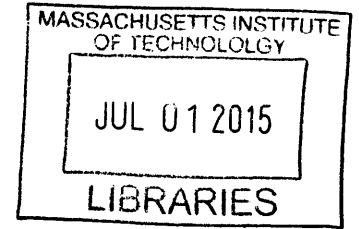


ARCHIVES



M-CELL ASSEMBLY

by

Dimitrios Mairopoulos

Diploma in Architectural Engineering
Technical University of Crete, Greece, 2013

SUBMITTED TO THE DEPARTMENT OF ARCHITECTURE IN PARTIAL FULFILLMENT OF THE
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M-CELL ASSEMBLY

by

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Submitted to the Department of Architecture
on May 21,2015 in Partial Fulfillment of the
Requirements for the Degree of Master of Science in
Architecture Studies

ABSTRACT

In this thesis I propose a self- assembly procedure called the Morphocell(M-Cell) assembly. This procedure is based on an assembly unit called the M-Cell. The M-Cell is comprised out of two components, the M-Block and the M-Clay (in which the M-Block is embedded). During the assembly procedure the M-Clay acts as the environment of the assembly for the M-Blocks. This allows a global, parallel assembly that is highly autonomous and has large error correcting capacities. When the assembly procedure is complete the M-Blocks have assembled into a spatial lattice. Then the M-Clay surrounds this lattice thus creating a solid object, the M-Object. The M-Object, which is the goal of this procedure, is a dynamic object that can be easily modified, expanded or dismantled. Furthermore, it can respond in various ways to its environment. This system was optimized through a feedback loop that was informed by constant digital and physical simulations. The findings of this thesis can have important applications in construction of structures in extreme-remote environments and in the fabrication-rapid prototyping field.

Thesis Advisor: Terry Knight
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1 | INTRODUCTION

This thesis consists of four chapters and an appendix. The first chapter is the introduction. In the introduction I will briefly describe the field that frames my research. Furthermore, I will refer to the initial inspiration of my work. The other three chapters are the Past, the Present and the Future. In the second chapter, the Past, I will refer to the key concepts of my work and analyze my system. Moreover, I will describe the evolutionary process that I followed to transform my vision into a working system. In the third chapter, the Present, I will present the final state of my system. I will analyze its capabilities and refer to its advantages and contributions. In the fourth chapter, the Future, I will explore future possible implementations of my work. Finally, in the Appendix I will present a variety of key experiments that were crucial for the evolution of my procedure.

1A | SELF ASSEMBLY

The system that I propose in this thesis is based on the concept of Self Assembly. Self-Assembly refers to the spontaneous arrangements of building blocks into greater structures through local interactions. This process is possible through “information coded (as shape, surface properties, charge, polarizability, magnetic dipole, mass etc) in individual components”, as Whitesides says (Whitesides and Grzybowski, 2002). Furthermore, he explains that these are the characteristics that determine the way the building blocks interact.

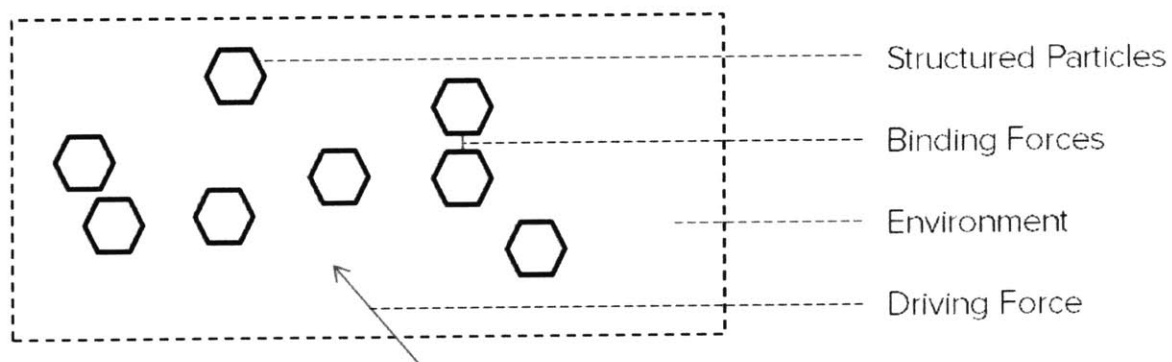
Self-assembly is a widespread procedure in nature. It can be met both in inorganic systems (such as bubble rafts, crystallization, polymerization, micelles) (Pelesko, 2007 p.44) and organic (such as protein folding, tobacco mosaic virus, ribosome) (p.62).

There are four basic features that characterize natural self-assembly procedures. These are the structured particles, the binding forces, the environment and the driving force. The structured particles are the building blocks of a self-assembly system. The binding forces are the forces that hold the particles together (examples of such forces are capillary, electromagnetic, chemical bonds). The environment is the means of assembly. The particles are embedded in an environment and this environment is crucial for the way binding forces act. Through the manipulation of this environment the binding forces and the formation of the particles can be changed. Finally, the driving force is what puts the system in motion (p.76).

The same four components that are implemented in the natural self-assembly systems are also used in engineered systems.

There are two main types of self-assembly, static and dynamic. Static systems are the self-assembly processes that reach a global or local equilibrium and do not dissipate energy. On the other hand, dynamic systems are self-assembly processes that remain stable through dissipation of energy (Whitesides and Grzybowski, 2002).

The M-Cell assembly system, being a self-assembly process, demonstrates the features of every self-assembly system. It implements building blocks that assemble through magnetic forces. Furthermore, this activity takes place in a very specific environment. Moreover, the M-Cell assembly system is a static system that reaches its final state through global energy minimization.

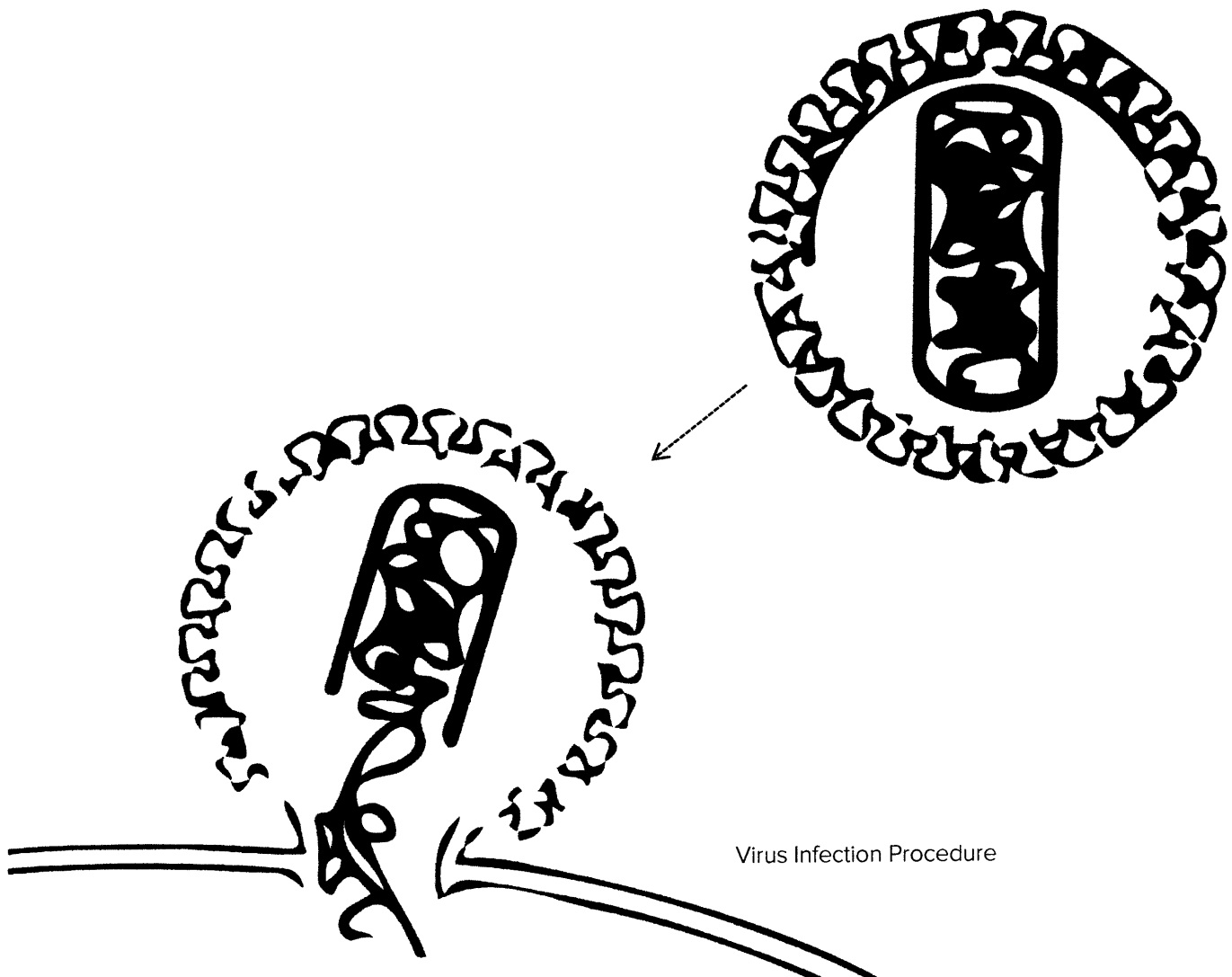


The basic features of a self-assembling system. (Pelesko,2007 p.69)

1B | INSPIRATION

The inspiration for the M-Cell assembly procedure came from the way viruses deliver content (DNA/RNA) to cells and affect their structures. Viruses are covered with a protein membrane which is called capsid. As the virus infects a cell, the capsid merges with the cell's membrane and injects its content into the cell's fluid (cytoplasm). Furthermore, the content moves in the cytoplasm and through different mechanisms, changes various structures in the cell.

What was particularly intriguing for me in this natural process was the way that the cells are able to contain the means of assembly (cytoplasm) along with the building blocks. Furthermore, I found fascinating that these two separate environments (of the cell and virus) merge to create a common 3d space where the blocks can freely move and assemble. This inspired me to investigate the extrapolation of this logic to a macroscopic self-assembly system. Therefore, my goal was to create a unit that would contain the environment needed for the assembly procedure. This environment would act as a catalyst to the procedure and assist it. Furthermore, this unit would also contain a building block. This building block would be designed to self-assemble with other blocks, thus creating emerging structures.



2 PAST

In this chapter I will analyze the steps that I followed in order to design my final system. First, I will illustrate the procedure and present the assembly unit, the M-Cell. Furthermore, I will talk about its components the M-Clay and M-Block. Then, I will analyze and present the different stages of the M-Block's evolution. Finally, I will focus on the problems of each stage and describe the solutions that I have implemented.



2A | M-CELL

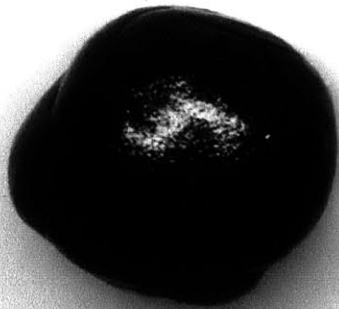
I started my experimentations on the M-Cell assembly procedure by creating an assembly unit called the M-Cell. The M-Cell is comprised by the M-Block and the M-Clay.

The M-Block is a building block based on simple geometrical solids. I chose these geometries based on their capacities to form spatial lattices when they accumulate. Furthermore, the blocks have embedded magnets which allow them to attract with each other and assemble.

The M-Clay is a term used to describe a Non-Newtonian viscoelastic fluid. This material can act as a viscous liquid or an elastic solid according to the magnitude of the forces that are applied on it. Moreover, the M-Clay is infused with magnetic particles that make it respond to magnetic fields.

The M-Cell is an M-Block submerged in M-Clay.

M-CLAY



- Silicon polymers – Non Newtonian fluid
- Acts as a viscous liquid - elastic solid
- Magnetic, other properties may vary

M-BLOCK



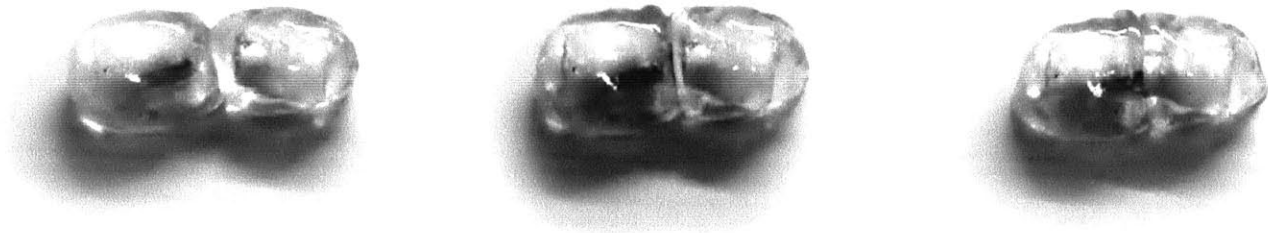
- Based on simple geometry that can form spatial lattices
- Embedded magnets
- Alternating patterns of magnets' polarities

2B | M-CELL ASSEMBLY PROCEDURE

The M-Cells are the protagonists of the M-Cell assembly procedure. They are designed to initiate the procedure when two or more of them come in contact. First, the M-Cells' M-Clay starts merging due to the properties of the material, creating a common blob. This M-Clay blob is the "environment" in which the assembly of the blocks will take place. This "environment" allows smooth and precise movements of the M-Blocks due to the high viscosity of the material.

