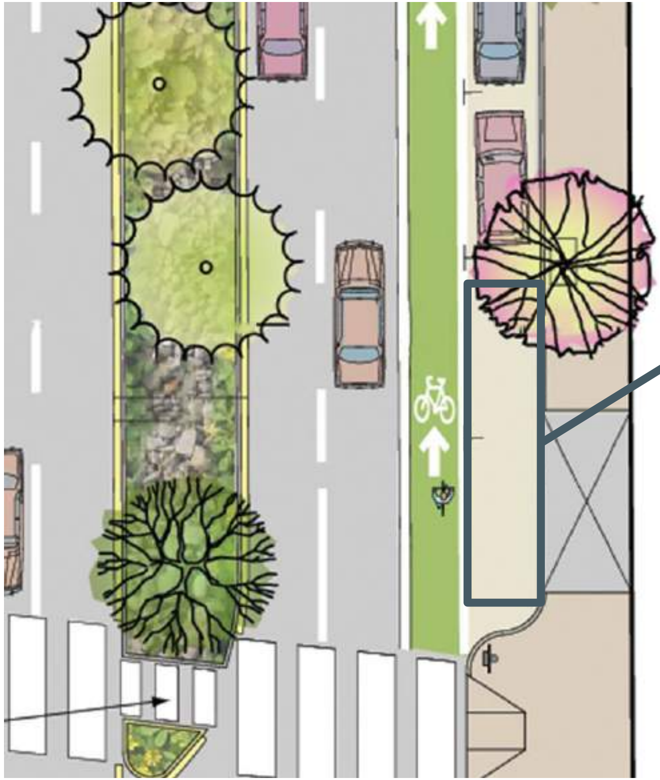
Parklets and Multifunctionalism

Gella and Makani

Role of Urban Spaces

The urban fabric is comprised of various spaces. The most prevalent space is the space of transit. Transit spaces are made of up of pedestrian and vehicular veins that run between stationary spaces, or spaces that one would come to a rest for the purpose of work, recuperation, or gathering. Recently, there have been additions to transit spaces that people congregate at to acquire small items such as trinkets and foods. The role of the collection of all of these spaces mentioned previously is the creation of a larger connected fabric for people to live and make a living. Urban fabrics are the brainchild of large congregations of people who no longer wished to live in small towns absent of work, people who looked to be involved in industry, and people who are seeking refuge from war torn countrysides.

What is a Parklet?



Possible Parklet Location

A parklet is a sidewalk extension that is a public space, and is intended for pedestrian rest. An average parklet is no larger than the space of a few parallel-parking stalls. A parklet sometimes reflects the theme of the business directly adjacent; other times, it is completely independent.

Parklets started in San Francisco, and have recently begun appearing in other cities around the US, such as: Los Angeles, Spokane, and Minneapolis. Parklets are often designed to be easily installed and uninstalled by using modular or prebuilt pieces that are assembled on-site.

Why Are Parklets Important?

Parklets convert a few on-street parking spaces into public open space and are a cost-effective way to activate streets, create more vibrant neighbourhoods, and promote economic vitality.

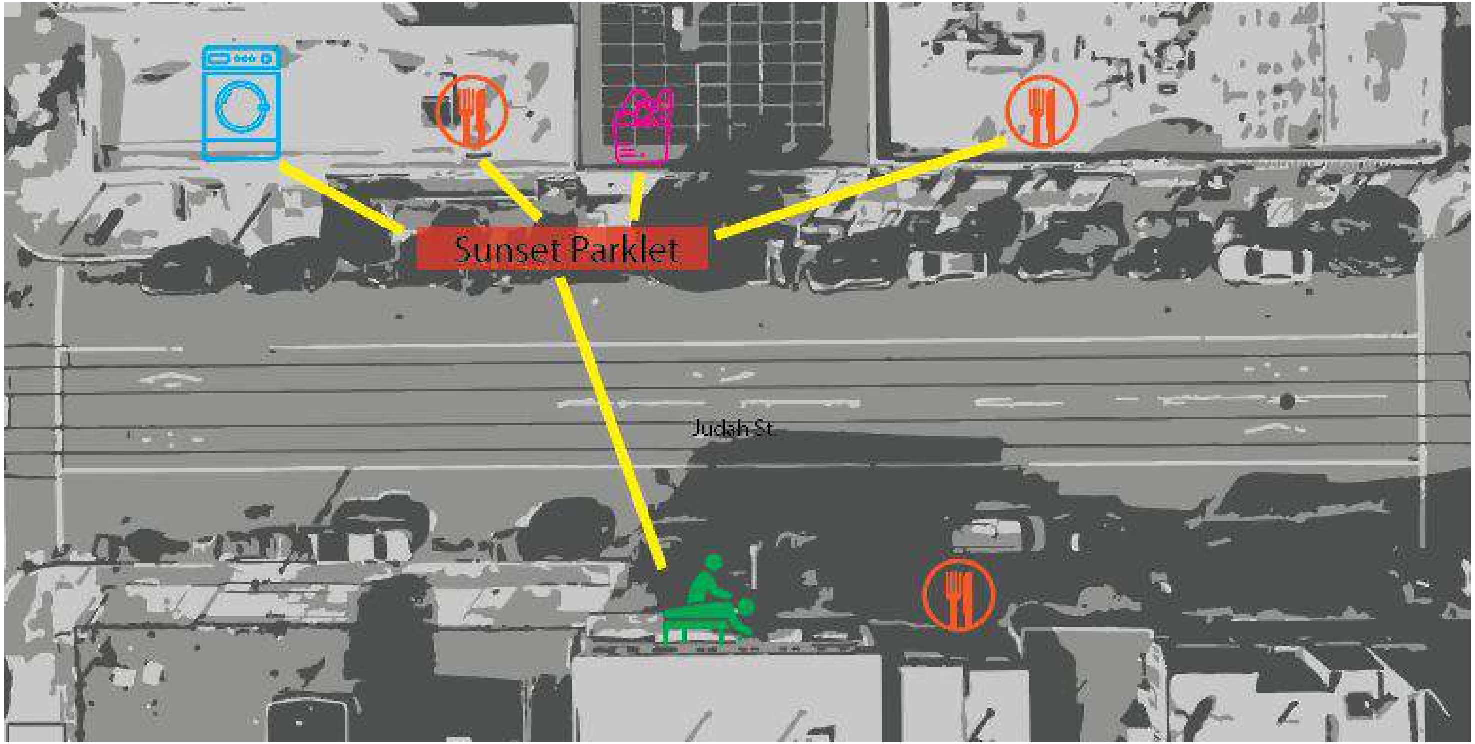
Parklet programs have been created in cities around the world as a way to support community-driven projects that allow people to use streets differently.These programs support creative spaces that add “people places” to the public right of way. Parklets also encourage walking and biking and create more attractive and inviting commercial districts.

