with the pin travel smaller than half of the pin tip radius. The interface signal designation is shown in Fig. 5.

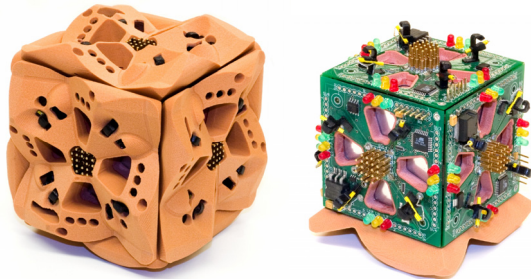


Figure 4. Stochastic modular robot with and without the compliance shells.

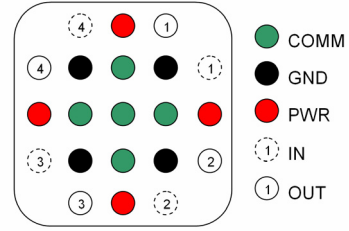


Figure 5. Symmetric and redundant electrical signal designation to the terminal pins.

After the latches are mechanically engaged, attached robot can be disconnected from the structure by actuating the shape memory alloy actuators of the latches (SMA, see Fig. 6) and reversing the fluid flow direction to push away the detached robot.



Figure 6. Mechanical latch with an SMA actuator.

### Reconfiguration process control

We also developed visual user interface software that provides intuitive means of control over the process of stochastic object construction. Fig. 7 shows several screenshots of this software. The user can change the number and location of the robotic modules in the resulting structure, selectively control valve and latch actuators for any of the substrate sockets or the attached modules, adjust or reverse the fluid flow. The software converts the visual user commands into the sequences of serial messages that are sent from the PC into the appropriate robot or substrate socket controllers.

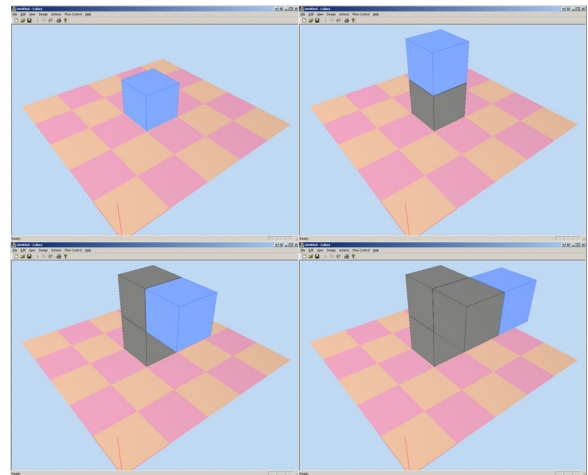


Figure 7. Visual interface for stochastic reconfiguration control.

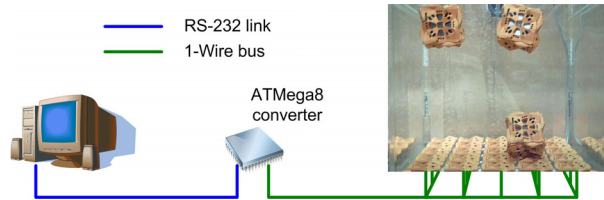


Figure 8. An external ATmega8 microprocessor is used to convert RS-232 signal from PC into 1-wire signal for the stochastic modules and vice versa.

For example, a visual interface command of adding a cube in a given location will result in opening the fluid valves of the assembled cubes and substrate sockets adjacent to this location to direct the fluid flow and the free floating cubes towards the point of construction. Conversely, a visual command of removing an assembled cube will result in disengaging the latches of the cube that is to be detached, opening the fluid valves of the adjacent cubes and substrate sockets and reversing the flow to push this detached robot away from the remaining structure.

The communication between the PC and the robot controllers is organized using modified Dallas 1-Wire protocol [6] according to the diagram shown in Fig. 8. The original protocol provided fully master controlled data reading and writing routines. Custom modifications were made to permit multiple masters to exist on one bus, and, in this way, to enable physical event-driven logic for the modular robotics reconfiguration. To provide a standard PC with access to 1-wire bus, an external ATmega8 chip was used as a bridge: it was connected to both the robot reconfiguration chamber with 1-wire bus, and to the PC via a TTL-adapted RS-232 interface.

An external USB camera is used to observe and record the processes of modular robot assembly and reconfiguration. A sample sequence of captured images of robot reconfiguration is shown in Fig. 9.

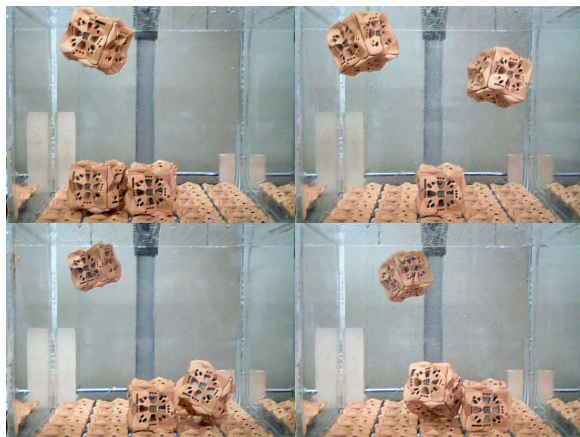


Figure 9. Example frames captured by the webcam show robot alignment and attachment to a substrate socket.

## Conclusions

We present an artificial environment constructed for experimental research in three-dimensional assembly and reconfiguration of modular robots and address three important technical challenges associated with achieving successful reconfiguration:

First, the robots must be provided with full freedom of volumetric motion and orientation. Proposed system supports the modular robots in 3D by making the modules neutrally buoyant in mineral oil. Even though this statement is quite simple, the practical difficulty of this particular task is quite high, and this factor can be prohibitive in achieving successful assembly and reconfiguration.

The second challenge is that of module alignment in a higher dimensional space, than for 2D stochastic systems. Our proposal with this regards is to first use the force of the directed fluid flow to drive the floating inactive modules towards the connection sites, and, when the modules are within a distance of physical contact from one another, choose their surface geometry so that it could align them correctly under the influence of the driving fluid pressure. This approach also serves as a solution to the third identified technical problem of global module actuation.

## Acknowledgement

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