In the next step the M-Blocks start attracting each other due to the magnetic fields of their magnets. The properties of the M-Clay in combination with the geometry of the block and the strategically placed magnets assist the blocks in error-correcting their relative positioning with each other. The goal of this error-correction procedure is the creation of a desired spatial lattice.

After some minutes the assembly procedure is terminated and the spatial lattice has been created. Then the M-Clay serves its second purpose which is to surround the lattice and create a solid object. This object is called the M-Object and it is the goal of the assembly procedure.



2C | M-OBJECT

The M-Object is a solid, dynamic object that is created by the combination of the product of the assembly procedure (spatial lattice) with the M-Clay. As soon as the assembly procedure is over the M-Clay is sculpted by the magnetic fields of the lattice's magnets. Therefore, it gives shape to the M-Object, a shape that follows the geometrical features of the lattice.

I initiated this thesis with the vision to design and optimize the M-Cells, their behavior in the M-Cell assembly procedure and the resulting product of that procedure (the M-Object). In the next pages I will present in greater detail the components of the M-Cell (the M-Clay and M-Block). Furthermore, I will refer to their role in the assembly procedure and analyze their evolution that led to my final optimized procedure.

COMPONENTS OF THE M-CELL

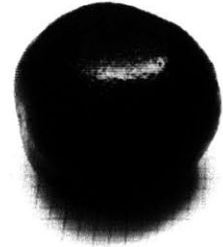
2D | M-CLAY

The first component that I am going to analyze is the M-Clay. The M-Cell is comprised by an M-Block submerged in M-Clay. The term Clay is used for a Non-Newtonian viscoelastic liquid (based on silicon polymers). This material can act as a viscous liquid or an elastic solid according to the forces that are applied on it. Furthermore, the term M-Clay is used to indicate that the material is infused with magnetic particles, compared to regular Clay that is not. Due to these magnetic particles the M-Clay can react to magnetic fields.

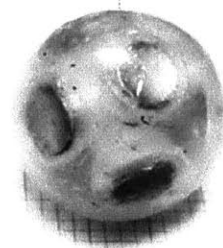
In every self-assembly procedure the environment of the assembly plays a significant role. In some cases it even acts as a catalyst for the assembly. One of the key goals of my procedure was to be able to encapsulate this environment in the M-Cell. In the case of the M-Cell assembly procedure this environment is the M-Clay. Therefore, an M-Cell contains both the blocks (building blocks of the assembly) and the environment. This offers a range of practical benefits. First of all the blocks can be moved to the assembly point without assembling. This can be achieved by reducing the temperature of the M-Clay. Furthermore, though temperature we can control the speed of the assembly procedure and even stop it. Secondly, it is crucial to the autonomy of the system since everything that is needed for the assembly is packed in a single cell.

Moreover, there are also benefits related with the actual procedure of assembly. These benefits have to do with the implementation of a parallel assembly procedure than a serial. By examining the scenario where the M-Blocks are accumulated (e.g. by throwing them on a pile) without the M-Clay, it is clear that a parallel assembly is impossible. In fact, the M-Blocks will assemble rapidly in relation to their closest neighbor. Therefore, there is no time to adjust their positioning globally according to all their neighbours. On the other hand, the M-Clay provides time to the blocks since the assembly does not happen rapidly. The blocks can now error-correct their positioning according to all their neighbours. The friction produced between the M-Clay and M-Block allows smooth and precise adjustments of their positioning. Thus, all the blocks act together as one system that “wants” to minimize its energy globally leading to a truly parallel procedure. Therefore, the blocks are more “informed” about their neighbours and as a result, the error correction procedure can be more “informed” as well. Subsequently, the final spatial lattice is less prone to errors.

M-CLAY



REGULAR CLAY



However, the role of the M-Clay is not limited to the above. After the assembly procedure is over the M-Clay is morphed by the magnetic fields of the spatial lattice. The final outcome of this procedure is the M-Object. Therefore, the M-Object is a solid object which is comprised of a spatial lattice ("bones") that holds in place the M-Clay ("flesh") through its magnetic fields.

To sum up, the M-Clay serves two purposes in the assembly procedure. First, it acts as the environment of the assembly, and secondly, it morphs into the skin of the M-Object thus giving it its shape.

Regular Clay can also be used in some cases instead of the M-Clay. The regular Clay does not have magnetic particles, and therefore, does not interact with magnetic fields. Hence, if it is used in an M-Cell assembly procedure, it will flow away as a liquid after the procedure is over, revealing the spatial lattice. This property has been very useful in my experiments for assessing the produced lattices. Furthermore, I was making use of transparent Clay for the same reason (in order to be able to examine the process of the assembly procedure through the Clay). Regular Clay can also be used in order to create supports during the assembly procedure. The Clay can provide support for parts until they are assembled. After the procedure is finished it flows away revealing the final M-Object.

An interesting aspect of the M-Clay / Clay is that it can be customized in production, and therefore, can have a very wide range of varying properties. These properties can affect or change in different ways the assembly procedure. Furthermore, they are transferred to the final M-Object. Therefore, qualities of the M-Object such as weight or material strength can be controlled according to the way the M-Clay is produced. Moreover, it can enhance greatly the dynamic nature of the M-Object. The M-Object can be "programmed" to react to environmental conditions such as temperature, light or radiation in certain ways. I believe that this is a very interesting area of study and can offer much to the enhancement of the procedure and the final M-Object. However, I decided to keep the parameters of my system controlled since this endeavor could be a whole new project in its own right. Hence, I chose in this thesis to create a system that is optimized for one kind of Clay. However, in the future I wish to pursue these experimentations and analyze their impact on my current system. In conclusion, in this thesis I used two kinds of commercial Clay, a magnetic one and a transparent non-magnetic.



2E | M-BLOCKS

DESIGN PROCEDURE

The next component of the M-Cell I am going to focus on is the M-Block. The M-Block is the building block of my M-Cell assembly procedure. I dedicated a significant portion of this thesis in analyzing M-Block geometries and interactions. This analysis aimed on the refinement of the M-block characteristics. My goal was to design M-Blocks that in every possible circumstance (relative positioning with its neighbours) would self-assemble with each other in an spatial grid. This ability is crucial for the final M-Object. Whereas a few errors could be incorporated, an abundance of them in the assembly of the grid would result into compromised structural integrity of the M-Object, and a disfigurement of its final shape. Therefore, I had to predict and eliminate from my procedure most of the possible problematic ways that the blocks could assemble.

This design procedure was based on a feedback loop that involved, thinking about the “forces” that shape my design, designing, testing the digital, testing the physical, and evaluating.

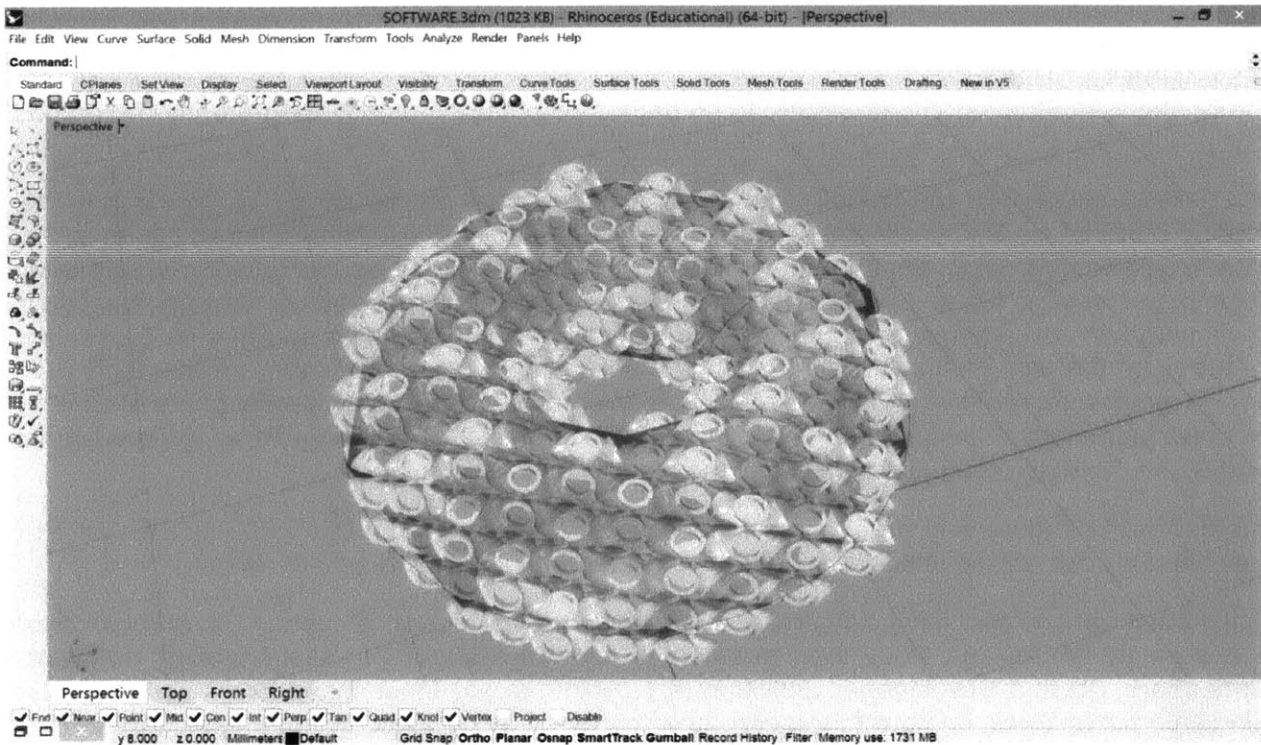
Digital visualizations and simulations were a crucial part of the design process. I used Rhinoceros to design my blocks and study their geometries and Maya physics to simulate their behavior. Furthermore, I built a Grasshopper definition that could turn any input shape into a spatial lattice using an input M-Block, in order to visualize how the blocks accumulate in larger assemblies. (This definition can also provide information about the positioning of the cells in the assembly that can be used in future stages of the project.)

However, apart from the digital experimentations that I engaged with, I have found that conducting tests in the physical world was also very important for the optimization of the block. That was due to the inevitable lack of our capacity to create fully representational models of the physical objects and their interactions. Hence both the digital and the physical world were used to test my blocks and inform my design according to my findings.

The fine tuning procedure started with testing the relative positions of the M-Blocks in the digital model and simulating their behaviors. Then, I 3d-printed the models and I replicated these tests in the physical world. First, I tested the effects of the magnets in different relative positionings scenarios. Then, I tested the possible paths that the blocks could follow during the assembly procedure. This allowed me to assess decisions about the geometry of the blocks that I had taken previously. Moreover, I searched for possible positionings and paths that could create errors in the assembly. Finally, I tested the blocks' behavior with the clay in an actual M-Cell assembly procedure. The observations that I made during all these tests allowed me to make informed decisions on how the geometry could be transformed in order to optimize the design.

Another factor that became more and more important as I proceeded with the experiments was that I was gaining experience on the way the blocks interacted. This was due to the physical-tactile interaction with the blocks. This experience allowed me to exclude potential designs, limit my pool of possibilities and pursue the fittest design.

Overall, I would compare my design approach with the way biological systems work: it involves generations of designs in which some “die” and some “evolve-mutate” to create a fitter one, based on their performance.



Grasshopper Definition for spatial lattice simulation

THE FIRST STEPS

I started the design procedure of the blocks by setting some general principles that would apply to all the blocks. These principles served as the initial constraints of my design. First of all, I was seeking geometries that would be able to create spatial lattices when they assembled. Furthermore, these block geometries had to be able to form a grid through simple relationships with their neighbours. Had these relationships been more complex (involving complex rotations and translations), there would be a greater chance of errors occurring during the assembly procedure. Therefore, I chose block geometries that had a discrete translational symmetry. This means, that the spatial lattice could be achieved just through the translation of the blocks (without rotation). Discrete translational symmetry was also helpful in predicting possible paths that the blocks could follow in order to assemble.

Secondly, the block geometries needed to have a great deal of symmetries. This would limit the necessary rotation angle while the block is correcting its position during the assembly procedure. Therefore, I could avoid large-angle rotations, since the maximum rotation that could be needed would be the angle of the block's rotational symmetry.

Furthermore, an important parameter was finding the equilibrium point in the amount of magnets that would be used in the block. Had I used too many magnets, they would be too close to each other. This could result into a lack of discretization of possible positions and produce

unpredictable results. However, if the magnets were too few, that would result in a large angle between the magnets. This would mean that if there was need for rotation in the error correction procedure, the blocks would have to perform extreme maneuvers. In some cases the blocks would be unable to do that, resulting to an error in the assembly. Moreover, due to the large angles there could be unwanted interactions with the sides of the magnets, thus resulting into local energy minima.

Finally, an important parameter that I had to consider is the type of the magnets that I would use. First of all, I decided to use disc magnets because they would offer me a larger surface area and therefore, a more stable assembly. The grade of the magnets was also an important decision that I had to take. Too powerful magnets would greatly speed up the assembly procedure and potentially cancel out the benefits of the smooth parallel assembly procedure that the M-Clay provided. Furthermore, if the range of the magnets was too large unwanted interactions would be created. On the other hand too weak magnets would mean that the blocks would be unable to surpass the friction or the M-Clay and would not be able to assemble.

