Self-Disassembling Robots Pebbles: New Results and Ideas for Self-Assembly of 3D Structures

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I. Introduction

We present our newest algorithms, results, and future plans for the robotic pebble system show in Figure 1 which is capable of forming shapes through uniform self-assembly followed by selective self-disassembly. In general, programmable matter systems are composed of small, intelligent modules able to form a variety of macroscale objects in response to external commands or stimuli. Our system is composed of 12mm cubic autonomous robotic *pebbles*, (first presented in [1]), capable of bonding and communicating with their neighbors. Starting from a loose collection of disjoint modules, we hope to show that our system, with the assistance of external stochastic forces, is capable of self-assembling into a uniform crystalline structure. Once this initial block of material is formed, the system is able to self-disassemble to form complex 2D shapes. Like geologic forces compact sediment into blocks of sandstone and a sculptor removes the extra stone to reveal a statue underneath, our system forms an initial uniform grid of modules and then subtracts the unnecessary modules to form a goal structure.

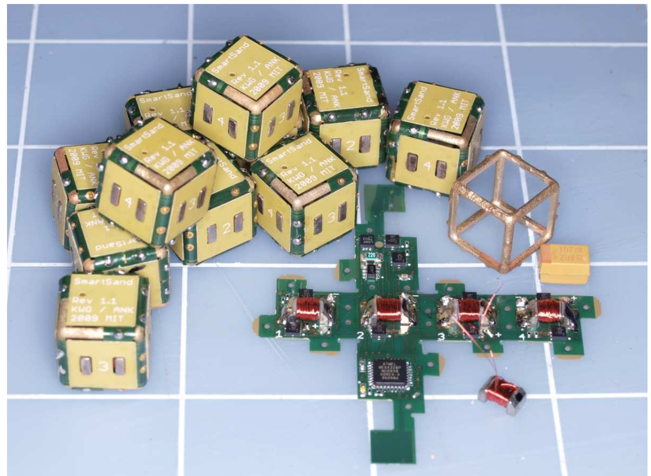

Fig. 1. Each programmable matter pebble is a 12mm per side, and together they are able to form complex 2D shapes using four electropermanent magnets able to hold 85 times the individual module weight. The pebbles are formed by wrapping a flexible circuit around a brass frame. An energy storage capacitor hangs between two tabs occupies the center of the module.

A. System Functionality

We aim to create a system of sand grain sized modules that can form arbitrary structures on demand. Imagine a bag of these intelligent particles. If, for example, one needs a specific type or size of wrench, one communicates this to the bag. The modules contained within first crystallize into a regular structure and then self-disassemble in an organized fashion to form the requested object. One reaches in, grabs the tool, and uses it to accomplish a meaningful task. When one is done with the tool, it goes back into the bag where it disintegrates, and the particles can be reused to form the next tool. Such a system would be immensely useful for an astronaut on an inter-planetary mission or a scientist isolated at the South Pole. Even for the average mechanic or surgeon, the ability to form arbitrary, task-specific, tools would be immensely valuable in inspecting and working in tight spaces.

B. Advantages of Self-Assembly/Disassembly

Designing an electromagnetic module capable of exerting the force necessary to attract or repel other modules from a distance greater than the size of a module has proven challenging. Shape formation with electrostatic or magnetic modules is more feasible when driven by stochastic forces, so that the actuators only need to operate over short distances.

Traditional self-assembling systems aim to form complex shapes in a direct manner. As these structure grow from a single module, new modules are only allowed to attach to the structure in specific locations. By carefully controlling these locations and waiting for a sufficiently lengthy period of time, the desired structure grows in an organic manner. In contrast, our system greatly simplifies the assembly process by initially aiming to form a regular crystalline block of fully connected modules. We make only limited attempts to restrict which modules or faces are allowed to bond with the growing structure. These restrictions are only to ensure that we achieve a regular structure. As illustrated in Figure 2, after we form this initial block of material, we complete the shape formation process through self-disassembly and subtraction of the unwanted modules.