Examples of Parklets

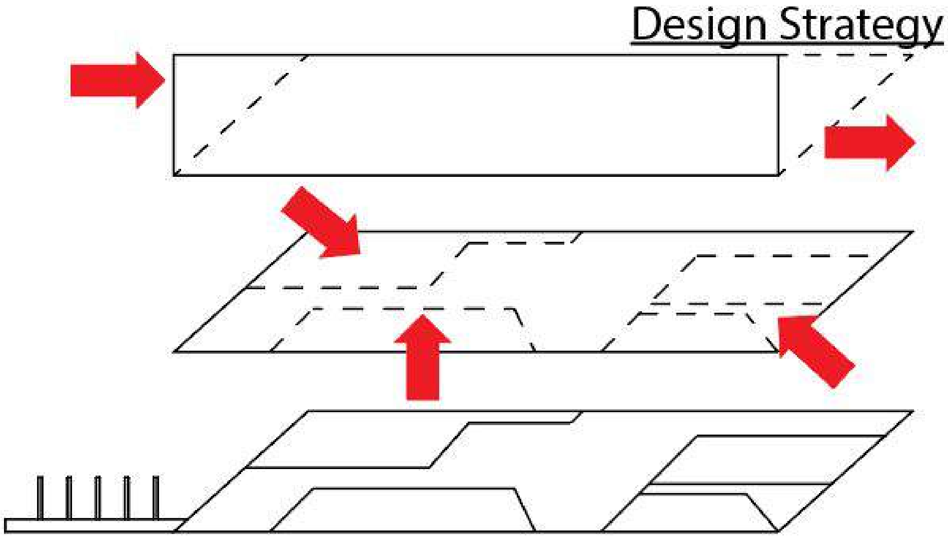
Sunset Parklet
Interstice Architects

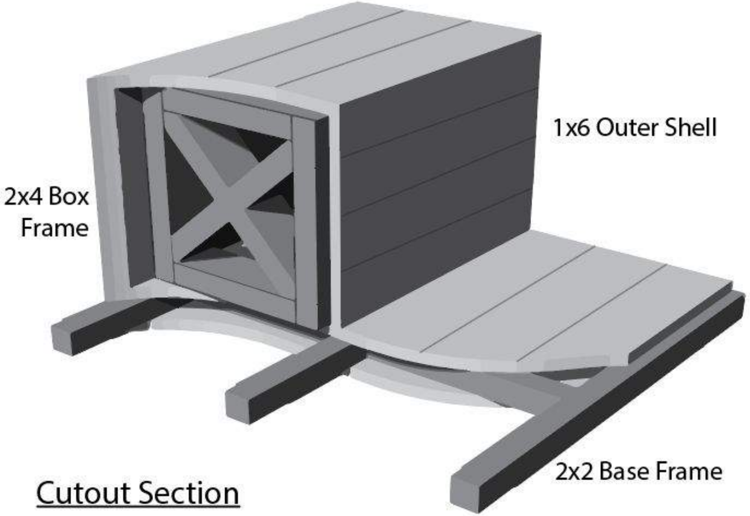
TwoXTwo
Iowa State UNiversity

Sunset Parklet

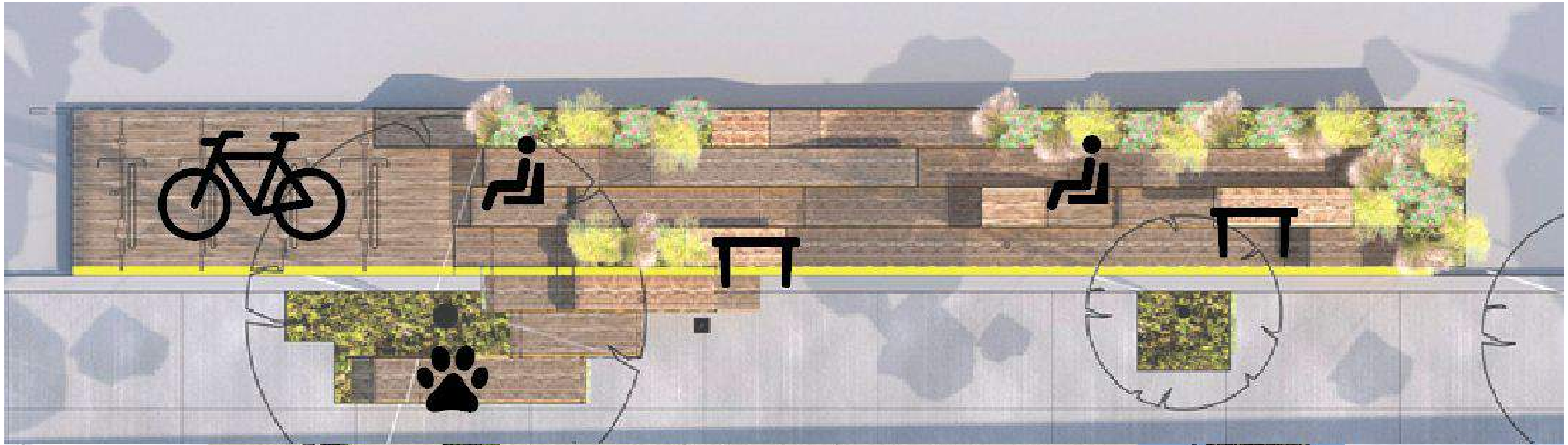


Sunset Parklet





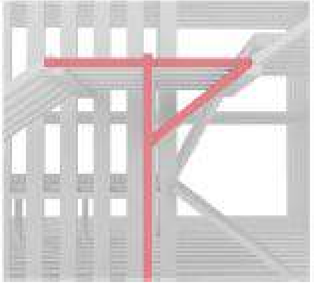
Sunset Parklet

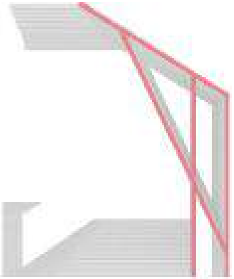


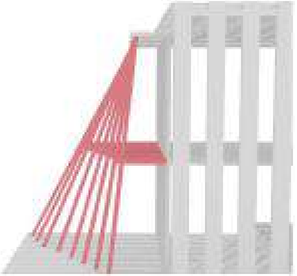
TwoXTwo

TwoXTwo

Structure Analysis------Triangle Structure

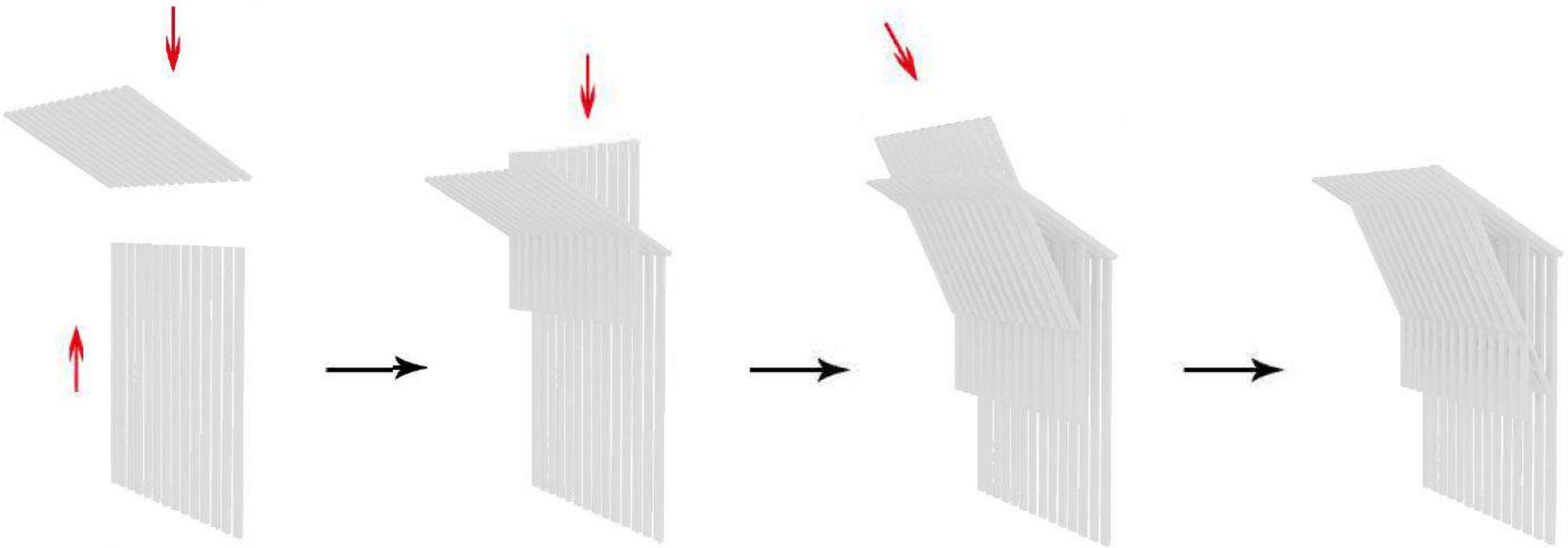






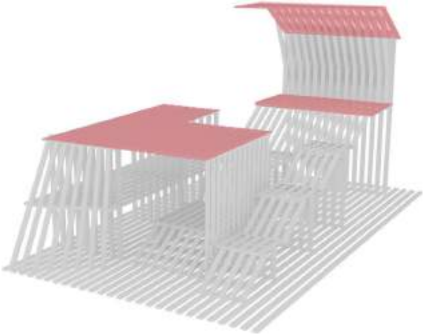
TwoXTwo

Structure Analysis

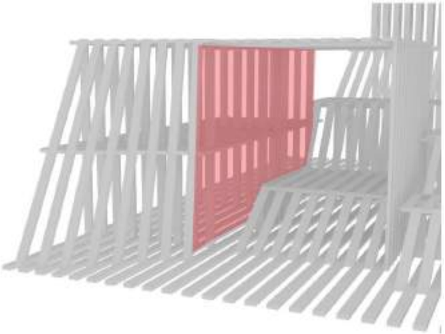


TwoXTwo

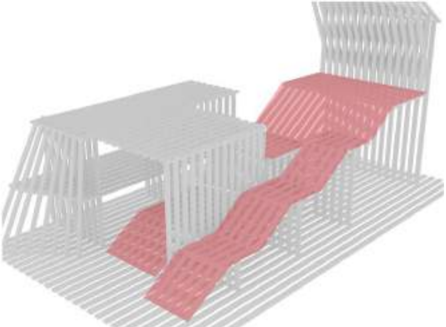
Multi-Function Space



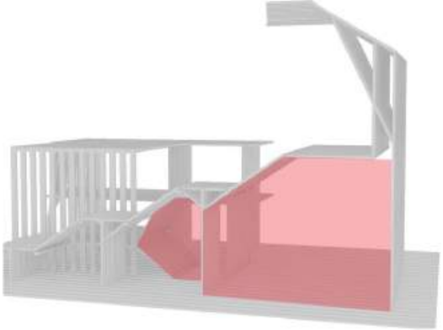
Canopy



Shelves



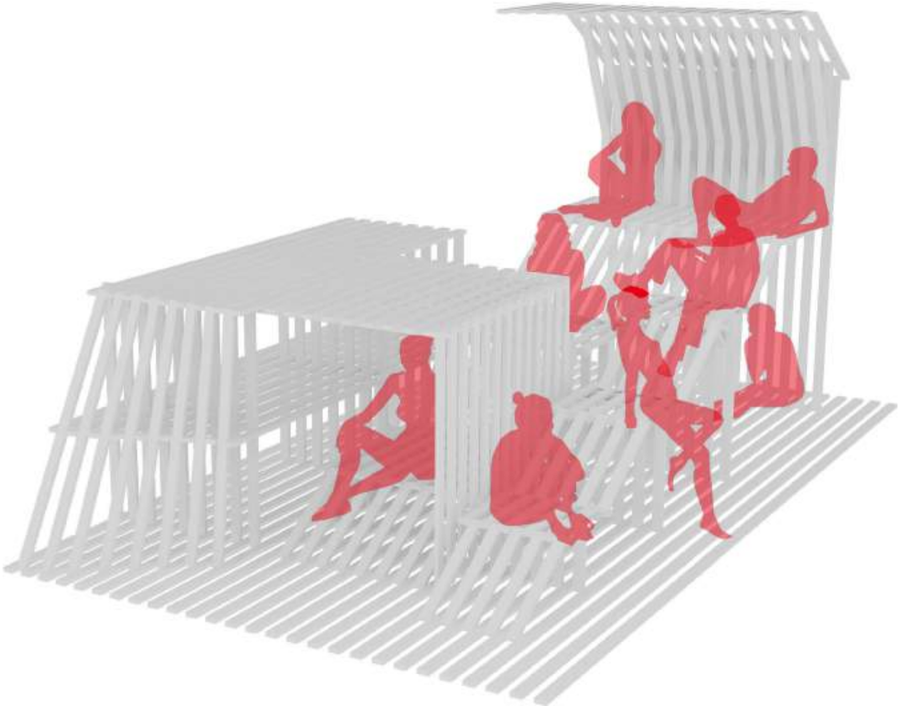
Seats



Shelters

TwoXTwo

Interaction



Definition of Multifunctionalism

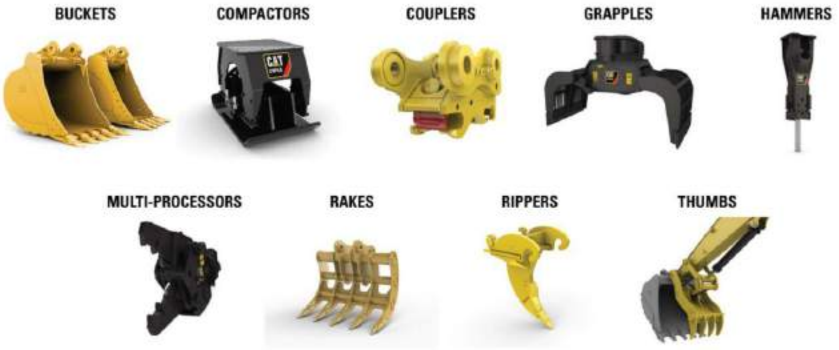
Multifunctionalism is the primary quality of anything that is intended to have multiple uses. Multifunctionalism represents human efficiency: the idea that any one item can serve a multitude of purposes. “Multifunctional” was not commonly used in literature until the past five decades. Correspondingly, humanity has moved (in the past few decades) towards practices that involve multifunctional tools, items, machines, furnishings, and other goods. Even careers and job practices now involve being a “human multitool,” where one has to have the ability to do multiple functions that require various branches of background knowledge. Multifunctionalism has become synonymous with productivity because multifunctionalism means getting multiple things done with less effort or cost.