I used two types of disk magnets in the blocks. In the first designs I used “large” disc magnets of: diameter 1.2cm, grade: N48 that would start to attract each other at approximately the distance of 3.5 cm. Therefore, after I designed and tested a few blocks I decided to scale the block down to half the original size for my experiments. This decision had to do mostly with practical issues that I encountered during the tests. These issues involved the following: First, the magnets were too strong, which made it really hard for me to work with during the creation of the blocks, but also during testing- the smaller scale was an easier scale to work with. Furthermore, I could create higher resolution- smaller scale M-Objects.

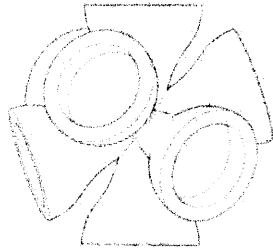
Due to all the above reasons I choose to reduce the size of the block and indeed all these problems were solved. In the smaller blocks I used disk magnets half the size of the original (0.6 cm). I also chose a lower grade for the magnets (N42). These magnets interference distance was approximately 2cm. The scale of the blocks was restored (to large) in the final block, due to the need for a higher resolution of its surface that was crucial for its error correcting capacities.

Finally, concerning the material and technique of 3d printing the physical blocks, all blocks that were intended for testing were made out of PLA in the Makerbot3D printer. This decision was based on the printer’s high speeds. This facilitated the easy and fast production of M-Blocks and allowed me to conduct a plethora of physical tests. Clear and black PLA were used for different blocks. Initially clear PLA was used; however it was switched to black in order to make it easier to access the result through the transparent clay. The final block was 3d printed in a FormLabs 3d printer in order to achieve a better resolution.

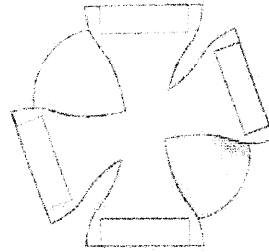
In the following pages I will present the different generations of the M-Blocks and their members. Each generation and member is a link in the evolutionary process that led to the final M-Block design. Therefore, I will analyze the difficulties that my system faced, and how I was able to tackle them through design decisions that I implemented in each of these links. Through this review I hope to offer an in-depth understanding of how the characteristics of my final M-Block emerged, and what is their role in the assembly procedure. Please note that in this thesis there was a large production of a variety of blocks. However, I will refer more extensively to the designs that were the milestones of the blocks’ evolution.

GENERATION A

ADDRESSING GENERAL ISSUES (GEOMETRY, MAGNETS)



Sample Block View

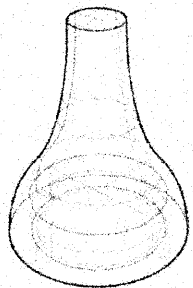


Sample Block Section

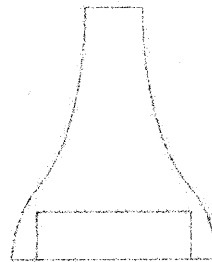
The first generation of blocks aimed in solving the general issues of the blocks' behavior in the M-Cell assembly procedure. These issues had to be addressed for all of my future blocks. Hence, there were some general criteria that emerged from this exploration for all future designs. The main issues that I addressed in this first exploration were: How do different reference solids (convex polyhedra) function in the assembly procedure and which serves my purpose the best, what is the equilibrium point in magnet number, grade and angle between them, what reference solid offers an even distribution of polarities and how does this distribution affects my assembly, how does friction interfere with the assembly procedure and how can I reach an equilibrium of surface area distribution of my block so they can benefit from the M-Clay friction.

I designed the geometrical typology of the first generation of blocks in the following way. The blocks' geometry was based on reference solids. However, the reference solids could not be directly used as blocks. That is because my candidate reference solids would obstruct the flow of the M-Clay, since they either leave very small gaps between them when they assemble, or none at all (space filling polyhedral). Therefore, I created new "star-shaped" geometries that would use these solids as a reference in the way they pack in space. However, they would also facilitate the flow of the M-Clay.

These new geometries have "legs" connecting the center of mass of the referenced solid to the center of each face of the reference solid. The magnets would be embedded at the ends of each of these "legs". The curved shape of the leg was designed to limit the magnetic field interference at the back and sides of the magnet



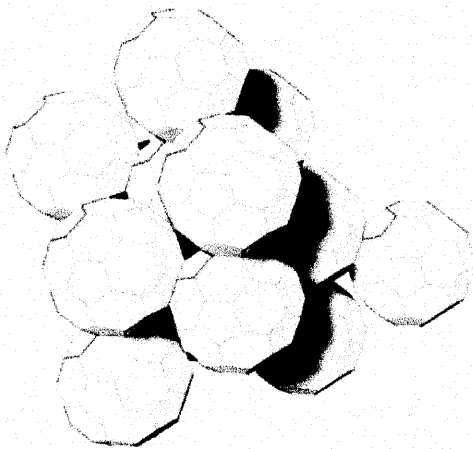
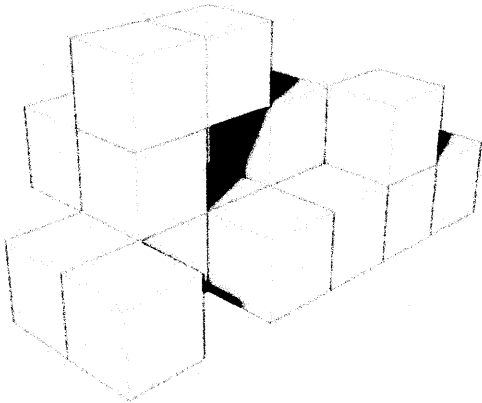
"Leg" geometry view



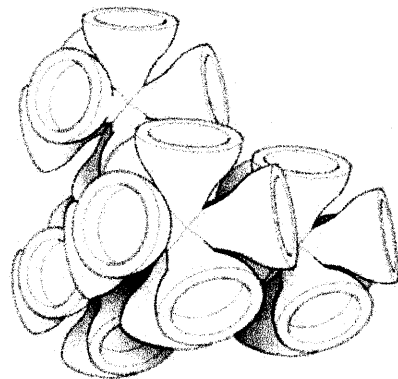
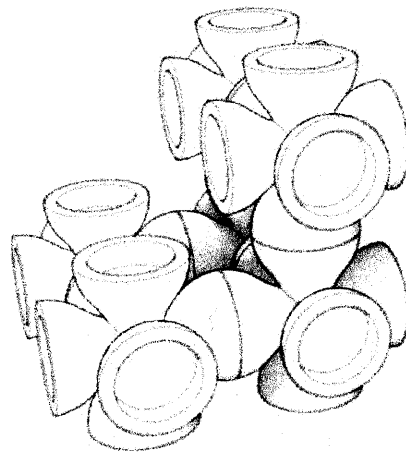
"Leg" geometry section

The choice of the reference solid for the assembly was a crucial design decision I had to take. My first choice was the cube, which was the simplest geometry that addressed the general issues described above. However, I quickly changed the reference solid to the icosahedron due to a range of problems that had arisen from the cube. One of these problems was that the angles between the magnets were too wide and therefore a lot of local energy minima could emerge. However the most important reason was the distribution of magnets.

CUBIC LATTICE VS
ICOSAHEDRON LATTICE



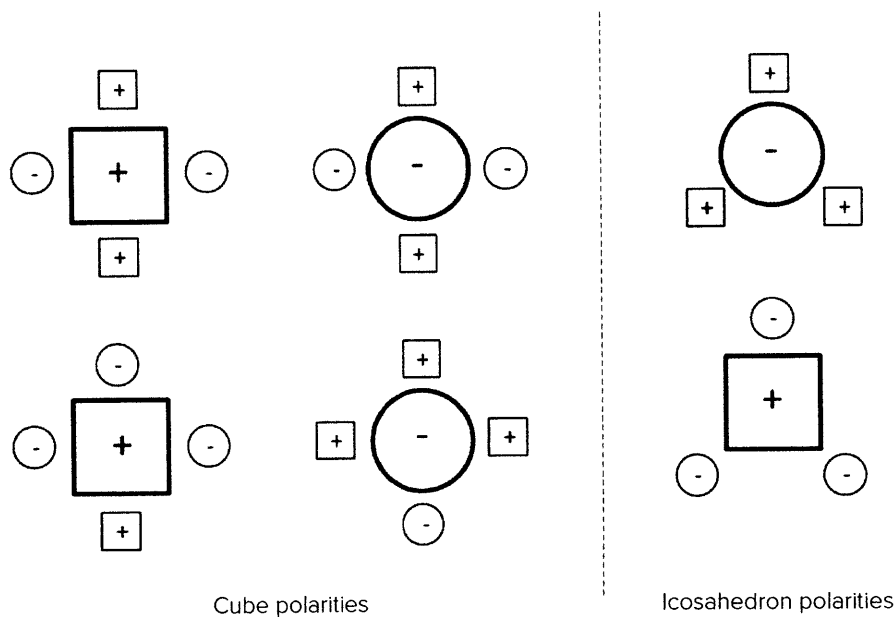
TRANSLATING REFERENCE
SOLIDS TO BLOCKS



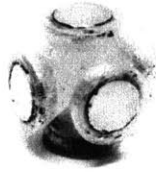
A decision that I took early in the design process was that the magnets would not be able to switch their polarities. I investigated scenarios in which I could use spherical magnets that could rotate locally, and therefore flip their polarities. This would facilitate the assembly procedure, since symmetries would not be broken by the use of different polarities. However, it would also create a range of different problems. Such would be, having to block the interactions of the magnets of the same block with each other which might prevent the flipping of the magnets (spherical magnets are axially magnetized as well and therefore have two poles like all other magnets). Furthermore, the flipping could be partial (e.g. 90 degrees instead of 180) and that could create unwanted assembly settings.

Because of this decision, I had to choose a reference solid that could provide an even distribution of polarities. Otherwise the symmetries of the blocks would be dramatically reduced which would render the self-assembly procedure impossible- it would result into assembly scenarios that surpass the capabilities of error correction of the system. Hence, one of the main reasons the cube was quickly discarded was due to the incapability of this reference solid for an even distribution of the polarities. The most even possible distribution in the cubic arrangement involved sides that were surrounded by two and other sides that were surrounded by one identical polarity. This created many problems in the assembly and therefore, I chose to change the reference solid to the icosahedron.

With the use of the icosahedron I was able to address both the angle problem and the polarity distribution problem. The angles between the magnets on the icosahedron were smaller and made the assembly more successful. The polarity distribution that could be achieved with the icosahedron was ideal since every pole was surrounded by three opposite ones.

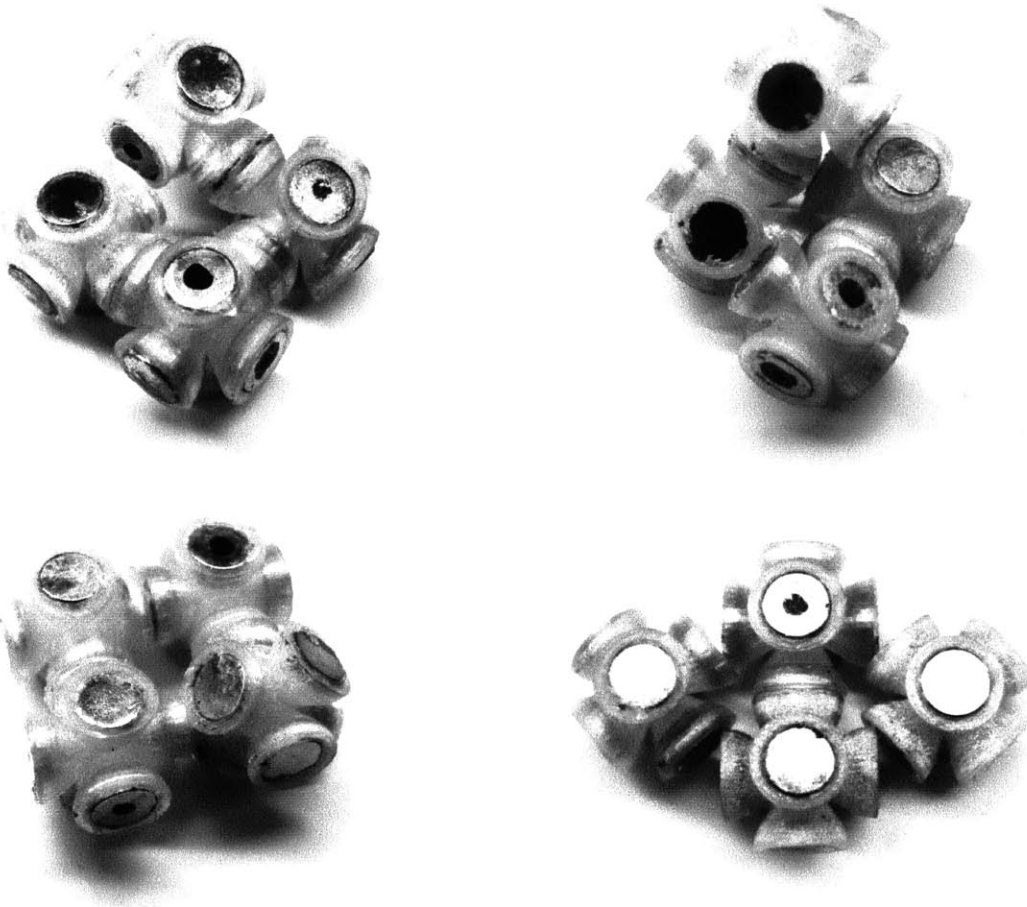


In the next pages I will present and analyze the geometry and behavior in the assembly procedure of the blocks of the first generation.