Subtraction has one distinct advantage over existing self-assembly techniques. Subtraction does not rely on complicated attachment mechanisms that require precise alignment or careful planning. Subtraction excels at shape formation because it is relatively easy, quick and robust. The drawback associated with subtraction is that the initial mass of material must be pre-assembled. While we do this by hand for our experiments, it could be automated. Our modules, due to symmetry in their magnet-endowed faces, are rotation

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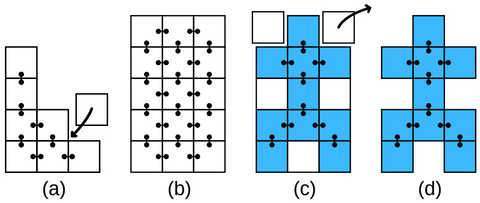

Fig. 2. To form shapes through subtraction, modules initially assembly into a regular block of material (a). Once this initial structure is complete and all modules are fully latched to their neighbors (b), the modules not needed in the final structure detach from the neighbors (c). Once, these extra modules are removed, we are left with the final shape (d).

invariant within a plane, so an inclined vibration table should function well to rapidly assemble large, regular sheets of modules. In the future, we envision deploying modules, such as spheres, which naturally pack 3D space efficiently.

It is also worth noting that as the individual modules in self-reconfiguring and programmable matter systems continue to shrink, it will become increasingly difficult to actuate and precisely control the assembly process. In particular, designing modules capable of exerting the forces necessary to attract their neighbors from significant distances will be challenging. Instead, these systems may find assembly and disassembly much simpler when driven by stochastic environmental forces. The modules addressed in this paper, which are able to latch together from distances approximately 20–35% of the module dimensions, could easily take advantage of these stochastic assembly mechanisms to form an initial structures. Our particular system also relies on external forces to carry the unused modules away from the final shape. (The EP magnets that we employ cannot both attract and repel.) In our system, this force is often gravity, but it could also be vibration, fluid flow, or the user reaching into the bag of smart sand particles to extract the finished object.

The remainder of this work will focus briefly on related work and the robot pebble system hardware. Following this introductory material, we will discuss hardware, algorithms, and experimental results relating to the self-assembly of the pebbles. Then we will address three methods to extend the system to three dimensions. Finally, we will conclude by proposing some directions for future work with the system.

C. Related Work

Our research builds on previous work in programmable matter, self-assembly, and self-reconfiguring robotics. The concept of self-assembly is not particularly new and others have studied its connections to chemical kinematics [2]. More recently, several interesting program-driven stochastic self-assembly systems are under active development [3]–[5]. Like the robotic pebbles we propose, these systems rely on rigid particles for shape formation. While not able to reconfigure, the Digital Clay project [6] relies on particles able to bond using permanent magnets. Other approaches to shape formation rely on modules with internal degrees of freedom that are able to modify their topology in some way [7]–[9]. There are also hybrid systems [10]–[13] in which neighboring modules join to accomplish relative actuation.

Other research has focused more directly on the concept of programmable matter. One particular system [14], uses rigid cylindrical modules covered with electromagnets to achieve 2D shape formation. Theoretical research has previously investigated the use of sub-millimeter intelligent particles as 3D sensing and replication devices [15]. More recent developments are utilizing deformable modules [16] as a way to realize programmable matter. Finally, the system described in [17] has no actuation ability, but demonstrates what may be termed ‘virtual’ programmable matter through the use of 1000 distributed modules to form an intelligent paintable display capable of forming text and images.

A limited amount of past research has focused specifically on self-disassembling systems as a basis for shape formation [18]. This past work was based on large modules (45cm cubes) with internal moving parts. Additionally, the modules lacked symmetry so they had to be assembled in a particular orientation. The work presented in this paper is an outgrowth of the Miche system presented in [18], but we have reduced the module size, eliminated all moving parts, and added symmetry to allow for arbitrary module orientations. Finally, the system presented here shows promise as both a self-disassembling and self-assembling system.

II. Hardware Summary

Figure 1 shows a collection of identical programmable matter pebbles and the components that comprise one module. The modules are 12mm cubes capable of autonomously communicating with and latching to four neighboring cubes using electopermanent (EP) magnets. Each module is formed by wrapping a flexible circuit around a brass frame. All electronic components are mounted to the inside of the flex circuit. The four EP magnets are able to draw in other modules from a distance, mechanically hold modules together against outside forces (with zero power dissipation), communicate data between modules, and transport power from module to module. The EP magnets are soldered directly to the flex circuits so that their pole pieces protrude slightly through four sets of holes in the cube faces. A capacitor mounted inside each module provides local energy storage eliminating the need for batteries in each module. Instead, DC voltage and current are injected into the system at one root module and transferred from module-to-module by the electrically isolated poles of the EP magnets. For more information about the system hardware, consult [1].