Examples of Multifunctionalism

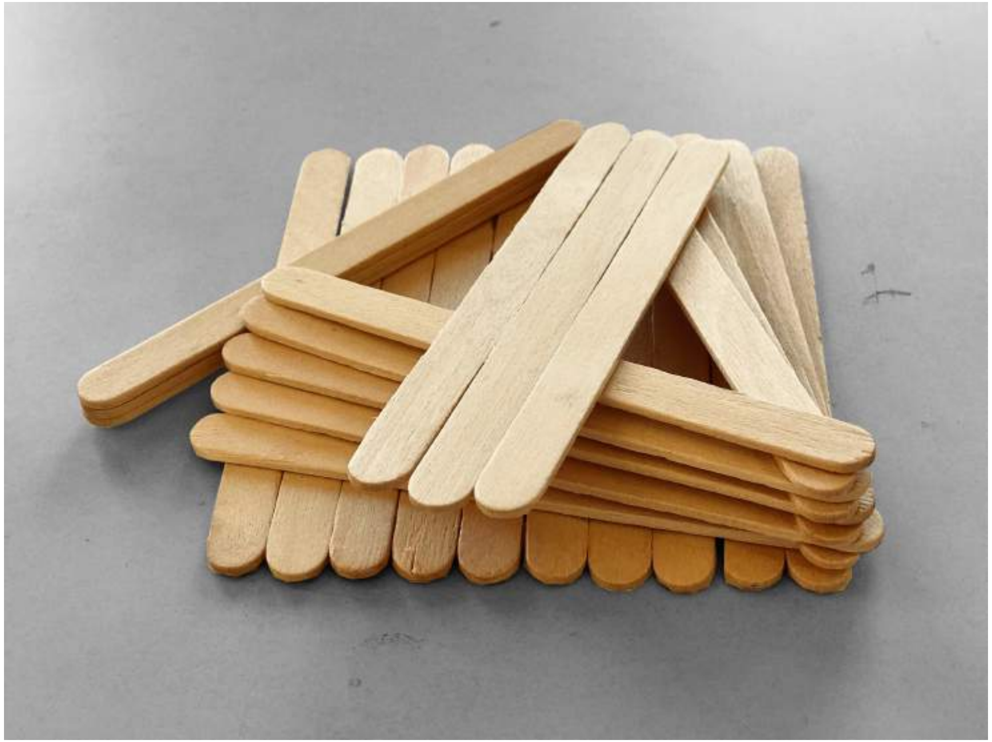
Creative furniture

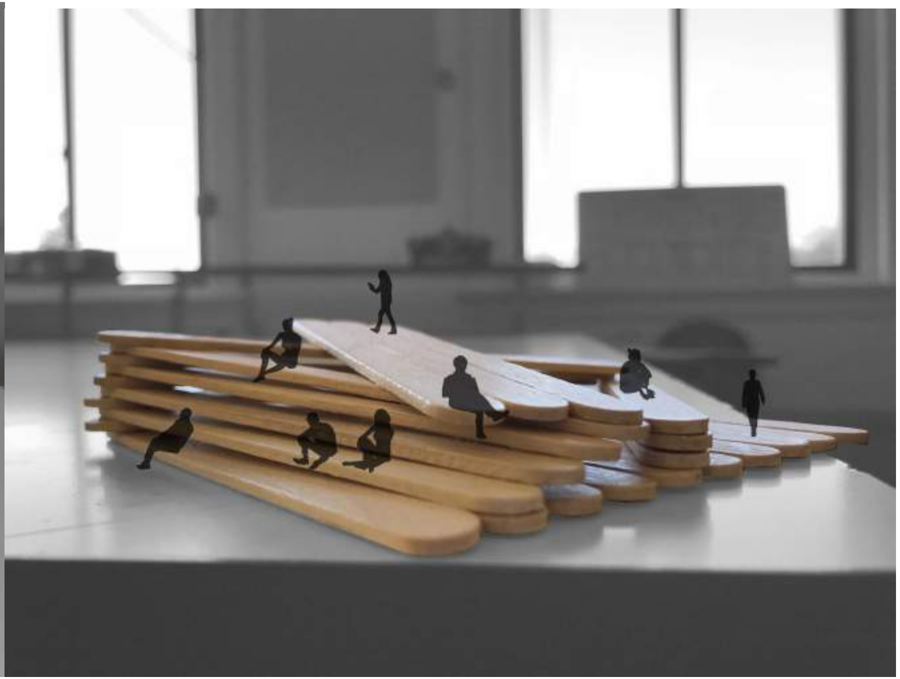
- Flexible for space saving
- Adjustable for every size
- Creative for multi-purposes

Examples of Multifunctionalism



Conceptual Models





Conceptual Models

Articles

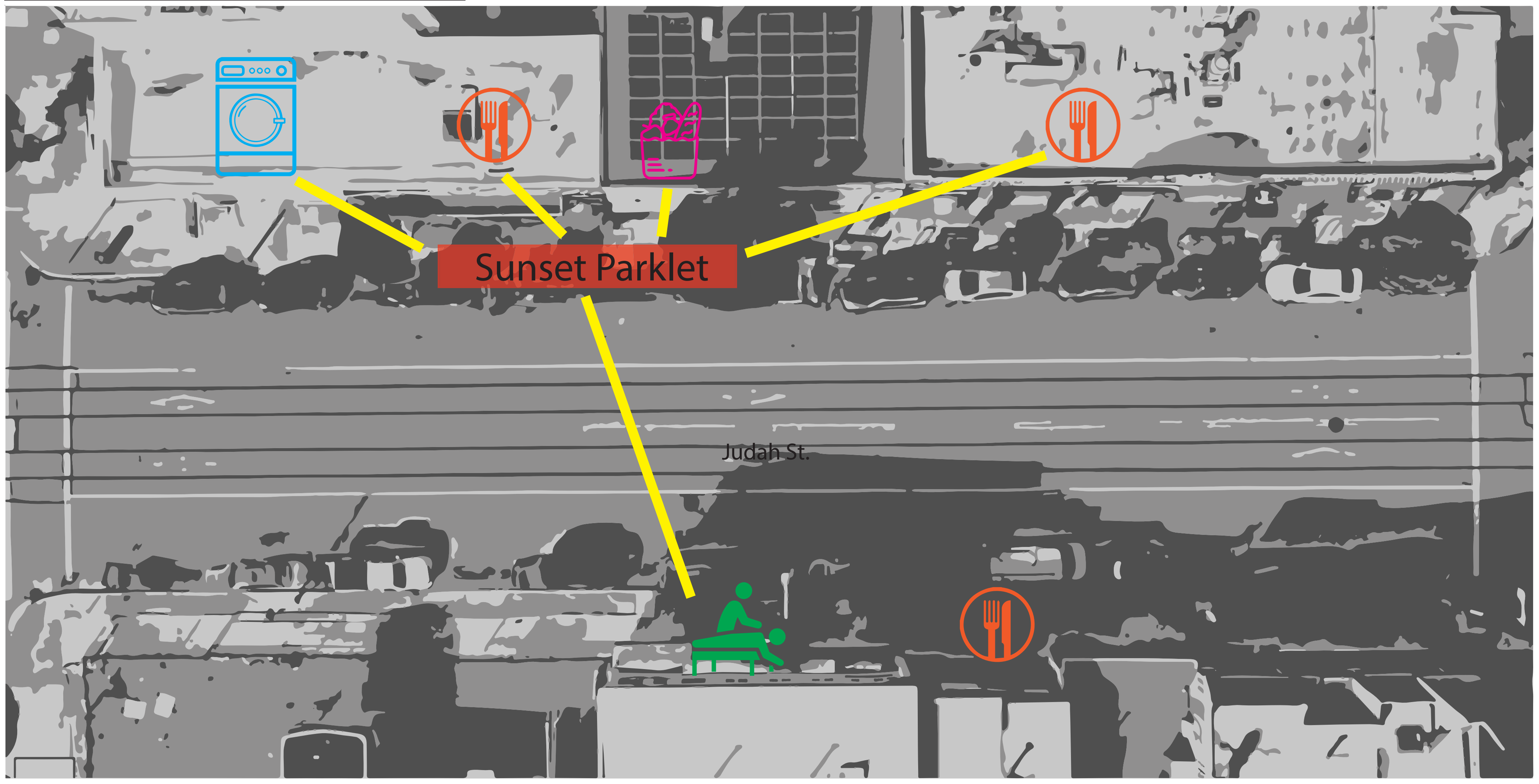
Magnetic Morphing:

"In an attempt to design shape-morphing multifunctional objects, this thesis uses programmable matter to design self-organizing multi-agent systems capable of morphing from one shape into another."