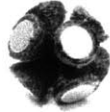


A/CUBE(LARGE)

A/CUBE(L) was the first M-Block, and was based on a cubic reference solid. With this block I was able to establish the general principle of the M-Cell assembly procedure, the fact that the M-Blocks can indeed move through the M-Clay and assemble. While this was an important first step there were a range of flaws in the assembly procedure. These flaws had mainly to do with problematic relative positioning and local energy minima errors. These occurred due to the wide angle between the magnets and mainly, the non-symmetrical polarity distribution. Generally, the findings concerning the M-Cell assembly procedure from this first block were really encouraging. The M-Clay indeed facilitated the assembly procedure, allowing a smooth transition of the M-Blocks. However, these findings were also indicative of the need for a new reference solid.

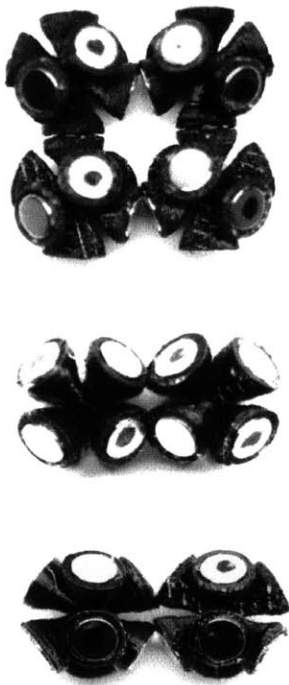


Samples of local energy minima

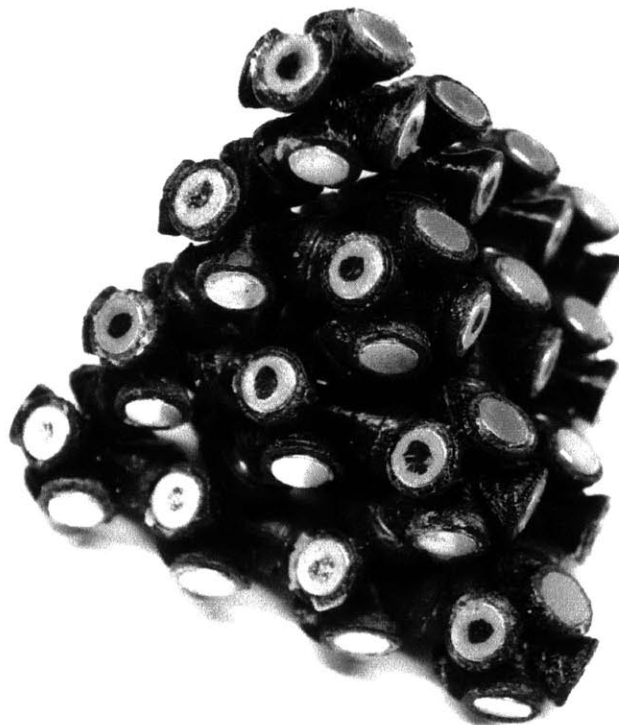


A / ICOSA_1

In the A / ICOSA_1, there was a transition from the cube to the icosahedron, as a reference solid. This transition occurred due to the smaller angles between the magnets and the more even polarity distribution that I could achieve with this geometry. This transition was very successful since the new reference solid was able to deal with these problems. As a result the experiments revealed a dramatic decrease in assembly errors and local energy minima. Therefore, I decided that the icosahedron could be established as the reference solid for all my future blocks. In spite of the general success of this block, there were still errors in the assembly that pertained. These errors had mostly to do with local minima states that would occur while the blocks were assembling. This was due to the lack of geometrical constraints on the surface of the blocks. These local minima however, produced interesting results since there were 3d areas created of aligned cells, like crystals. Moreover, another issue that I had to address was the fact that occasionally, gaps would be created between the cells. This was due to the high friction between the M-Blocks and the M-Clay, in combination with the weaker, smaller magnets. In general the results of this design were quite satisfactory and proved an important step in the evolution of the M-Block.



Samples of local energy minima



Sample of spatial lattice

A/ICOSA VARIATIONS

The following blocks are variations of the of the A/ICOSA block that I experimented with, however they were discarded for various reasons.



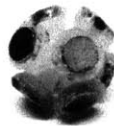
A/ ICOSA_1(LARGE)

This is the large version(x2 scaled) of the A / ICOSA. I conducted some experiments with this block, but soon I found that it was more practical experimenting with smaller-sized blocks. Therefore, I created a smaller version of this block which was the A/ICOSA



A/ ICOSA_1B(LARGE)

This was a modified version of the A/ ICOSA 1 L. In this version the magnets that share the same polarities, either protrude or are depressed. This was a way of testing the effects of less symmetrical blocks. The hypothesis was that the target positions might be more discrete and the magnets could “find” them easier. However, there were unwanted interactions with the back of the protruding magnets, and therefore, it was discarded. Less symmetry created more problems than it solved. Therefore, I decided to exclude these designs for my future blocks.

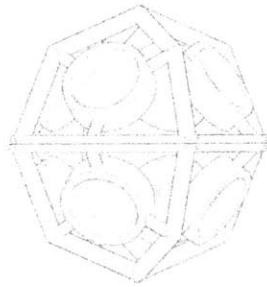


A / ICOSA _1[TRASPARENT]

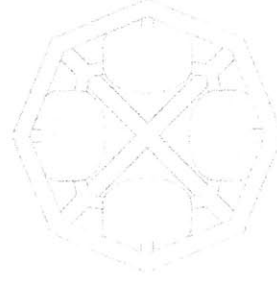
This model is a previous transparent version of the A/ICOSA_1. The color switch from this block to the black version allowed a better and easier assessment of the assembly when it was finished, through the transparent clay.

GENERATION B

ADDRESSING LOCAL ENERGY MINIMA AND FRICTION

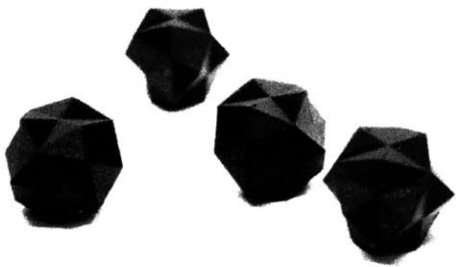


Sample Block



Sample Block Section

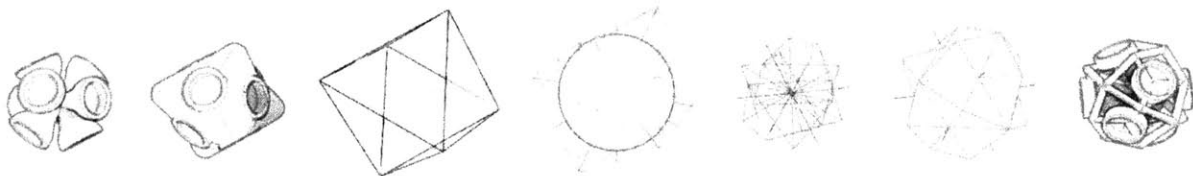
Through the first generation of M-Blocks I was able to address and solve the main issues of the M-Cell assembly procedure. However, there were still secondary problems pertaining. The most important ones were the creation of some local energy minima and the high friction of the M-Block. Therefore, this new generation of M-Blocks focused on the refinement of the geometry to address these problems. I investigated thoroughly the reasons that the local energy minima emerged. Through this investigation I was able to create a new reference solid that was based on the icosahedron.



New reference solid



The geometry of this new solid, included edges that would not allow the creation of local energy minima, and would facilitate the error correction process of the M-Blocks. Furthermore, I implemented a new wireframe design in order to reduce the friction of the block.

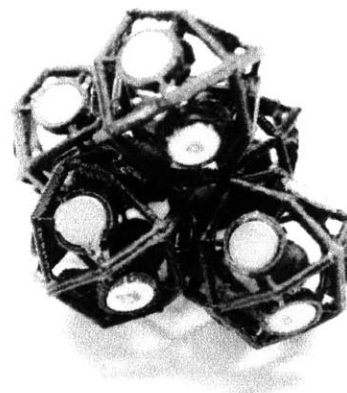
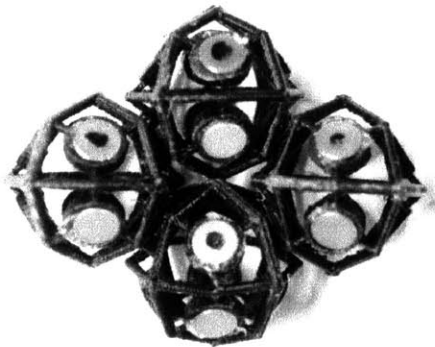
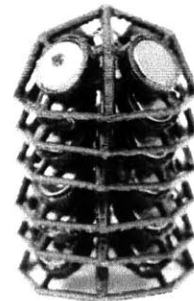
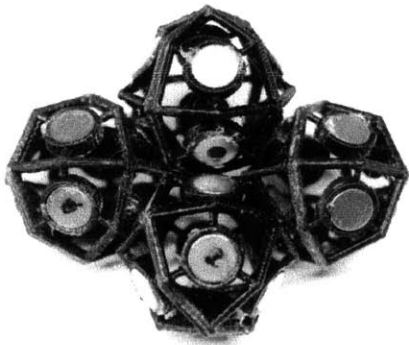


New reference solid production procedure



B/ICOSA_1

The B / ICOSA_1 was my first attempt to solve the problems of the previous generation. The incorporation of new edges in the geometry showed promising results in preventing local energy minima that occurred in previous designs. Even though some of them still pertained they had become more unstable. This means that they were less likely to occur and more likely to be corrected by the other blocks assembling. Furthermore, the wireframe indeed reduced the friction of the block with the M-Clay. However, the block still needed a great deal of refinement in order to fully exploit the capabilities of this new geometry. Therefore, I had to seek the optimal: angles between the members of the wireframe, the optimal relationship of the scale of the wireframe to the magnets, and the optimal amount of protrusion of the magnets. Furthermore, another problematic state of this design was that occasionally the corners of the wireframe overlapped during the assembly procedure. This prevented the blocks from aligning themselves optimally with their neighbours.



Samples of local energy minima, block packing and spatial lattice

B/ICOSA_2

In these variations I examined whether the change of ratio between the wireframe and the magnets and/or the protrusion of the magnets could diminish the overlapping-corners problem, and destabilize even more the local energy minima states. Unfortunately, none of the following designs were successful.



B/ICOSA_2A

In the B/ICOSA 1B I scaled down the frame to avoid the angle overlap. Whereas, I managed to solve the overlapping problem, I still could not prevent some of the energy minima of the A / ICOSA. Moreover, the design became very fragile.



B/ICOSA_1C

Another approach to the problem was the combination of scaling down the wireframe and making the magnets protrude more. This design was less successful than the previous ones, because the geometrical restrictions (edges) that were introduced in Generation B did not work. The block had too much freedom, and therefore, there were a range of new local energy minima that emerged. Furthermore, the large protrusion of the magnets created unwanted interactions with their sides, which also led to more local energy minima errors.

B/ICOSA_3 – 4.

Since the previous B/ICOSA_2 series was not particularly successful (in fact the blocks performed more poorly than the B/ICOSA_1), I decided to change my strategy. I implemented more radical changes that did not affect just the ratio of the block to the magnets, but also the angles of the wireframe itself.



B/ICOSA_3

The B/ICOSA_3 block is based on the B/ICOSA_1. In this design I created a more round-shaped block. This shape emerged from smoothing some of the corners of the wireframe. The first goal of this block was to solve the overlapping problem of the B/ICOSA_1. This was easily achieved with this new design. The second goal was to test whether a more round wireframe would make the blocks slide on each other, without getting obstructed by their corners. In theory this could reduce my local energy minima states. However, this was not successful either. The round shape provided to the blocks a higher degree of freedom that led to the creation of more local energy minima.