III. Self-Assembly

As mentioned above, we wish to demonstrate that our system of robot pebbles can form arbitrary shapes through a two-step process. First, we want a loose collection of modules to self-assemble into a regular crystalline structure. Once this initial block of material is formed, we wish to sculpt it into an arbitrary shape using self-disassembly.

Previous work [18] has successfully demonstrated the self-disassembly process. This work aims to explore the self-assembly step by using external stochastic forces to drive the modules around small platform until they bond into a uniform structure.

A. Hardware

As shown in Figure 3, we built a simple vibration table to test the ability of the pebbles to self-assemble in the presence of stochastic environmental forces. The table was built from an inexpensive back massager. We anchored the massager to a heavy aluminum plate and mounted an acrylic assembly platform to the top of the massager. The pebbles are placed on the top of this platform and allowed to move freely. The acrylic tray has edges which keep the pebbles from falling of the platform. Additionally, there is a universal joint between the massager and the assembly platform which allows us to arbitrarily incline the platform.

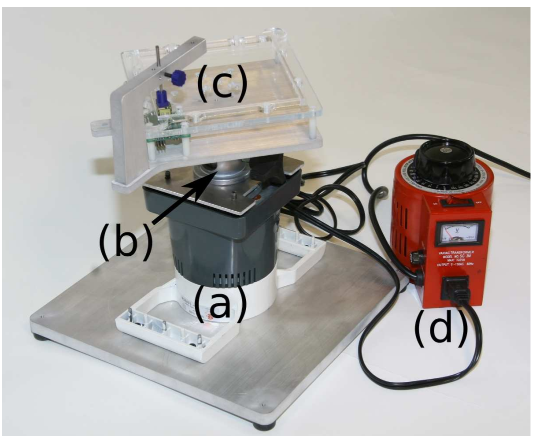

Fig. 3. To aid in self-assembling, we built a simple vibration table from a $100 back massager (a) and a Panavise universal joint (b) which allows us to control the angle of the assembly table (c). A variac (d) allows us to control the speed of vibration.

For self-assembly to occur, the pebbles must be provided with power. The acrylic assembly platform contains three locations where a single root pebble may be anchored: the center of the platform, the middle of an edge, and a corner. Below these three anchor point there are gold-plated pogopins which transfer power and communication signals to matching pads on the bottom of the pebble. When self-assembling, the module at this anchor point activates its EP magnets to help attract unpowered modules as they pass by. When an unpowered, unattached module comes close enough to the root to be drawn in, the module will bond with the root and immediately receive power. Once it has power, it communicates with the root module and activates its EP magnet to significantly strengthen their mechanical bond. It also activates its three other magnets to attract additional free pebbles that are circulating on the platform. This process repeats until all free modules have been attached to the growing structure.

B. Algorithms

During the self-assembly process, we want to ensure that no gaps are formed in the growing structure. By preventing gaps, the self-disassembly process is able to form the widest variety of shapes. Additionally, gaps weaken the structure and reduce the available communication paths. If we allow new modules to be accreted at any location on the growing structure, it is easy to create concavities in the structure that are theoretically difficult and practically impossible to fill. For example, a loose module will never fill a spot in the crystalline lattice that is already surrounded on three sides.

To avoid holes in the self-assembled structure, we propose a simple distributed algorithm that only requires local information. Based on this information, each free module coming into contact with a potential bonding site on the solidified structure must decide whether to permanently bond with the structure or move on and look for another bonding site.

The algorithm makes two assumptions. First, all modules know the location of the root module. This is easy to hard-code into each module's process as location (0,0), for example. Second, once each module is added to the structure, it can determine it's (x,y) position. This requirement is also easy to meet. The user informs the one module anchored to the assembly platform that it is the root and therefore at location (0,0) and that it is rotated 0°. Using this information, the root can inform the module added to its right that the new module's location is (1,0). Likewise, the module added below the root is at location (0,-1), etc. Based on which of its faces the new module receives this message, it can determine its orientation. Now that the newest module knows is location and orientation, it inform its newest neighbors of their location. More details, and a proof that this algorithm is correct are proved in [18].