Magnet-Based Interactive Kinetic Bricks:

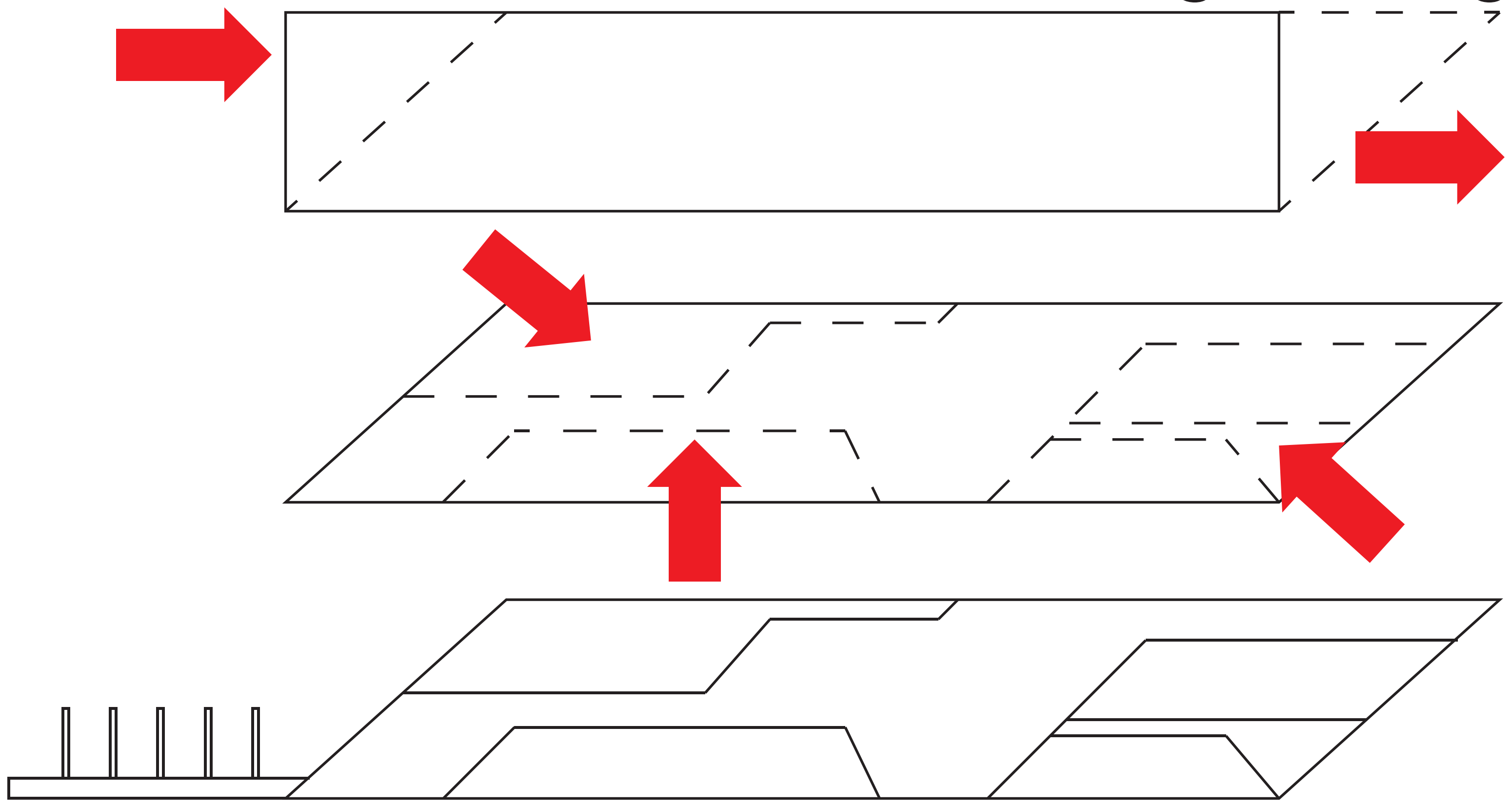
"By the use of magnet in digital design, this research examines new methods for performing simple and affordable kinetic structures so as to create interactive relations between architecture and human being."

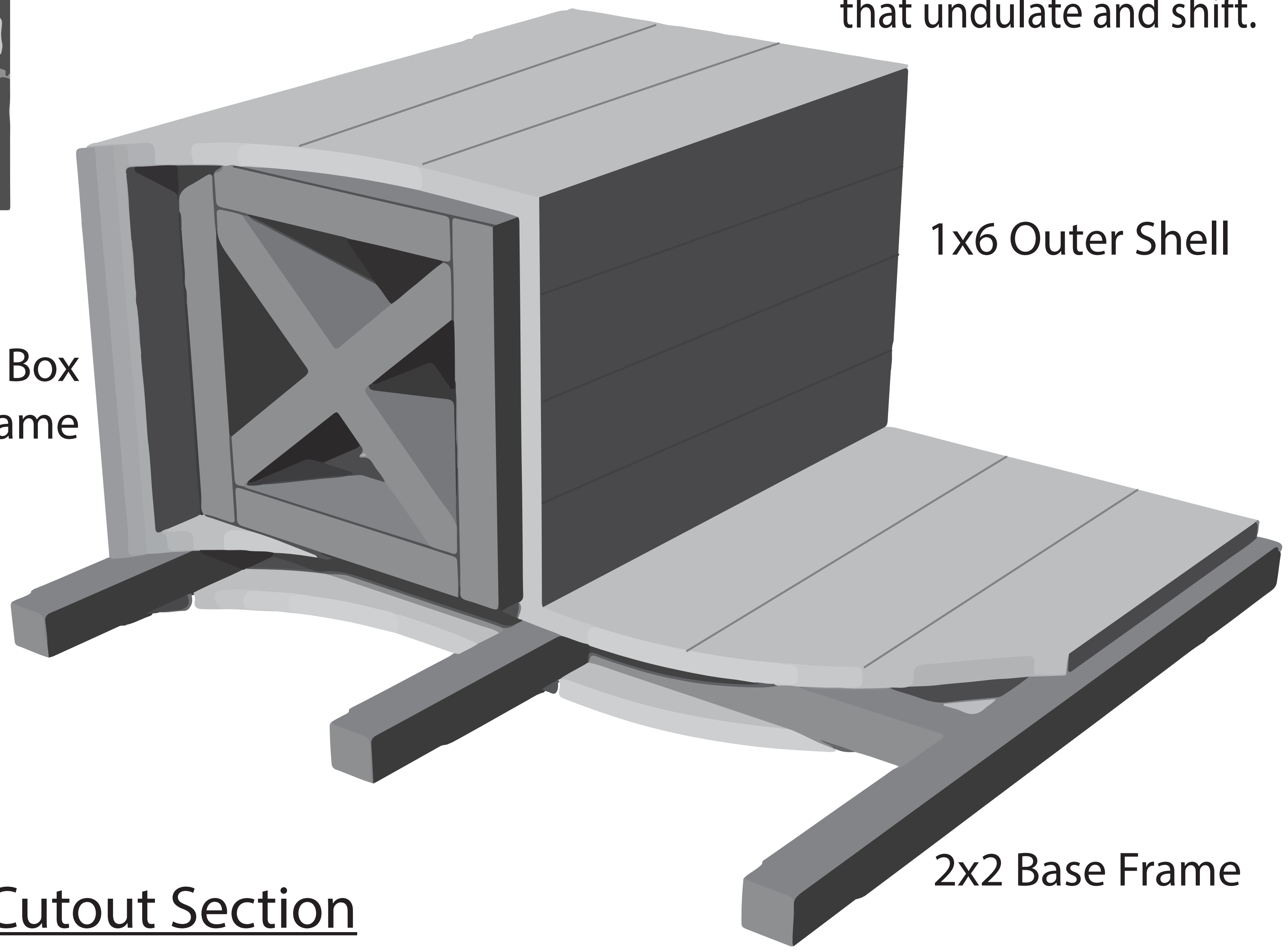
Interstice Architects
Sunset Parklet



This parklet is located in San Francisco on Judah Street between 44th and 45th Aves. The parklet holds a 50′ x 6′ footprint directly in front of Sea Breeze Cafe. The parklet serves multiple small businesses as a place for both patrons and the public can congregate or rest. The parklet also serves multiple functions. Its unconventional angularity and planar surfaces serve various purposes can be utilized in different ways such as tabletops, benches, lounge-style seating, and shelter from the elements. The parklet includes bike racks, a bike pump station, planting opportunities, leash ties, and a dog watering area. The overall design is loosely based on sand dunes that undulate and shift.

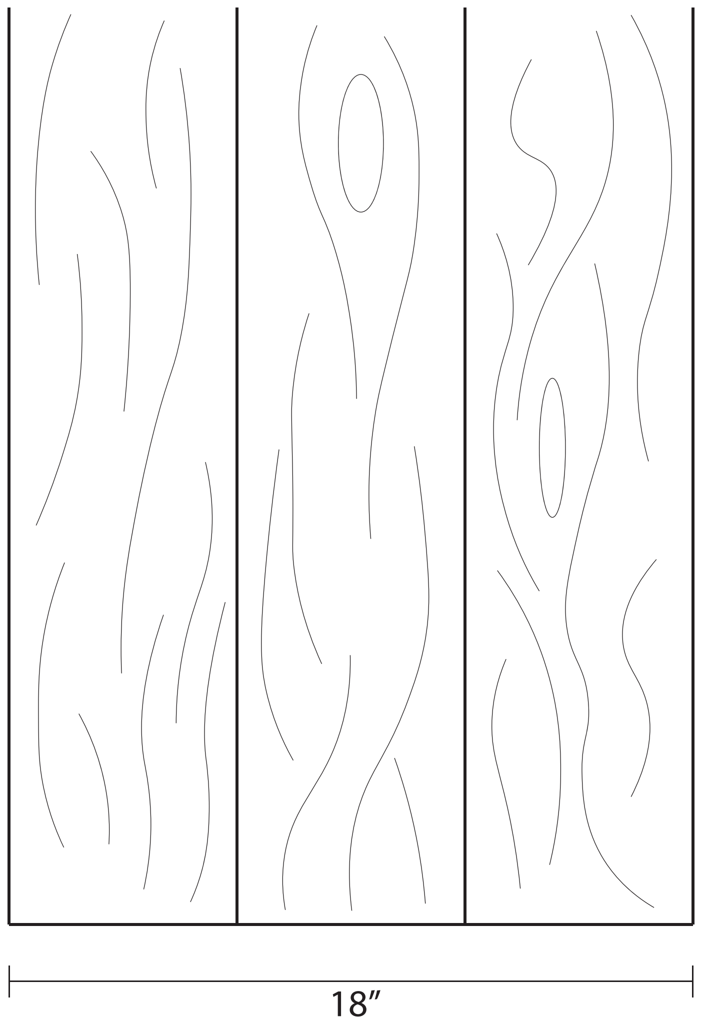
Design Strategy



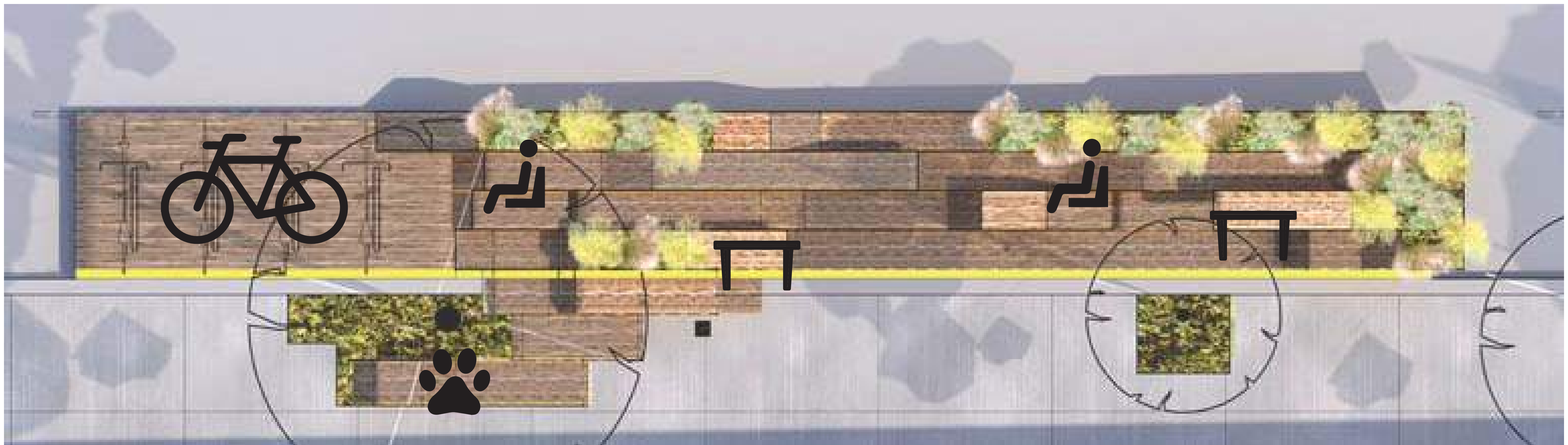


Cutout Section

One "track" is 18 inches in width and runs the length of the site. Each 18 inch assembly is made up of three 6 inch boards.