B/ICOSA_4

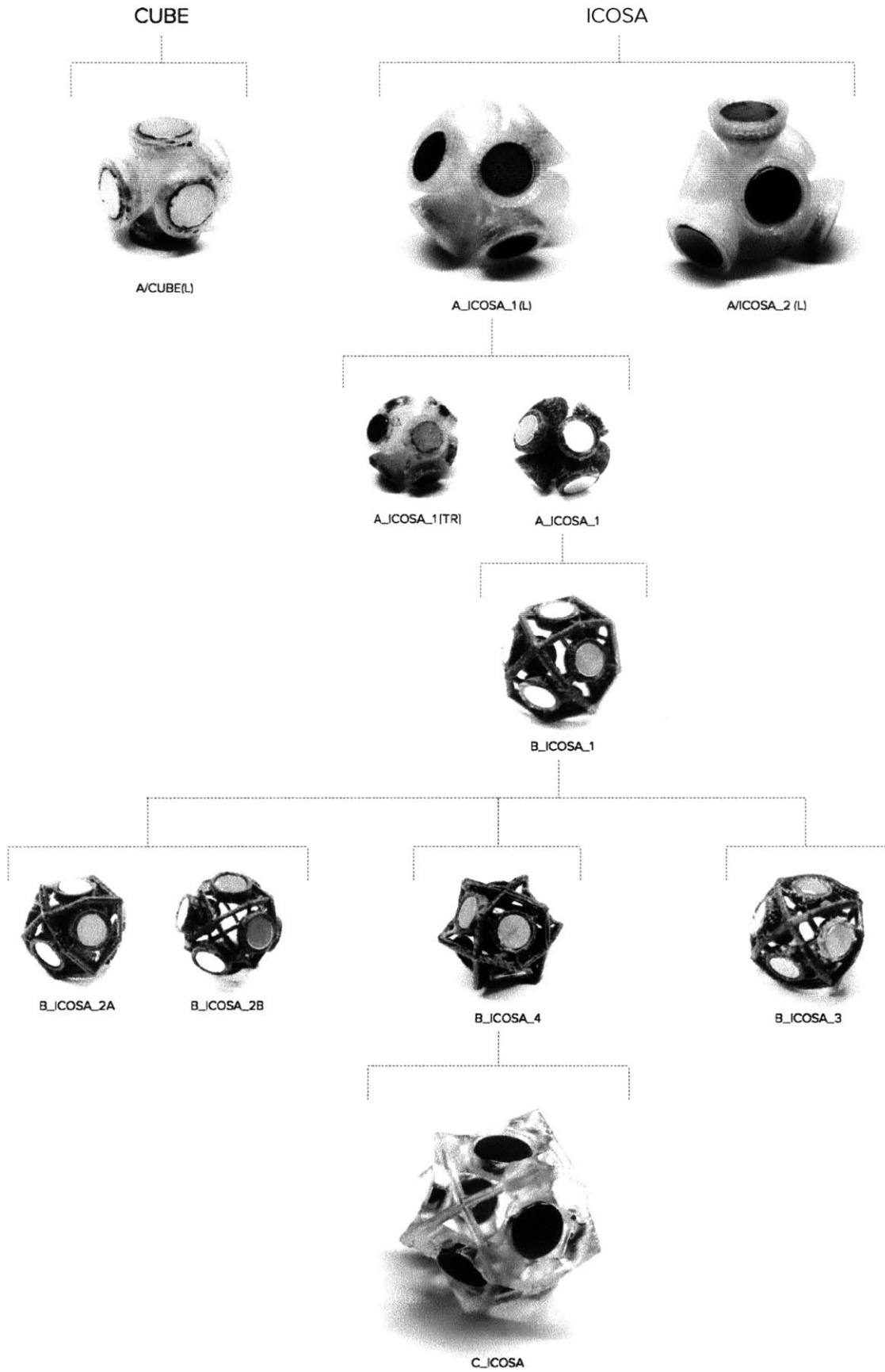
The B/ICOSA_4 was the final design of the Generation B. This block was the result of a radical redesign of the B/ICOSA_1 edges. This redesign was based on a very meticulous study of the forces that apply on the blocks when they assemble and of the possible paths that they can follow. The knowledge that I had acquired from the other B/ICOSA designs was also crucial to understand the impact of the block's geometry on these paths. Therefore, I was able to carve these paths by creating constraints, and as a result, limiting the blocks' freedom of movement. This effort resulted in a very successful block. The performance of the new blocks was very satisfactory. The blocks were able to assemble correctly in most of the cases. Furthermore, as the number of the blocks in an assembly increased, the error capacities of the system also increased. Local energy minima were also very limited.



Samples of local energy minima and spatial lattice

The B/ICOSA_4 concludes the review of the M-Block evolutionary steps. This also signifies the end of this chapter. In this chapter I illustrated my initial vision for the M-Cell assembly procedure and how that evolved over time. In the next chapter I will present the current-final state of the M-Cell assembly. These two chapters should be considered as a natural continuum, since the decisions that shaped the final components and procedure can only be understood through the evolutionary process that was followed.

M-BLOCKS FAMILY TREE



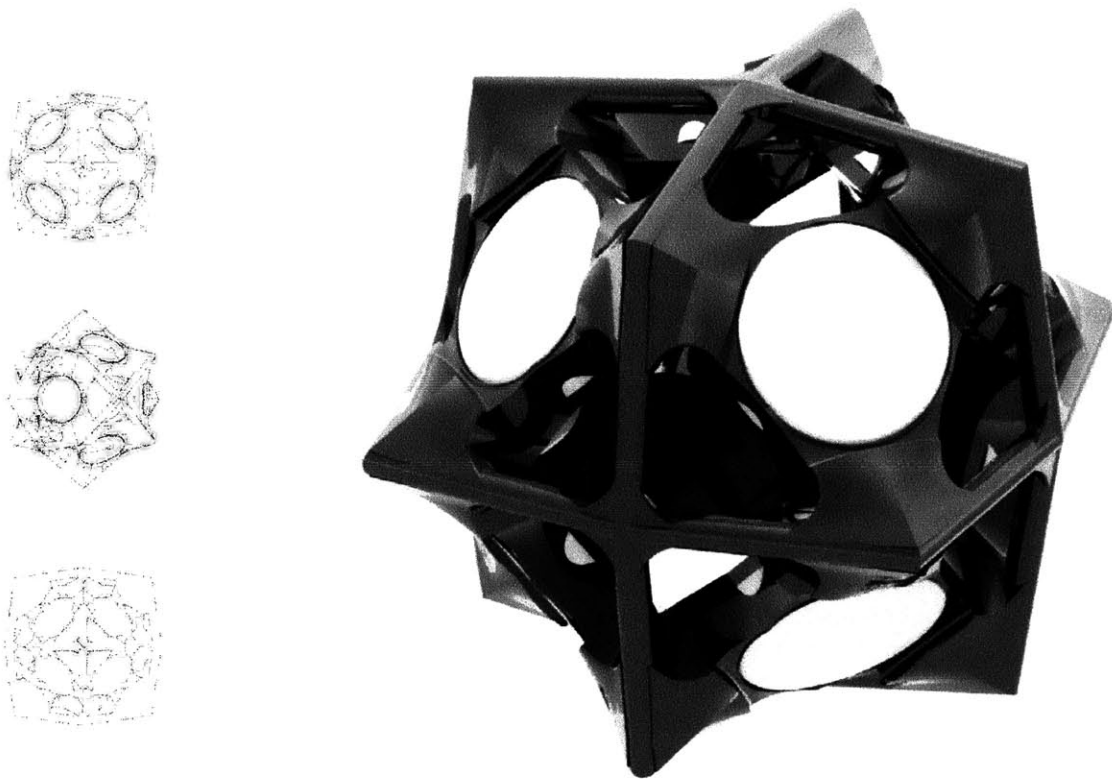
3 | PRESENT

In this chapter I will present the optimized, final version of the M-Cell procedure and the M-Block. Then, I will describe the different assembly types and how different kinds of control over the assembly procedure can benefit the system. Finally, I will focus on the advantages of the procedure and its possible implementations.



3A | NEW M-BLOCK

The newest, final M-Block is the C/ICOSA. The C/ ICOSA is an extremely refined version of the B/ICOSA_4. The geometry of the B/ICOSA_4 produced very satisfactory results. Local energy minima were reduced to only one (when two blocks came together). This one remaining local energy minimum was not possible to completely eradicate. However, it was possible to destabilize it even further. Therefore, I attempted to make this energy minimum so unstable that it could be easily corrected by other cells. Moreover, I wanted to make the interaction of the cells even smoother and create geometries on the blocks' surface that would make the blocks "lock" with each other. This would increase the stability of the produced spatial lattice after the blocks assembled.



I was able to achieve this by following the same design logic as in the B/ICOSA_4. Hence, I managed to investigate in a greater depth the forces and the paths that the blocks follow. I performed a range of physical and digital simulations to collect this data. Then, I translated this data into surfaces that cover the parts that engage in interactions on the M-Blocks. The varying inclinations of these surfaces guide the blocks into the correct positions. Furthermore, through these surfaces, I managed to destabilize the local energy minimum. With a small amount of energy the block can escape the local minimum "energy pit" and be guided to the "designed energy minima pits" (the correct assembly positions). Finally, I restored the large scale of the block in this last design. This decision was taken, because the fine refinements of this design were more effective in a larger scale model, due to the better resolution it could provide. This design concluded my experimentations with the M-Blocks since my goals were met.

3B | M-BLOCKS AND M-CLAY

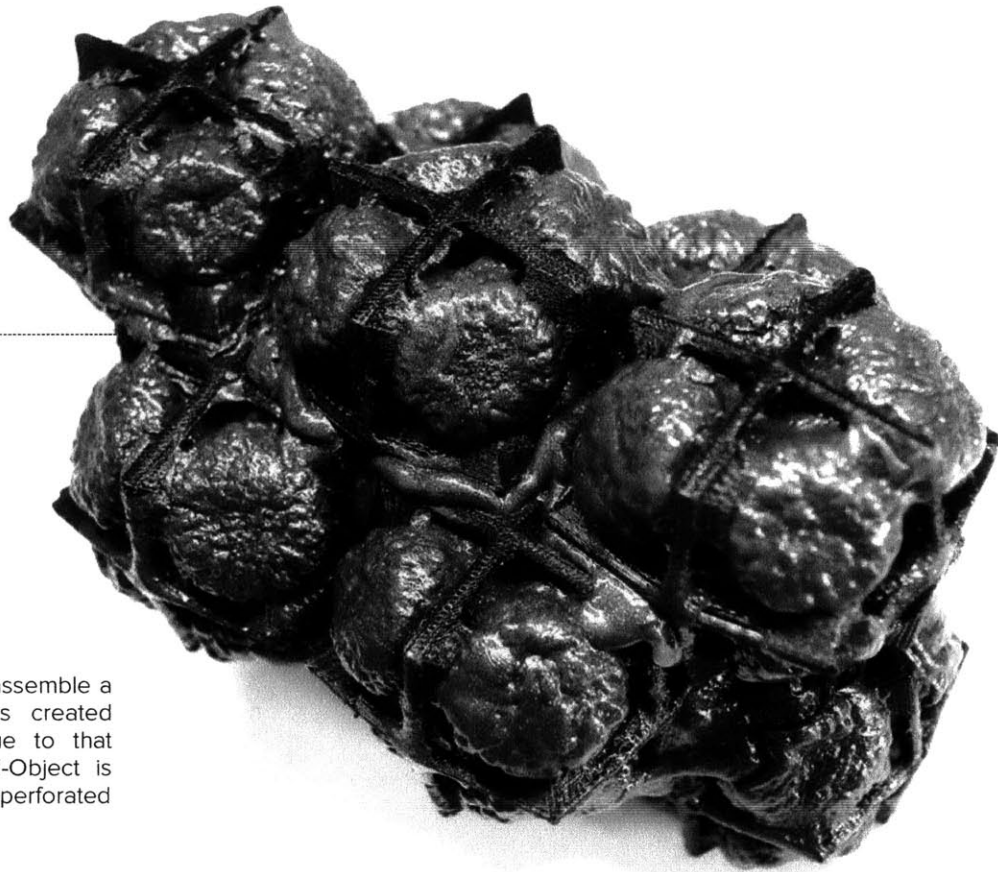
In my experimentations with the final block I reached an interesting finding. The C/ICOSA was successful enough to create a spatial lattice without the M-Clay. This scenario was not valid with the previous blocks, since they did not share the same error correction capacities. One of the experiments that I conducted with the new block was rolling-throwing a block towards another. The results were mostly positive, since there was a relatively high percent that the blocks would assemble correctly. Furthermore, in the case an error occurred, the impact force from the another block could destabilize it, and make the blocks error-correct. However, this procedure only had some value if it was implemented serially (one block at a time). That is because of various reasons: First, it is very hard (and impractical to attempt it,) to release all the blocks at the same time, without a medium like the M-Clay. Even if this is achieved the result would be chaotic due to the strong forces that would be applied. The serial error-correction capacities of this system would be lost since all the impact force would be applied at once and then the procedure would cease. Any errors that might occur in the spatial lattice won't be able to be corrected without the extra energy delivered from the impact of another block.

Therefore, even though this procedure works to some extent, it cannot reach the error-correction benefits of an assembly procedure that makes use of the M-Clay. That is due to the capacity of such procedure for a truly parallel assembly.

The role of the M-Clay remains the same in this last version of the M-Cell procedure. However, there has been a minor change that optimizes the procedure. This change has to do with the fact that the M-Block is partially and not fully submerged in the M-Clay. This is achieved by filling the interior of the M-Block with the M-Clay. Due to the magnetic forces of the embedded magnets the M-Clay will naturally flow out and cover the block. However, the edges of the block will remain free. This way I was able to reduce the unnecessary friction between the blocks and the M-Clay, while on the same time have the full error-correcting capabilities of the M-Cell assembly procedure. This refinement does not compromise my goal for a solid final object. On the contrary, when the blocks assemble the M-Clay from the inside and the surface of the block is redistributed and the seams between the blocks are sealed.