The algorithm, begins as the free module receives power when it comes into contact with a module already a part of the crystallized structure. Immediately, the module queries its neighbor to determine its location. Based on this location, the module then constructs a *root vector* pointing back to the root module. The vector may have x- and y-components. The new module permanently bonds with the structure if it detects that it has neighbors in both the x- and y-directions of the root vector, if they exist. For example, consider a new module that determines its location is (10,2). As shown in Figure 4, the root vector is then (-10,-2) which has both x- and y-components. As a result, the module only bonds with the structure if it has neighbors at (9,2) and (10,1). Instead, if the new module were located at (0,-5) and the root vector was (0,5), the module in question would only bond if it detected a neighbor at (0,4).

If the new module does not detect neighbors in the appropriate locations, it informs whatever neighbors it is contacting, and they deactivate their connectors allowing the pebble to continue moving under the influence the table's vibrations. The already solidified module keeps this connector deactivated for a fixed period of time to allow the rejected module to move out of range of its attractive

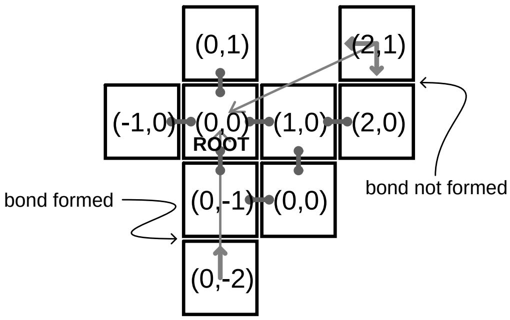

Fig. 4. During self-assembly, modules only permanently attach to the already assembled structure if they detect immediate neighbors along a vector that points back to the root module. The module at (2,1) does not attach because, while it has a neighbor along the y-component of its root vector at (2,0), it does not detect a neighbor at (1,1) along the x-component of the vector. The module at (0,-2) does attach to the crystallized structure because it detects a neighbor at (0,-1), along the y-component of its root vector. The root vector does not have an x-component, so the module does not attempt to detect neighbors at (-1,-2) or (1,-2).

force. Eventually, the connector is reactived in hopes that the bonding site will have become valid.

C. Experiments

In preliminary experiments, the vibration table works well to align the pebbles into a grid pattern. When the assembly table is tilted about 10°, along its diagonal, a set of 15 pebbles forms a lattice within 15–20 seconds. As expected, the resulting shape is often concave. To test our self-assembly algorithm, we plan to compare it to the naive algorithm which bonds two neighboring modules wherever they come into contact. We will perform these experiments in the following weeks leading up to the workshop.

IV. Extensions to 3D

The current generation of robot pebbles is only able to operate in the plane. Furthermore, the pebbles cannot be flipped upside down. If they are, the EP magnets, when activated, change from attracting to repelling. To expand the number of practical applications of the system, it needs to be able to operate in three dimensions. We see three different approaches to achieving a 3D programmable matter systems.

A. Rotation Invariant Pebbles

The first option is the obvious solution: place electropermanent magnets on all six faces of the pebbles making them invariant to any 90° rotation. This solution provides the greatest flexibility and highest degree of redundancy when assembling the modules into a 3D structure.

The six-connector solution is not without drawbacks. The flex circuits in the current version of the pebbles are already severely space limited. By adding two additional EP magnets, we would eliminate the area currently dedicated to the processor and power conditioning circuitry. (The additional EP magnet would also require additional drivers further increasing the component density.) The EP magnets are large components with respect to the size of the flex circuit and must be placed in the center of each face. As a result, they subdivide the remaining flex circuit area into many small parcels that are difficult to utilize for components other than surface mount resistors and capacitors. This awkward division of flex circuit area would make it difficult to utilize an ASIC that combined all of the circuitry into one IC. One way to avoid this problem may be to modify the design of the flex circuit to create an additional “floating tab” that occupies the middle of the cube and is large enough to contain the ASIC.

The second problem with placing EP magnet connectors on all six faces is that the connectors would need to be redesigned. Currently, the connectors are only 2-way symmetric, but they would need to be 8-way or axially symmetric in the 3D system. Figure 5 shows a cross-section of one possible design of an axially symmetric EP magnet.