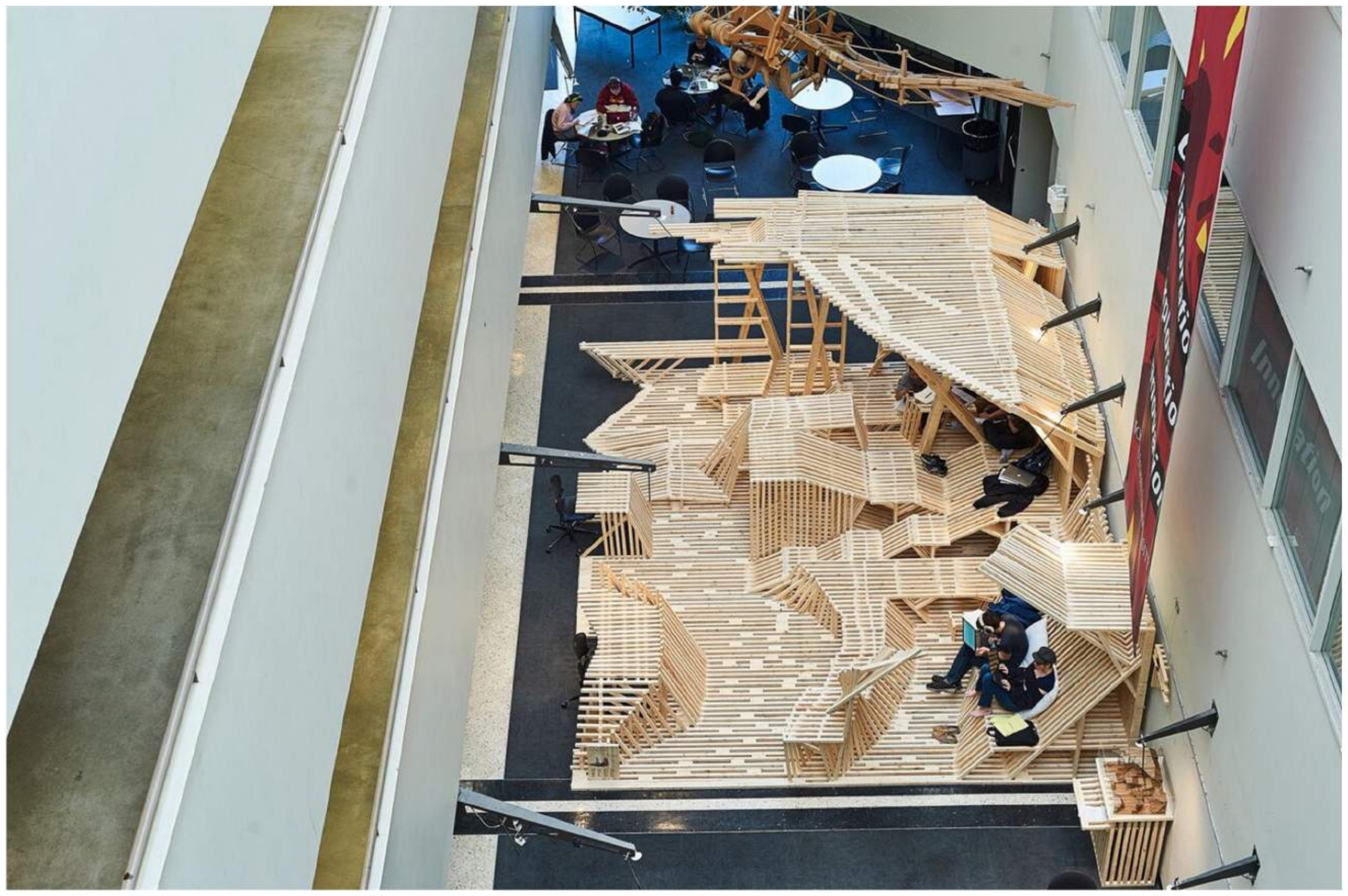


x4



Images from Contemporist article

Phase 01 - Case Studies

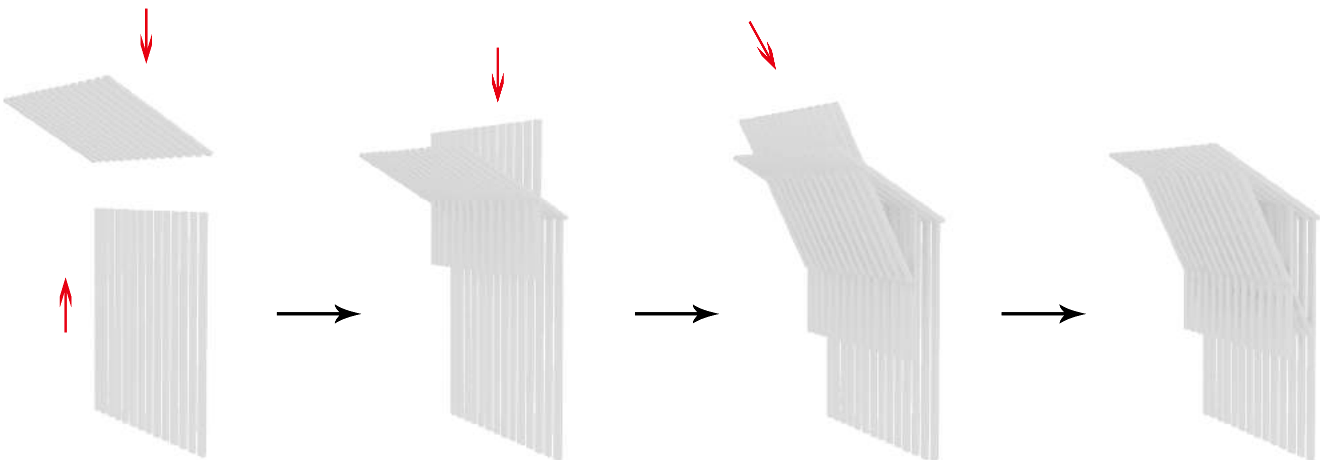


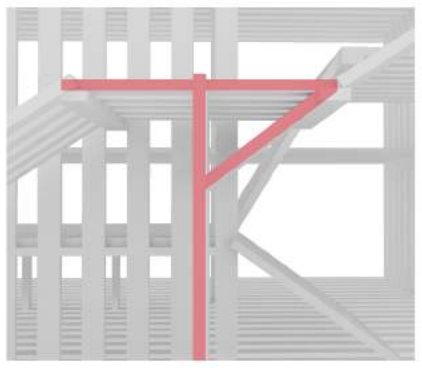
TwoXTwo

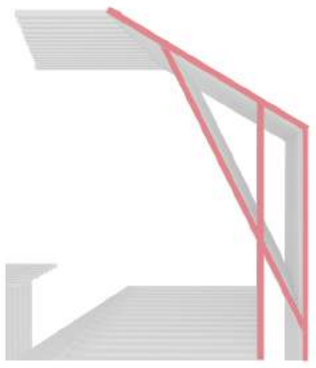
TwoXTwo is an in-depth exercise towards an understanding of public space through the rethinking of formal proportions and conventions of program and privacy. The project is primarily composed of 2x2 lumber pieces. The final assembly appears as a kinetic and continuous surface that incorporates various spatial qualities such as inclines, overhangs, ledges and pockets. Similar in form, SHoP Architects' Dunescape served as major inspiration to the project.