M-Clay embedding the M-Blocks



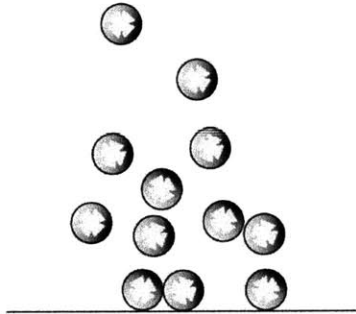
When two M-Cells assemble a seam of M-Clay is created between them. Due to that feature the final M-Object is solid and cannot be perforated

Sample M-Object (10 M-Cells)

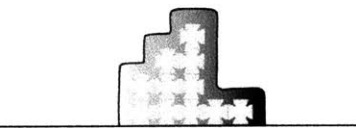
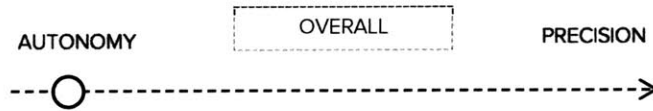
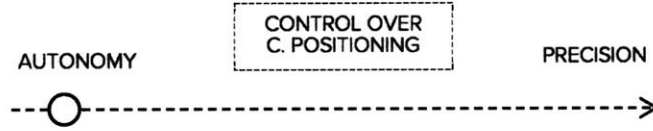
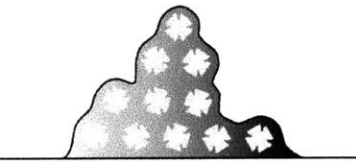
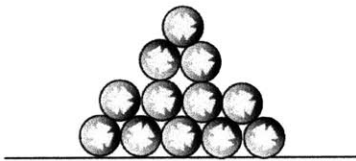
3C | ASSEMBLY TYPES

In this thesis I have experimented with multiple ways in which the M-Cells come together in order to assemble (assembly types). The assembly types are defined by two parameters of control over the system. These two parameters are: control over the M-Cell positioning, and control over the boundaries of the assembly. All the assembly types that I have investigated for my system emerge from various combinations of these two types of control. The level of control that will be applied affects the precision of the final product's shape. However, as the control over one of these two parameters rises the system becomes less autonomous. Therefore, according to the goals of the assembly procedure either autonomy or precision can be prioritized. Thus, an instance of a system that lies between this autonomy-precision spectrum emerges. In the following pages I will present the three "extreme" instances of my system. Possible real world implementations can use characteristics of these three assembly types to customize and optimize the assembly procedure.

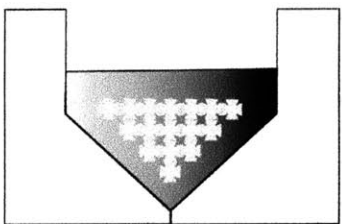
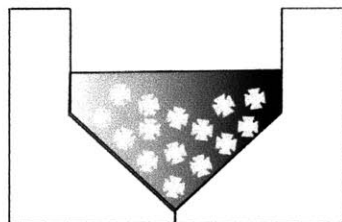
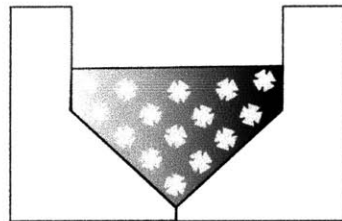
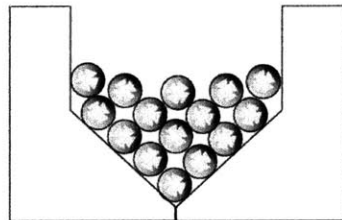
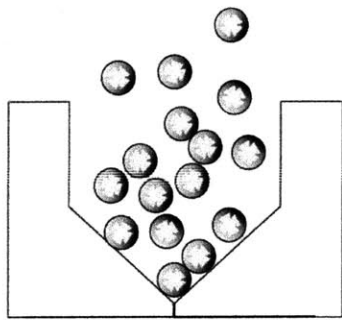
RANDOM PLACEMENT



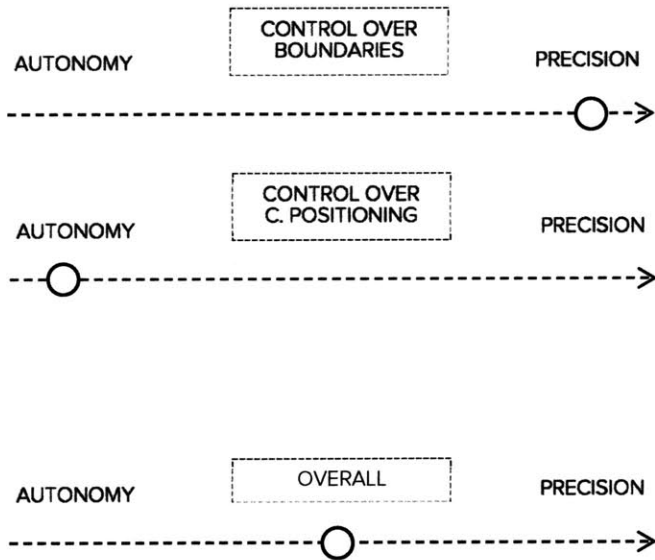
The random placement assembly procedure prioritizes autonomy over precision. There is minimum control over M-Cell placement (M-Cells are just thrown-accumulated in a pile) and minimum boundary control (the ground is the minimum possible boundary). This assembly type could be useful in situations that demand the fast deployment of large structures at areas that are not accessible. However, while the general volume of the final object can be determined there is little control over the exact shape of the final object. The following two diagrams show the level of control over the system and how this affects the dipole of autonomy and precision. The final diagram expresses the overall autonomy of the system after the combination of the two control parameters.



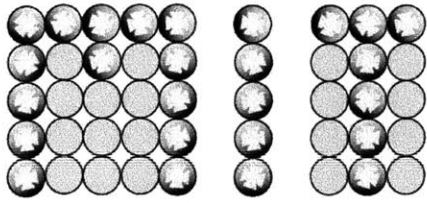
RANDOM PLACEMENT WITH TEMPLATE



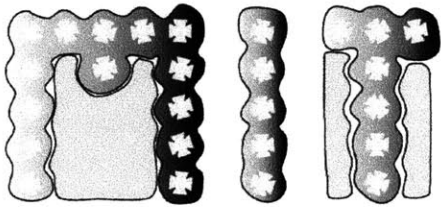
The random placement with template assembly type focuses on control over the system boundaries. In this system I am using a mold that creates a boundary around the assembly area. This boundary acts as a global constraint to the system. This way I am able to gain more control over the final shape of the structure. This type of assembly is a middle ground for general autonomy and precision. Since there is a need for a mold the system is not as autonomous as the previous one, however, it still preserves the benefits of a random placement of M-Cells. Therefore, in this system there is a high control over the boundaries, but a low control over the M-Cell positioning. This sums up at an overall medium autonomy and precision.



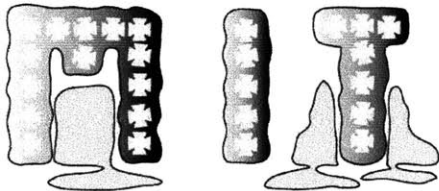
CONTROLLED PLACEMENT



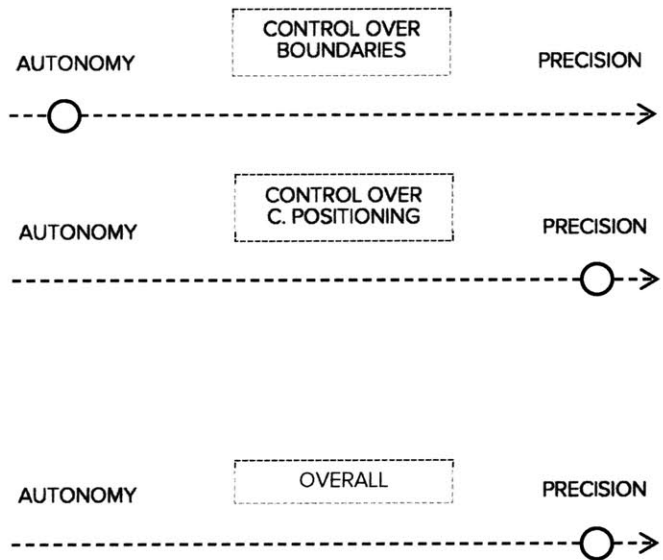
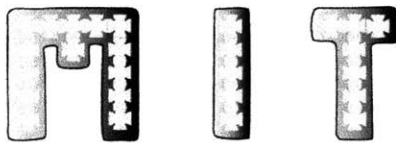
In this final assembly type I am controlling the M-Cell positioning. This control is local compared to the global control in the previous type, and therefore, it concerns a single cell each time. Thus, in the controlled placement assembly type each block is placed in the vicinity of its goal position. The block still translates and rotates locally to correct its positioning and assemble with its neighbours.



Regular, non-magnetic clay can be used as supports for the assembly procedure (empty cells in the diagram). These supports will “melt” away after the assembly procedure is over.



With this type of assembly the shape of the final structure can be predicted with high precision. However, the autonomy of the system is limited. Such assembly type can be used in an automated procedure where each cell would be picked and placed in the vicinity of the correct position. The benefits of this procedure are that while it requires a pick-and-place mechanism this mechanism can be very simple and not very accurate. That is because each cell has the capacity of error-correcting its position. In order to assemble analogous blocks that don't follow the M-Cell assembly procedure, very complicated and precise automated machines would be required.



3D | ADVANTAGES – IMPLEMENTATIONS

In this thesis I have described a complete fabrication system that begins with the assembly components and ends with the final product. Its advantages are mainly focused into two phases of this system, the procedure itself and the produced object.

There are many advantages that make the M-Cell assembly procedure unique. The most important are the following; first, its high autonomy. Other similar self-assembly systems need a specific environment and an external supply of energy to enable the procedure. However, in my system everything needed for the assembly is packed in a single M-Cell (Environment- M-Clay, Energy-dynamic energy of the magnets).

Furthermore, another unique feature is the error correction mechanism of my system. Many similar macroscopic self-assembly procedures that use magnets get the energy that the system needs to assemble, externally (e.g. from shaking or heating). (Stambaugh et al.,2003)(Tibbits, Olson, 2012). Furthermore, these procedures are not truly parallel. Due to the large forces of the magnets that grow exponentially when the distance is minimized, the units assemble according to their closest neighbor. Furthermore, the error correction is applied through assembling and disassembling components. On the other hand, my procedure due to the properties of the M-Clay is truly parallel. Moreover, my error correction technique works in a different way; it does not use trial and error like other procedures. Instead it creates a global energy minimization system through parallel assembly. Hence, each unit is better “informed” about the positioning of its neighbours and adjusts its position according to them. While the other systems demand a constant flow of energy to the assembly environment, in my system all the necessary energy is embedded in the M-Cells.

The other instance of the system that makes an important contribution is the outcome of the M-Cell assembly procedure, the M-Object. An M-Object is literary a liquid morphed into a shape that is forced by the M-Blocks’ spatial lattice. This gives to the M-Objects a range of significant advantages.

First of all when the M-Object is created the M-Clay seals all the seams between the M-Blocks. This results in a solid object that cannot be penetrated by natural elements such as air and water. Secondly, the M-Clay itself has self-healing capacities due to its liquid nature. Since the M-Clay forms the M-Object’s skin, that skin can heal from damage such as cracks or scratches.

Moreover, M-Objects remain dynamic. This means that they can be expanded or repaired with the addition of other M-Cells or M-Objects. Furthermore, they can be altered; parts can be removed or completely dismantled. Also, M-Objects’ components can be reusable. They can be dismantled and M-Blocks can be reused with the same, or other kinds of M-Clay, and in other kinds of assemblies.

Finally, there can be custom production of M-Clay which can have a vast range of different properties. These properties are adopted by the M-Object. Hence, the dynamic nature of the M-Object can be even more enhanced—the M-Object could react to external and environmental conditions such as temperature, humidity, radiation, sound waves, light.

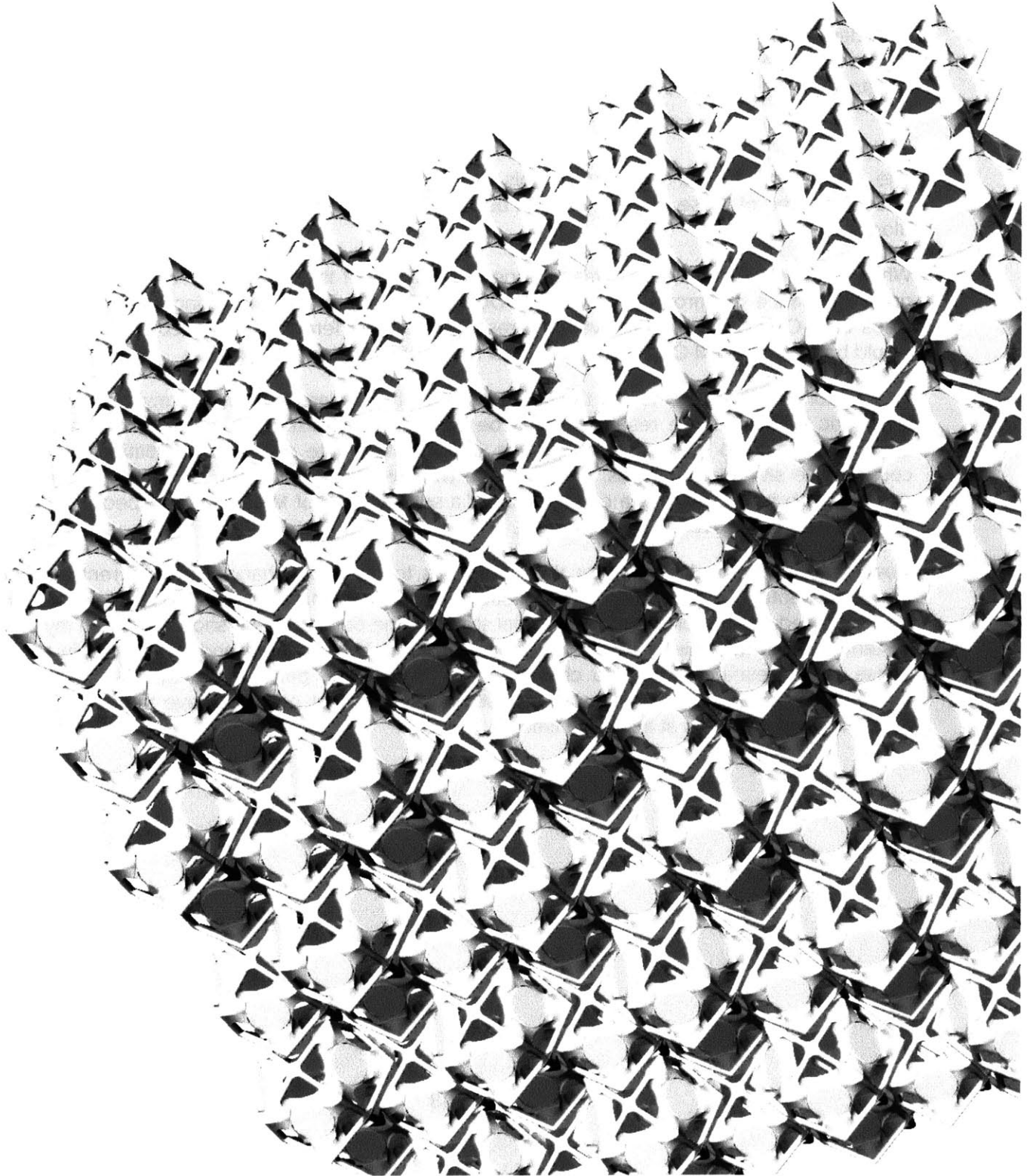
Due to these and other advantages, my system can have beneficial implementations into many fields; first of all, in the field of construction and especially in the construction of emergency structures in extreme conditions or remote areas. Compared to existing techniques my system can offer greater autonomy, easier deployment and emerging structures that can't be perforated by the natural elements (such as wind, water and the sun). Most of the emergency structures that are currently available cannot offer these levels of autonomy and also have more complex deployment methods that often involve multiple procedures. Furthermore, the dynamic nature of the final product can be excellent for such structures. Not only can these structures be easily modified, but they can also be designed to adapt and respond to the environment of deployment.