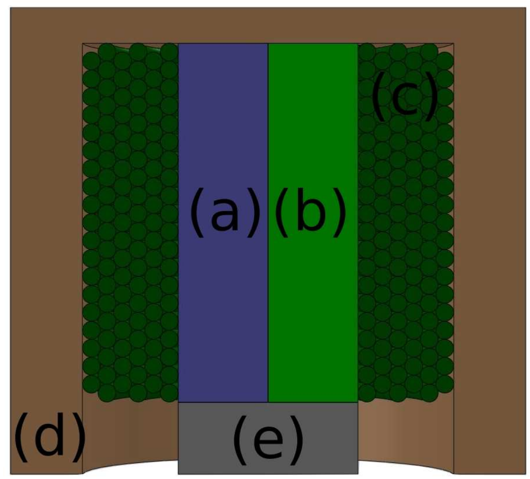

Fig. 5. An axially symmetric electropermanent magnet could be created by placing two half round magnets (a,b) next to each other to form a core than is then wound with a coil (c) and placed inside of a ferromagnetic cup (d). A small cap (e) is attached to the exposed end of the magnetic core to prevent fringing fields from giving rise to attractive forces when the EP magnet is deactivated.

B. Out of Plane Connectors

An alternative to employing six active faces in each pebble is to create two or three distinct types of pebbles, each capable of bonding with neighbors in separate planes as shown in Figure 6 One can think of this strategy as forming a structure as a stack of unbonded layers and then bonding the neighboring layers together with special “out of plane” pebbles. We could continue using our current set of pebbles for bonding in the X-Y plane, but we would then design two new types of pebble (still with just four connectors) capable of bonding in the X-Z and Y-Z planes. Starting with a sheet of X-Y type pebbles, we could replace some of the modules with X-Z and Y-Z modules. On top of each of these new pebbles we would place another X-Z or Y-Z module, respectively. Then, the remainder of the second layer could be filled with the standard X-Y pebbles.

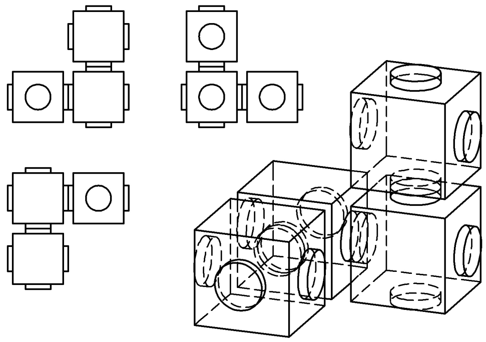

Fig. 6. By using distinct types of pebbles capable of bonding in either the X-Y, X-Z, or Y-Z planes we can create 3D structures using only four connectors per module.

For a large structure containing an equal proportion of all three types of modules, there will, on average, be one third of neighboring faces which are not connected. In comparison to a system in which there are EP magnets on all six faces, this will weaken the structure and limit the communication pathways through it. As with the rotation invariant system, the connectors will need to include additional degrees of symmetry because stochastic forces will ensure that the modules touch in every possible orientation.

C. Active and Passive Faces

The third option for creating a 3D system is to use a combination of active and passive connectors like the configure in the Miche system [18]. Three connectors could be ferromagnetic plates and the other three could be EP magnets. This setup alleviates the space constraints inside the pebbles, but forces the all pebbles in a structure to be oriented identically. If their orientations are not homogenized, there will be locations were two passive connectors are adjacent. If we ever hope for the system to self-assemble in the presence in stochastic forces, the active/passive connection mechanism is untenable.

V. Future Directions

The self-assembly algorithm presented here is completely distributed and only relies on information from a module's closest neighbors. As a result, the assembly process can happen in parallel over the whole perimeter of the growing structure–an important feature when assembling structures from hundreds or thousands of modules. The algorithm also extends to 3D systems. Instead of checking just the x- and y-components of the root vector for neighbors, the module attempting to attach to the structure will also need to check for a neighbor in the z-direction.

One aspect of the algorithm that needs optimization is the time delay between when a module rejects a bonding site and when that bonding site is reactivated. This time is likely dependent on the number of free modules in the system and the severity of the stochastic forces acting on it. We suspect the delay could be shortened if the EP magnets had the ability to repel, in addition to attract. Such functionality is with reach, but requires additional mechanical and electrical complexity.

Given that we know how to form an initial structure devoid of holes, future research should also focus on how to explicitly form holes in the structure. Without holes in the initial structure, the final shape formed after the self-disassembly process will also not have holes. By purposefully including holes in the self-assembly process, the completed shapes can also have holes.

We hope that by uniting the ideas for self-assembly and 3D shape formation presented here that we can move the robotic pebbles one step closer to *smart sand*. While there is still work required to further miniaturize the pebbles, the current system is a useful testbed that allows us to quickly test the concepts and algorithms that drive the self-assembly and self-disassembly processes.

VI. Acknowledgments

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