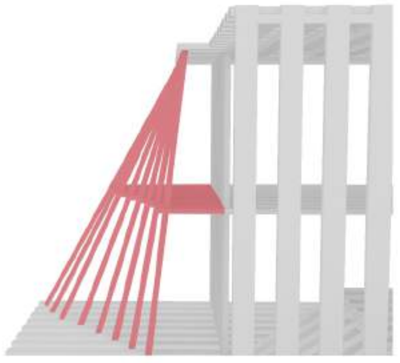
Structure Analysis

Triangle Structure

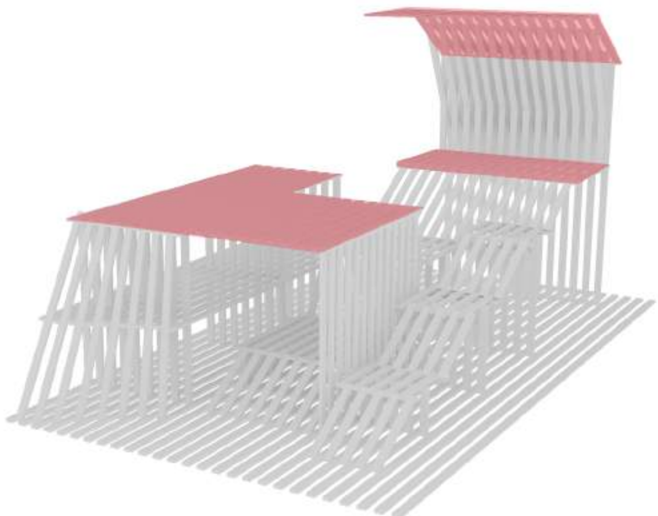




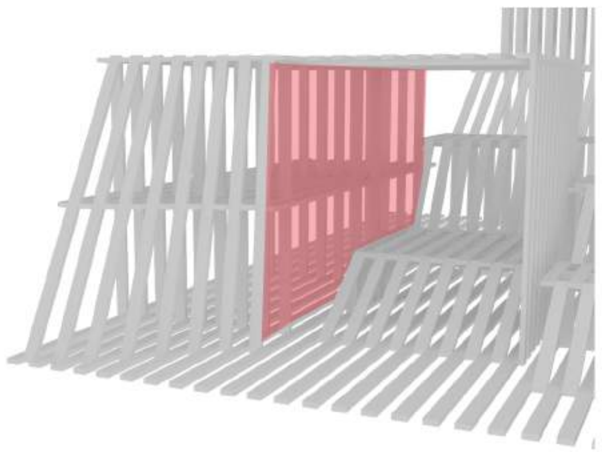




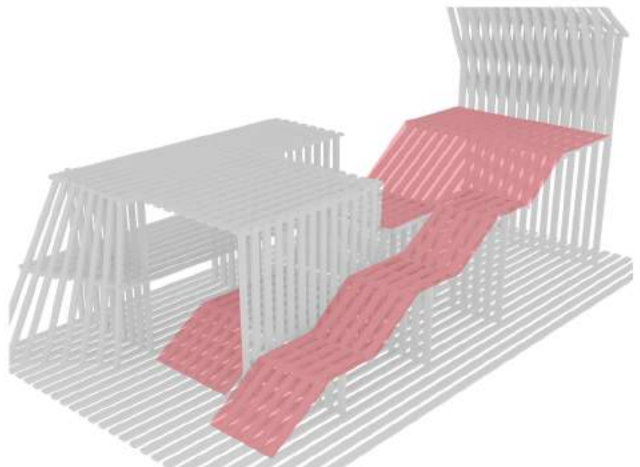
Multi-Function Space



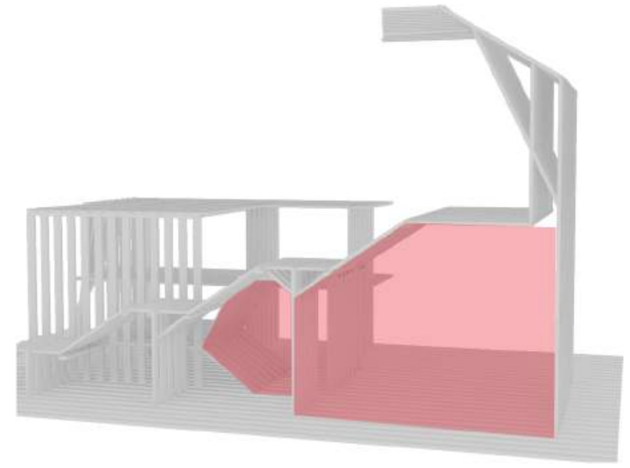
Canopy



Shelves



Seats

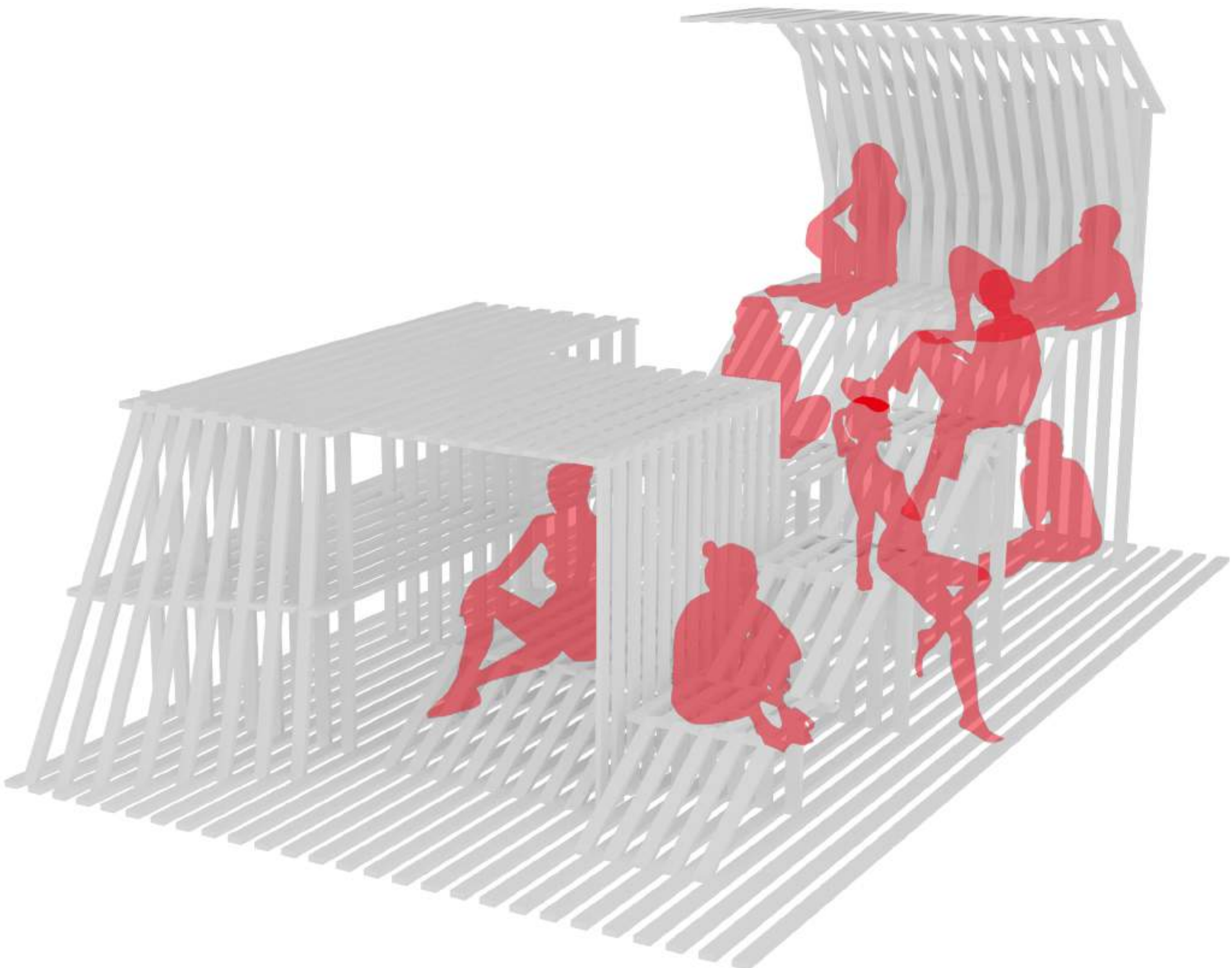


Shelter

Multi-Function Furniture

- Flexible for space saving
- Adjustable for every size
- Creative for multi-purposes

Interaction



Magnet-based Interactive Kinetic Bricks

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Brick has been used in construction since ancient times and has been respected among other tectonic materials through out the history. Novel technologies recently have opened new horizons in using brick in architectural design. This paper investigates innovative implementation of bricks in kinetic architecture. Kinetic structures usually employ complex and high-cost mechanisms to come into force and their movements might be limited to some conditions. By the use of magnet in digital design, this research examines new methods for performing simple and affordable kinetic structures so as to create interactive relations between architecture and human being. Magnetic energy is applied in two ways to move a roof made of brick which is considered a heavy and masonry material. Consequently, it represents the hidden potentials of magnet as a renewable source of energy.

Keywords: *kinetic architecture, interactive design, parametric design, Bricklaying, magnet energy*

INTRODUCTION

Nowadays explosive growth of digital technology has affected the core of architectural design. Certainly, digital tools offer new possibilities that were inconceivable only a few years ago (Picon 2010). This research arises from a project in design studio of Tarbiat Modares University (TMU) defined as "Interactive Transforming Canopy with Particular Reference to Computational Design Thinking". The canopy seems to be a pavilion to exhibit cutting-edge technologies which developed by TMU students, understanding that, the canopy itself should show high level of interactivity. As a result, the design team were challenged to examine their ideas and innovations through designing the canopy. The coherence between theoretical ideas and design to performance process was the main issue of this experience. The design team did their best to combine endogenous ideas as well as indigenous materials with digital technologies in order to find a way to design a kinetic structure with heavy and masonry materials like brick. It was an impressive task to bridge local materials (such as brick) to new shape of interactive atmosphere which was asked in the design terms of the canopy.

INSPIRING BRICKWORKS

Brick construction counts with a long and rich tradition in architecture, which can be traced back to the origins of our civilization and reminds us of soil and nature. Because of accessibility and unique features, it has been employed widely in traditional architecture with variety of forms in each place. It was used in different parts of a building as structure or decoration in facade. Amazing samples of brick works around the world exemplifies our ancestors' progresses in producing and employing this material. As an example, among Iranian ancient buildings, Zanbil Ziggurat, porch Ctesiphon, Isfahan and Yazd Grand Mosque and Rabat (Museum of brick work) can be mentioned.

Despite the long history of bricks and masonry in the built environment, they usually include limited possibilities to be applied in the design. For that reason, digital technologies can assist in developing proper methodologies for masonry (Al-Haddad et al. 2011) to meet contemporary design requirements and integrate new geometric possibilities. As noticed by Campbell (2005, 13), brick's evolution overtime has been grounded in two major areas: brickmaking technologies and brickwork techniques. While the first one sets the physical properties of the material (i.e. weight, dimensions, resistance, appearance), the second one defines the space for design creativity and efficiency of masonry constructions. The developments in brickwork techniques tend to be driven by structural and aesthetic goals, supporting the materialization of magnificent brick walls, arches or vaults, and also ornamental surface effects (Sousa et al. 2015, 362). By implementation of parametric design methods various forms can be created. This is what many contemporary designers are looking for. In recent years, some innovative brickworks have been created by designers which opens new horizons toward adoption of brick in contemporary architecture. It is important to highlight two magnicant monuments inspiring the design generators i.e. Cloaked in Bricks and Spris Café.

Cloaked in Bricks

Cloaked in Bricks is a residential project designed by Admun Design & Construction Studio and located in Ekbatan, Tehran, Iran. It consisted of a façade design and lasted from 2013 to 2015. This project is an attempt to propose a prototype addressing the current issues of residential architecture in its region through bridging between old and new, proving how local materials and patterns can be used in new ways creating an architecture responding to both functional requirements and aesthetics.

Figure 1
The facade design of Cloaked in Bricks project.