Another field that could be benefited from my system is the field of fabrication and rapid prototyping. Currently, the advance fabrication techniques available involve complex machines and programming. With my system these could be simplified since objects can be created either without any machines or with the use of very simple ones. That is possible because the positioning of the building blocks does not have to be accurate, since the system has the capacity of error correction.

Furthermore, current fabrication techniques produce objects that are "finished". In the case of my system the assembly procedure is never "finished", thus, the objects remain in a dynamic state. This means that they are highly modifiable. Moreover, it means that they can be easily disassembled and with the same building blocks a new object can be created. In addition, my system provides the possibility to include the parameter of time in the objects. That refers to how these objects respond and change according to their environment over time. This could be considered as another layer that can be fabricated and included in the design procedure. That capability stems from the dynamic nature of the M-Clay.

4 FUTURE

In this chapter I will summarize the work of this thesis. Furthermore, I will provide examples of possible future directions in which my project could evolve.



4A | SUMMARY – FUTURE WORK

In this thesis I have presented the M-Cell assembly procedure. First, I referred to the field that frames my work and to the inspiration of the procedure. Then, I described the procedure and presented my assembly unit, the M-Cell. Furthermore, I talked about its components the M-Clay and M-Block. I analyzed the methodology of the M-Block's evolution and presented its different stages. Moreover, I focused on the problems of each stage and described the solutions that I have implemented. In the next chapter, I presented the optimized version of the M-Cell procedure and the M-Block. Then, I described the different assembly types and how control over the assembly's boundaries and the cell positioning affects the final object's precision and autonomy. Finally, I focused on the advantages of my system and the possible benefits from its implementation in construction for extreme conditions and in rapid prototyping.

The system that I have proposed in this thesis has a great potential for evolution in multiple directions. One of these directions could be experimenting with different kinds of M-Clay and M-Blocks.

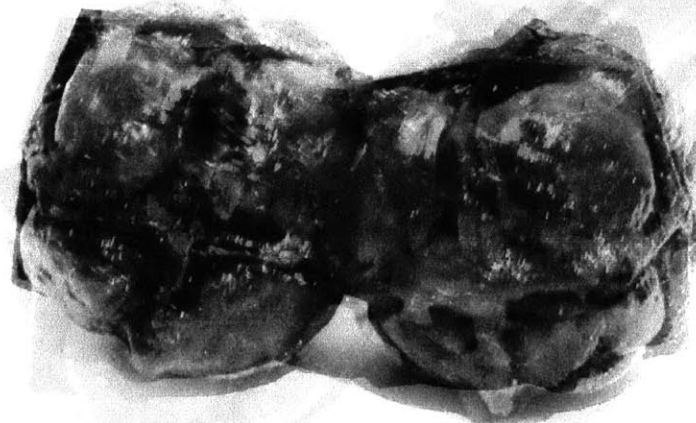
While creating my own M-Clay was not one of the goals of this thesis, this research direction can greatly enhance the properties of the M-Objects. Therefore, experimenting in creating different kinds of M-Clay could produce very interesting results. Different materials could be studied that would bestow to the M-Objects a whole new range of intriguing properties.

Furthermore, new geometries for the M-Blocks could be researched. While in my thesis I proposed a generic M-Block, more research could be done in customizing the existing, or creating new blocks according to more specific settings. This would create even more optimized results that could tackle site-related issues. Finally, these two directions could be combined, and research could be conducted on how a combination of a specific type of M-Clay with a specific type of M-Block can enhance even more the results.

However, my personal focus after this thesis has to do with enhancing the current system. In previous chapters I have presented a limitation of my system that concerns the dipole of autonomy (of the procedure) and precision (of the final shape of the object). I have shown that with my current system in order to achieve autonomy precision has to be sacrificed and vice versa. In the next phase of my research I wish to challenge this "uncertainty principle" of the M-Cell assembly. Therefore, I have designed and started testing a system that could achieve maximum levels of autonomy and precision at the same time.

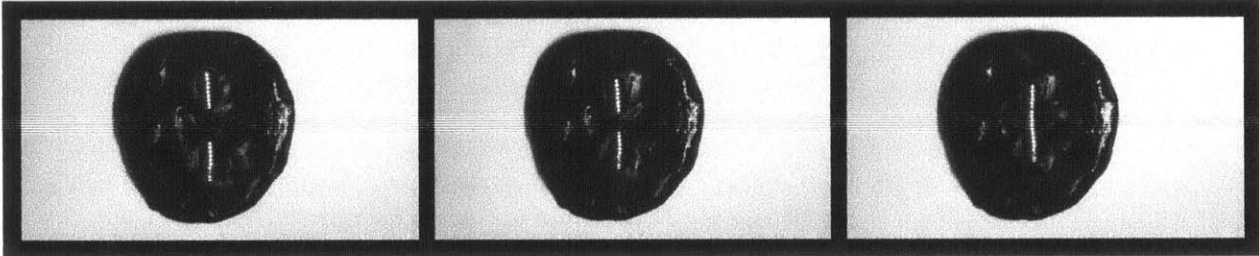
APPENDIX | EXPERIMENTS

In this section I will present the most important experiments of this thesis. These along with many other experiments, findings and observations that are not listed in this section were used throughout this thesis to optimize parts and procedures. Some of the experiments included in this section have been repeated more than once, with different configurations. Therefore, the results listed in each experiment might refer to findings from multiple repetitions. Moreover, similar experiments are not listed. Finally, the experiments follow a chronological order.



1. PROOF OF CONCEPT

1A. MAGNETS ASSEMBLE AXIALLY THROUGH THE CLAY



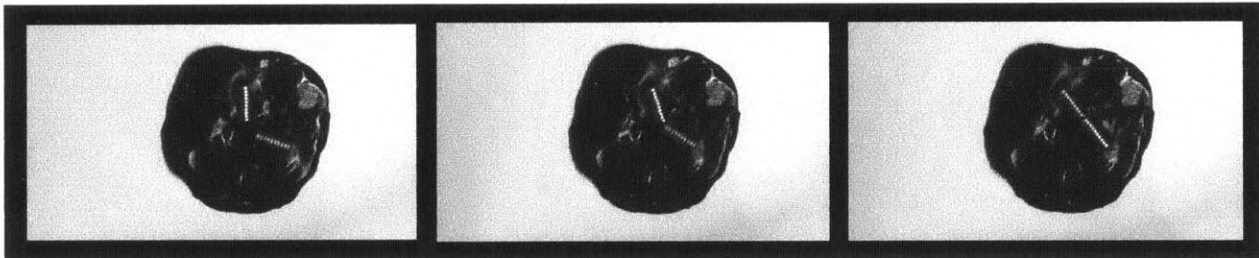
Goal: Magnets can move through M-Clay and assemble smoothly

Method: Two rows of magnets are placed axially in magnetic Clay

Parts: M-Clay, 2 linear rows of disk magnets N42 $d=0,6\text{cm}$

Results: Hypothesis is confirmed

1B. MAGNETS ASSEMBLE BY ROTATION THROUGH THE CLAY



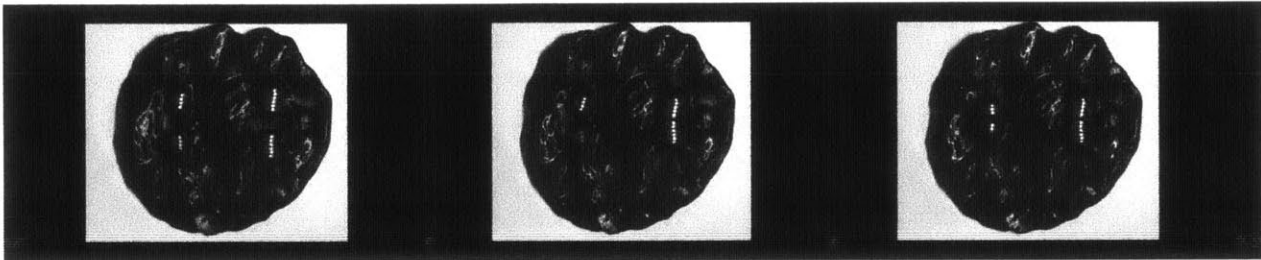
Goal: Magnets can move through the M-Clay, correct their relative positioning through rotation, and assemble smoothly

Method: Two rows of magnets are placed in an angle in magnetic Clay

Parts: M-Clay, 2 linear rows of disk magnets N42 $d=0,6\text{cm}$

Results: Hypothesis is confirmed

1C. ASSEMBLY SPEED ACCORDING TO MAGNETIC FIELD



Goal: Magnets with different magnetic fields assemble at different speeds

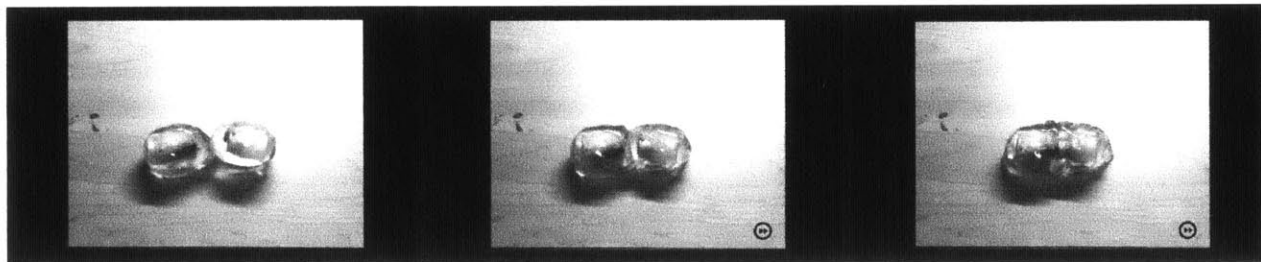
Method: Two sets of magnets are placed axially in magnetic clay. The first one has fewer magnets (less powerful magnetic field).

Parts: M-Clay, 4 linear rows of disk magnets N42 $d=0,6\text{cm}$

Results: Hypothesis is confirmed

2. M-BLOCKS ASSEMBLY

2A. WITH REGULAR CLAY



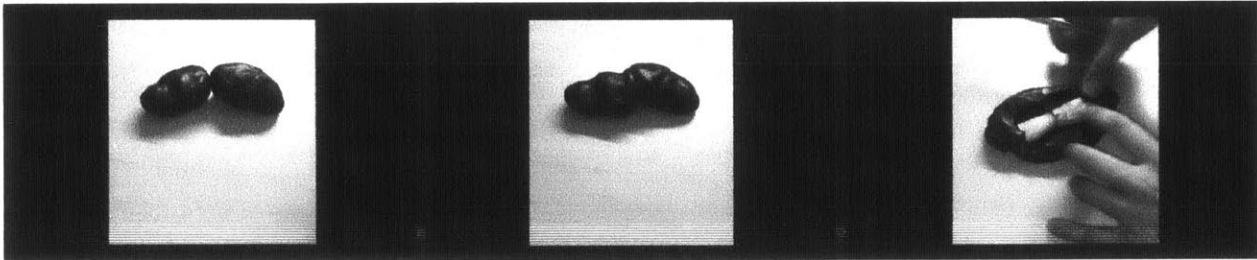
Goal: PLA Blocks with embedded magnets can assemble through the Clay. Magnets can surpass the friction of the clay and assemble smoothly

Method: Two sets of drop-like blocks are created with a disk magnet embedded at their edge. The two blocks are placed mirrored to each other axially. Transparent clay is used to access the position of the magnets at every instance.

Parts: transparent clay, 2 PLA drop shaped blocks with disk magnet N48 $d=1,2\text{cm}$ embedded at their edges.