Brick appeared to be a proper choice for the façade covering since it has always been used as a local building material in Iran meeting environmental needs while creating numerous aesthetically beautiful textures. The complex form of the façade, limited construction period and economical conditions of the project forced the project team to search for a new construction method for implementing the façade. The appropriate method seemed to be eliminating mortar by punching the bricks (Figure 1). Finally, parametric design software facilitated the texture design process. Despite the complex form of the facade the construction process was easily executable by workers through simple instructions prepared by employing a system of coding [1]. As a contemporary praised building, it focused on dancing brick to show flexibilty of masonry materials.

Spris Cafe

Spris Cafe with 28sqm space, designed by Hooba Design Group is located in Nejatollahi street in center of Tehran surrounded by Iranian handicrafts shops, neighboring the building of Iranian handicrafts Organization. The aim of the project was to renovate a gift shop and change it to a cafe, considering the small size of the project and its location the main idea inspired by the urban context to transform the traditional elements into an architectural interior space.

Figure 2
The combination of bricks in Spris Café .

Figure 3
The interior of Spris Café, facing the roof.

In designing the spatial diagram, the materiality concept is based on an integrated geometry continues from outside to inside. The neighboring building, Iranian handicrafts Organization with brick facade, was the inspiration to use the same material for the cafe. Concerning the small size of the project, a brick with 5*10*20 dimensions sliced into eight smaller pieces of 5*5*5 centimeters which one side of the bricks glazed in turquoise blue color. The terracotta bricks are also hygienic as they covered with antibacterial layer (Figure 2).

One of the main issues of design was creating a visual variation of the form in a small space. In this concept, the situation of visitors in relation to the project is significant in order to understand the form as they can differently perceive the composition of colors on the bricks regarding to their position (Figure 3). The turquoise blue glazed side of the bricks are facing south shaped with the monolithic geometry of brick laying that was modeled by the 3D diagram started from the pavement of the pedestrian and continues inside of the café [2]. In this case, zoomorphic and transitive character of brick, makes spiritual space which remind traditional architecture of Iran.

Case studies show that recent architectural projects focus on innovative understanding of brick while lack of movement made them conventional rather than cutting-edge architecture.

DESIGN TO PERFORMANCE

It is believed that through implementation of parametric design, we can create movement and rhythm in brickworks making it much more dynamic. Therefore it was assumed that interactive approach toward adoption of brick in architectural design process might be pioneer answer to the design question. The design team had two challenges concerning the design process:

1. How to create movement in a number of objects simultaneously?
2. How to create movement in heavy and masonry materials like bricks?

In order to find an energy efficient source of movement the design team decided to adopt Magnet as a source of energy. Electromagnetic energy is an extensive renewable resource that has been underestimated in many fields such as architecture. We believe that using magnet as a source of energy will open new approaches and causes huge effects in future buildings. Additionally, there is a new approach toward applying magnetic fields in architecture namely "Magnetic Architecture". The cur-

Figure 4
The prototype representing the roof structure in scale 1:10.

rent focus of magnetic architecture explores the design opportunities of a new building process from phase one: simply using recycled iron-based material controlled with-in a magnetic field (Diaz and Dubor, 2013). Magnetic architecture might be seen as a potential to increase the flexibility of additive process to reach the architectural scale.

MECHANISM OF USING MAGNETS THROUGH KINETIC BRICKS

The idea of moving bricks is based on the interaction between two energies: the electromagnetic energy of the magnet and the weight of the brick. In other word, magnet pulls the pieces of bricks upward, while the weight of bricks pulls them to the ground. Using this interaction between these energies made the design objective to be focused on the Roof of the pavilion. Therefore, a specific detail was needed to hang the pieces of brick from roof, so that the magnet would absorb them. After all, punching the brick in minor section and reinforcing them with some iron-made bars seemed to be an appropriate solution.

The design was modeled in Rhinoceros ((C)McNeel) with the parametric design plugin Grasshopper ((C)David Rutten/McNeel). The surface was converted into a series of EPS bricks with 250x100x50mm, which is one of the standard dimensions of commercial bricks. In total, the model comprises 700 bricks placed vertically and ordered in one level. Firstly, each brick was punched from its minor section and then a bar inserted and fixed within it to suspend the brick from the roof. Additionally, a grid of holes was made within the roof as a base for bars. The holes were created in the square shape and also bars were rectangular in order to fit in the holes and avoid undesirable rotation while moving (Figure 4). The suspended structure of bricks enables them

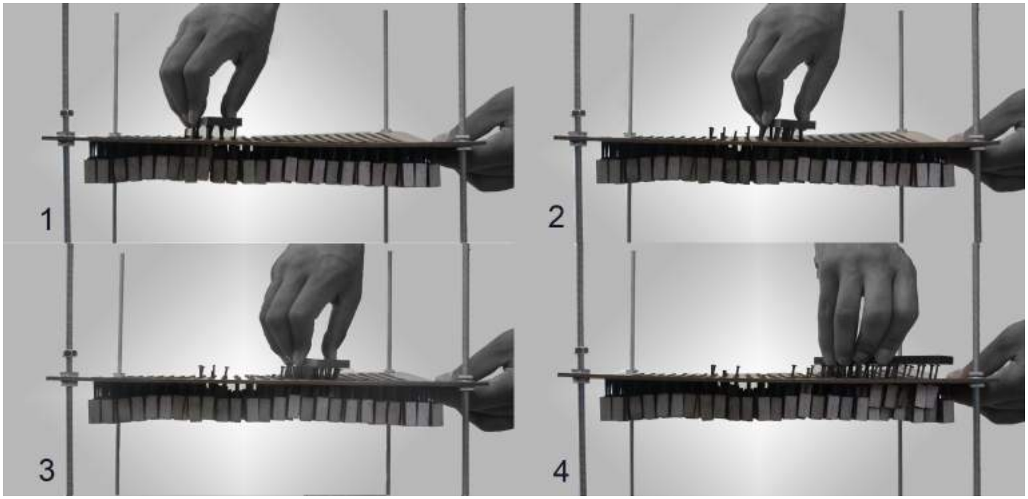

Figure 5
Moving the magnet on top of the roof and rhythm in bricks.

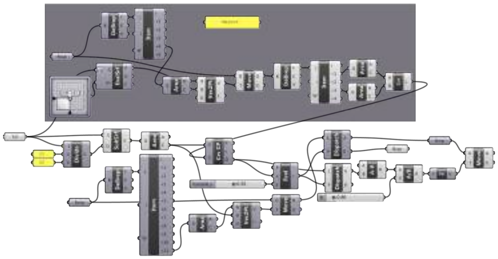

Figure 6
The algorithm of grasshopper plugin related to movement of brick based on magnet.

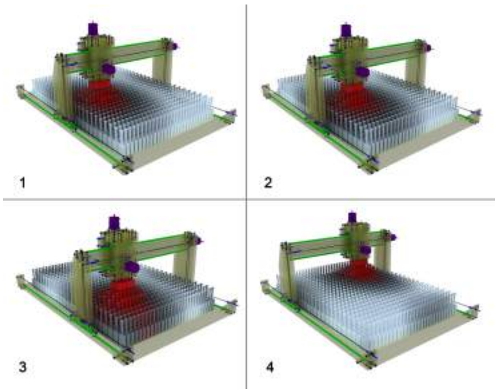

Figure 7
3D modeling of roof structure and 2-axis robat moving on top of that creating rhythm in bricks.

to move vertically through the holes when a magnet absorbs them. The length of bars is adjusted in a way that enables bricks to move less than 20cm vertically so as the integration of the roof structure would not be damaged. While the bricks move in a series, they form some waves in the roof which attracts the user.

At this stage a system was needed to be defined for generating magnet energy so that it can overcome the weight of bricks to move them upward. To produce the required magnetic energy, two ideas were brought up and examined i.e. Permanent Moving Magnet (Magnetic Field) and Temporary Fixed Magnet (Electromagnetic Field).

1. Permanent Moving Magnet (Magnetic Field). The first idea is based on using a permanent magnet and moving it (the source of energy) on top of the brick grid. The iron bars within each brick would be absorbed by the magnetic energy generated by the moving magnet, creating a wave in the different parts of the roof (Figure 5). To actualize this idea, extensive investigates were done and the results were examined by altering the factors in Grasshopper model (Figure 6).. Finally, it ended up with the idea that a 2-axis robot (like Motorizable

2-axis X-Y) is needed to receive the commands from Grasshopper and move on the roof surface based on those commands. The commands are transferred to the robot by Ardoino kits. As a result, the robot moves the magnet attached to it and enables the bricks to move in a special order (Figure 7).

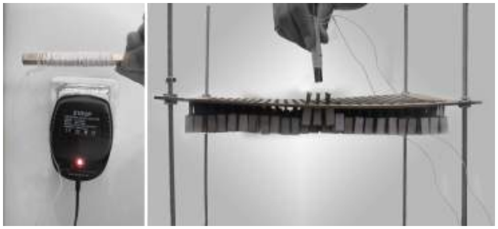

Figure 8
Temporary magnet made of steel with cable around it carrying electrical current.

Linking the robot with Grasshopper gives us the opportunity to draw various patterns and move the whole structure based on that to create those patterns on the bottom view of the roof. Also, we can equip the pavilion with some sensors to catch the presence of human in the space and transfer them to the robot to move based on human movement inside the pavilion. Consequently, the parametric design of pavilion leads to an space with which people could engage in interactive relations.

2. Temporary Fixed Magnet (Electromagnetic Field). The second idea is based on using an electromagnetic grid with fixed components which includes some temporary magnets located on a regular basis. Temporary magnet refers to a piece of steel with some cables turned around it. By exerting an electric current involving the pieces of steel, they would transform to magnets and produce electromagnetic field (Figure 8). As the position of magnets is fixed in this method, by altering the amount of electric current, the amount of voltage is changed and subsequently the power of electromagnetic field would be variable. If we place the magnets in a grid order, they cover the whole parts of the roof and variability of electromagnetic field causes the bricks to move vertically and create waves.

CONCLUSION

The results of the project show that magnetic energy might play a crucial role in future of kinetic interactive architecture. This research opens a new horizon in computer-aided design while needs extensive researches and practices to be recognized as a design and construction method. Implementation of Magnet has the following benefits:

1. Magnetic energy is a renewable source of energy and is generated without damaging the environment.
2. It reduces the costs of a project during the design to construction process. As an example, to construct kinetic structures by using modern technologies high-cost systems is needed, but using magnets seems to be an affordable method for creating movement in space, because the energy generated for moving one object practically causes several objects to move.