Results: Hypothesis confirmed

2B. WITH M-CLAY



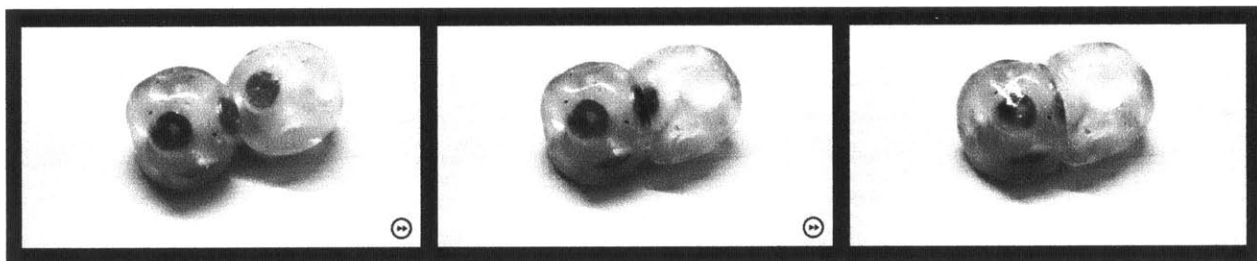
Goal: PLA Blocks with embedded magnets can assemble through the M- Clay. Magnets can surpass the friction of the M-clay and assemble smoothly

Method: Two sets of drop-like blocks are created with a disk magnet embedded at their edge. The two blocks are placed mirrored to each other axially. The M-Object is cut open with a knife to access the result

Parts: M-Clay, 2 PLA drop shaped blocks with disk magnet N48 d=1,2cm embedded at their edges.

Results: Hypothesis confirmed

3. A/CUBE L (x2) ASSEMBLY TEST



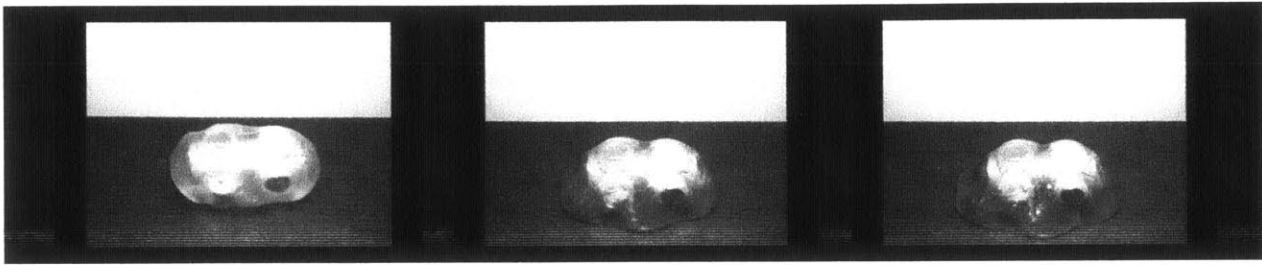
Goal: Test M-Cell assembly with two A/CUBE L. Access positioning error-correction (translation-rotation).

Method: Two A/CUBE_L blocks are placed next to each other. Magnets of same polarities are facing each other.

Parts: transparent clay, 2 PLA A/CUBE_L blocks

Results: The blocks rotate and translate until they assemble with magnets of the same polarities. This experiment demonstrates the large capacity of error correction of the blocks' positioning. The initial position of the blocks needed a complete 90 degrees rotation in order to achieve assembly.

4. CLAY "MELTING"



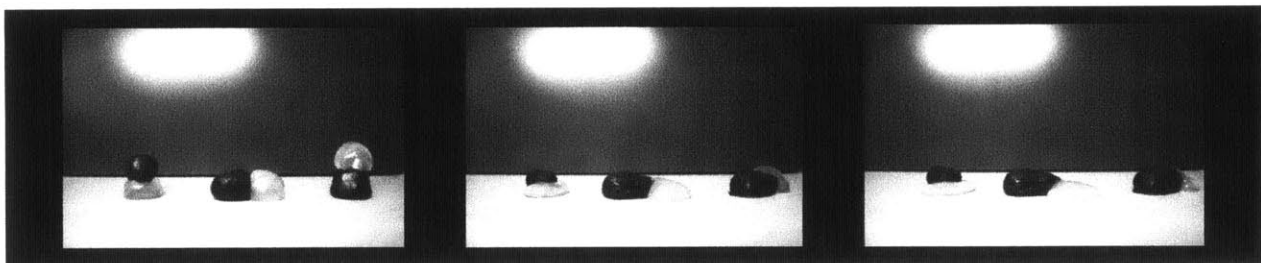
Goal: Prove that non-magnetic clay flows away from the assembly, thus revealing the structure. Therefore, especially transparent non-magnetic can be a valuable testing material since it allows the assessment of the assembly. Furthermore, this would indicate that non-magnetic clay could be useful as supporting material in assemblies.

Method: Time lapse of the melting procedure of the non-magnetic clay of two assembled A/CUBE L blocks.

Parts: transparent clay, 2 PLA A/CUBE_L blocks

Results: The results confirm the hypothesis. The melting occurs really fast during the first hour and then slows down significantly. After a day, very little residue is left on the blocks.

5. M-CLAY – NON-MAGNETIC CLAY INTERACTION



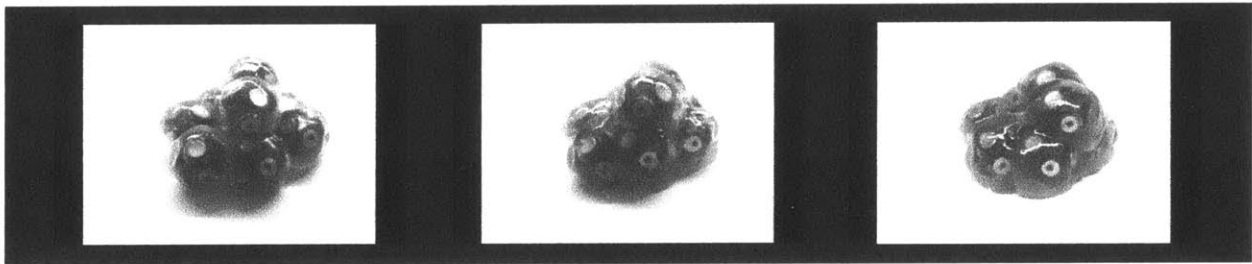
Goal: investigate the interaction of M-clay with non-magnetic clay. Test the premise that non-magnetic clay could be used to create supports for the M-Cell assembly that would later flow away. Test the interaction of the two types of clay and whether they merge into one material.

Method: Two spheres of m-clay and non-magnetic clay are placed on each side of a rod magnet. There are 3 sets of this arrangement. The first is placed with the n.m-Clay below the M-Clay the third with the M-Clay below the n.m-Clay and in the second one they are placed parallel to the ground.

Parts: transparent clay, M-Clay, 2 rod magnets N42 d=0.6 h=1,5cm

Results: The hypothesis was confirmed since the M-Clay remained around the magnet whereas the non-magnetic Clay flowed away. The M-Clay enveloped the whole magnet, moving away the n.m Clay. An interesting finding was that the two types of Clay did not merge together except at a very small layer at the seam between the two materials .This finding supports the claim that n.m Clay could be used as support since it does not mix with the M-Clay and leaves only a really small amount of mixed residue on the surface of the M-Clay.

6. B/ICOSA_1 (x9) M-CELL ASSEMBLY TEST (RANDOM PLACEMENT)



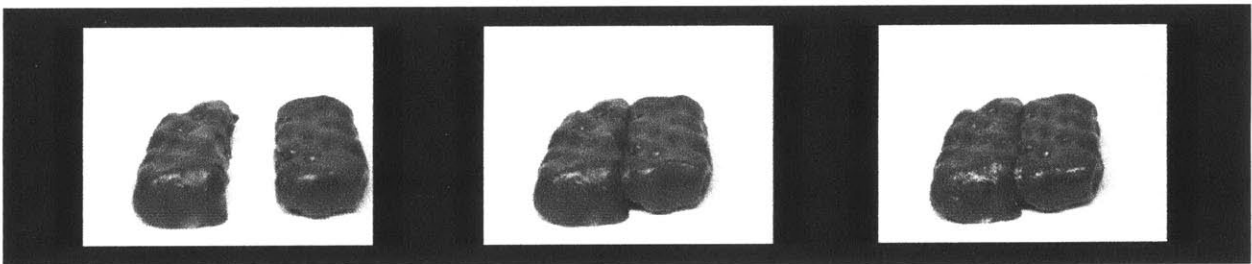
Goal: Test M-Cell assembly with 9 B/ICOSA_1

Method: 9 B/ICOSA_1 cells are stacked

Parts: transparent clay, 9 PLA B/ICOSA_1 blocks

Results: The results of the assembly were encouraging. Most of the blocks assembled correctly. However, there were some local energy minima noted. In some experiments the few local energy minima produced areas that were uniformly assembled, but with different directionality relative to other areas (crystal-like formations). Less common were gaps in the assembly due to high friction and low magnetic field intensity.

7. MERGING OF TWO M-OBJECTS



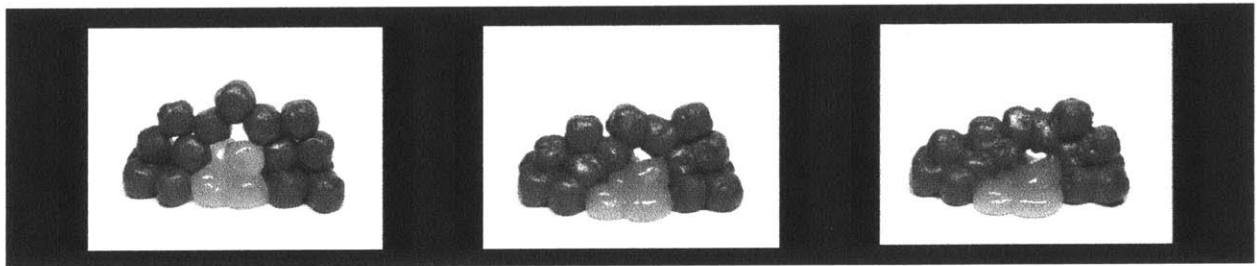
Goal: Prove that two M-Objects can merge into one.

Method: 2 M-Objects are placed next to each other

Parts: M-clay, 2 M-Objects each consisting of 12 PLA B/ICOSA_1 blocks

Results: The hypothesis of the experiment was confirmed. The M-Objects after a few minutes of contact started to create a common seam, as seen in the pictures. After a few hours the M-Objects have totally merged and the seam was undetectable.

8. CLAY AS SUPPORT



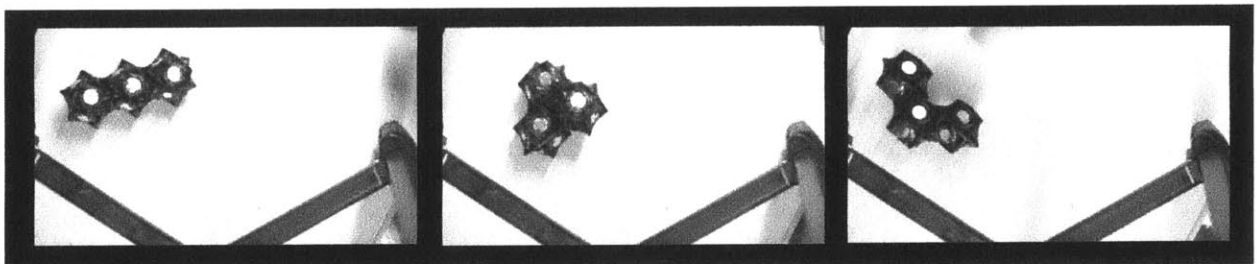
Goal: Test the regular non-magnetic Clay as support in a control placement assembly. Experiment with the possibility to create openings or arches in a M-Object.

Method: 13 B/ICOSA_1 cells in an arc formation, supported by 4 non-magnetic clay spheres

Parts: M-Clay, transparent clay, 13 PLA B/ICOSA_1 blocks

Results: The hypothesis that the non-magnetic Clay can support an opening and then flow away is confirmed in this experiment. However, more experimentation has to be conducted regarding the temperature of the non-magnetic spheres. That is because the Clay needs to be more viscous when the placing of the spheres occurs, for there is no internal structure holding them like the M-Cells. This means that in larger assemblies they will start flowing away before all the cells can be placed.

9. BLOCK THROWING



Goal: Test the effectiveness and error correcting capacity of the C/ICOSA block, without Clay

Method: Throwing serially 3 C/ICOSA blocks towards each other

Parts: 3 C/ICOSA blocks

Results: The results of this experiment support the design choices of the final block's geometry. Despite the fact that blocks were thrown randomly to each other, there was a high chance they would error correct and assemble correctly with each other. Furthermore, in the case of a local energy minimum between two blocks, there was also high chance that when a third block was thrown to them, it would correct their positioning.

10. C/ICOSA (X5) M-CELL ASSEMBLY TEST (RANDOM PLACEMENT WITH TEMPLATE)



Goal: Test M-Cell assembly with 5 C/ICOSA

Method: Throwing 5 C/ICOSA cells in a container

Parts: M-Clay, 5 PLA C/ICOSA blocks, container

Results: The results of this experiment illustrated the effectiveness of the M-Cell assembly procedure. A container was used to test the limits of the procedure. The container would make the assembly procedure harder because the M-Cells would have more spatial constraints. These constraints add external forces to the system. Therefore, the system also needs to balance these forces in the error correction procedure which makes it harder to achieve the correct results. However, the system was indeed able to overcome these constraints and the blocks assembled in their correct positions.

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