Endless potential of brick makes it a flexible material for contemporary architecture. The results of the research emphasized on potential ability on combination between traditional material and kinetic character of contemporary interactive monuments.

REFERENCES

Al-Haddad, T, Gentry, R, Cavieres, A, Carpo, M, Cho, J, Wagner, L and Zaitsev, A 2010 'Representation + Fabrication: Connecting descriptions and artifacts in the digital age', *Proceedings of 1st International Conference on Structures and Architecture (ICSA)*, Guimarães, Portugal

Campbell, JWP 2005, *História Universal do Tijolo*, Caleidoscópio, Portugal

Diaz, GB and Dubor, A 2013 'Magnetic Architecture: A New Order In Design', *1st eCAADe Regional International Workshop*, Porto, pp. 237-245

Picon, A 2010, *Digital Culture in Architecture: An Introduction for the Design Professions*, Birkhäuser Architecture, Basel

Sousa, JP, Varela, PA and Martins, PF 2015 'Between Manual and Robotic Approaches to Brick Construction in Architecture', *Proceedings of eCAADe 2015*, Austria, pp. 361-370

[1] http://architizer.com/projects/cloaked-in-bricks/

Magnetic Morphing

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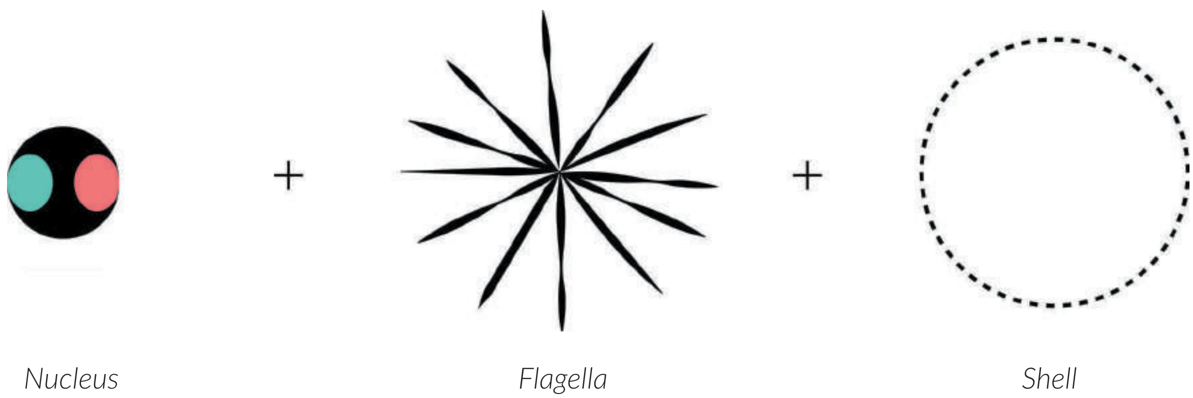

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1 Agent Design Components.

ABSTRACT

In an attempt to design shape-morphing multifunctional objects, this thesis uses programmable matter to design self-organizing multi-agent systems capable of morphing from one shape into another. The research looks at various precedents of self-assembly and modular robotics to design and prototype passive agents that could be cheaply mass-produced. Intelligence will be embedded into these agents on a material level, designing different local interactions to perform different global goals.

The initial exploratory study looks at various examples from nature like plankton and molecules. Magnetic actuation is chosen as the external actuation force between agents. The research uses simultaneous digital and physical investigations to understand and design the interactions between agents. The project offers a systemic investigation of the effect of shape, interparticle forces, and surface friction on the packing and reconfiguration of granular systems.

The ability to change the system state from a gaseous, liquid, then solid state offers new possibilities in the field of material computation, where one can design a "material" and change its properties on demand.

INTRODUCTION

Influenced by unprecedented technological advances, individuals' expectations of what an object can and should do are becoming greater and greater. These high expectations in turn pressure the search for innovative ways to embed intelligence into objects in order to make them multifunctional, and capable of responding and interacting with their surroundings. The ability of an object to morph from one shape to another has been a problem that many researchers in various fields have tried to approach. These have ranged in size and technique from large architectural explorations to swarm microrobots. Chuck Hoberman's transformative structures and the new cutting-edge pop-up origami robots are good examples of objects that seamlessly transform from one shape to another. However, the concept of the discretization of structures into small simple objects that swarm and self-organize, creating different complex shapes, offer more potential in terms of flexibility of reconfiguration and ease of construction. A good example of this approach is Harvard's Kilobots (Rubenstein et al. 2014).

Nevertheless, the bots are still relatively expensive to fabricate and require a lot of maintenance. The research done in the project fills the gap in terms of creating passive simple agents that could be cheaply mass-produced. Using material computation, one can design local intelligence to perform different global goals. Having reconfigurable granular systems could have multi-scale applications from microrobotics to architecture (Dierichs and Menges 2012).

BACKGROUND

Biological Inspirations

The project has three main driving biological inspirations: self-assembly, for understanding interparticle interaction strategies, plankton, for their geometric complexity and variation, and the structure of molecules, as an inspiration for phase change. Understanding how self-assembly works in nature, and the study of biological examples where shape has a great effect on self-assembly, was crucial in the investigation process. The agents' shapes and surface chemistry could control the packing behavior, selectivity, and dynamics of the self-assembled biological structures (Cademartiri et al. 2012). Some of these strategies are furthermore implemented in the research. Plankton are creatures that drift with water currents, which is a perfect analogy for the passive agents in question, as they drift together and cluster to form beautiful mesmerizing formations (Sardet 2015). During Victorian-era expeditions, the geometric complexity of plankton was thoroughly studied and documented (Haeckel 1998). From these drawings and analysis, the complex geometry of their microscopic shapes could be expressed as the assembly of three components: the nucleus, the shell or body, and the flagella that help in the drifting and interlocking of the individual plankter to one another (Figure 1). The third biological inspiration is molecules, and in particular, water molecules. The individual molecules have a constant shape and distinct polarities, but with different molecular configurations and grid structures, the whole system starts to have different properties and transforms from a gaseous to a liquid to a solid state. The same analogy would be used later to describe the agents' systems when transformed into different global states.

Precedents

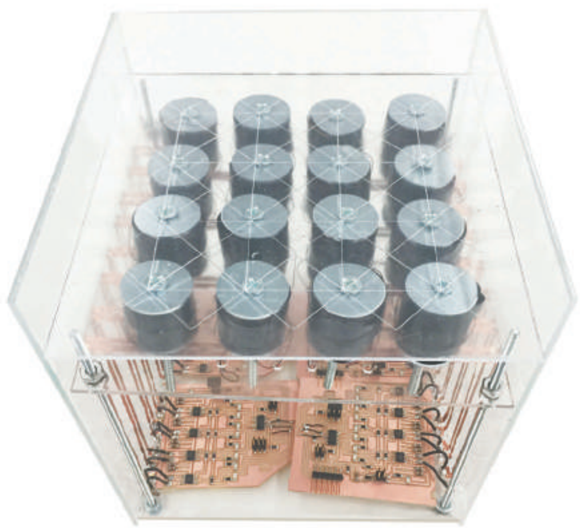
The effect of the shape of particles on overall structural behavior has been studied by a number of researchers, either to achieve the greatest packing fraction or to create granular material with special properties (Duran 2012; Pöschel 1998). Although complex non-convex shapes could provide more opportunities for creating interlocking or entanglement behavior, there are limitations and complications in regards to the modeling of interparticle forces. Therefore, advances in digital fabrication and rapid prototyping made it easier for the physical experimentation of their behavior (Athanassiadis et al. 2014). The promise of granular systems comes from the ability to transition the system between fluid and solid states on demand. The addition of interparticle attraction and repulsion forces has been proven to help in this reconfiguration (Cox et al. 2016). However, the effect of the particle shape in the rearrangement of the granular systems hasn't been systemically investigated yet.

METHODS

Actuation

When choosing the external actuation method, a number of techniques were explored to search for the optimal solution in terms of precision and large variability of movement.

The first method explored was the use of vibration to move granular material as well as other larger elements. There is existing research in the field of cymatics on how sound and vibration at different frequencies can be used to actuate small granular material to form different complex geometric patterns (Jenny 2007). As complex as the shapes seem, cymatics has been used until now as an exploration and visualization technique to understand the effect of different sound frequencies; there hasn't, however, been enough research on how to design these waves to reach specific targeted patterns. Vibration was also recently used in the actuation and movement of larger objects. A good example is the project "Cilllia," where intricate hair structures were 3D printed, and using external vibrational waves, researchers had precise control over the objects based on the 3D printed hair direction (Ou et al. 2016). Using the same technique, though, it is very hard for an object to have multiple movements using different



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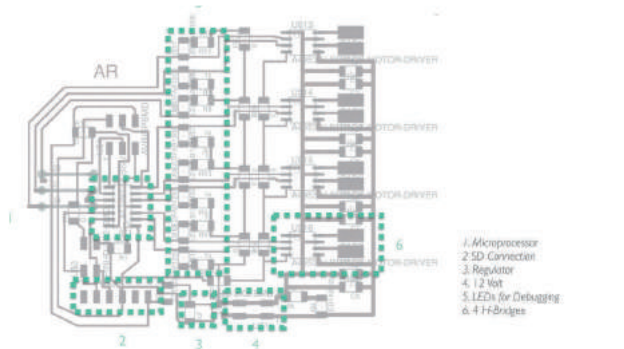

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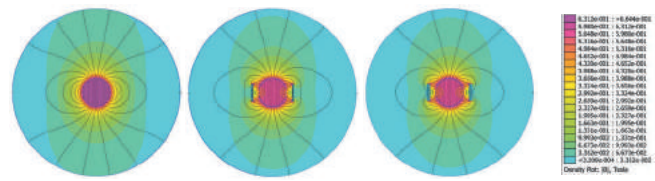

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vibrations, because the movement direction is already embedded in the 3D printed hair pattern.

The second set of actuation methods investigated were heat and humidity, as these have been heavily explored in architecture and material computation. Shape memory material, as well as the use of material swelling, offer great potential in terms of the passive actuation of objects using only the natural environment. However, most of the research conducted in this field managed to stimulate discrete singular movements in objects. The ability to use different temperature or humidity values to create different effects and movements on the same object hasn't yet been investigated.

Magnetic actuation was the third and chosen external actuation method. External magnetic actuation is now widely used in the field of microrobotics, controlling a wide range of movements like swimming, flying, and crawling (Miki and Shimoyama 2002; Honda et al. 1996; Miyashita et al. 2015). There has also been research on the independent control of multiple agents using the same magnetic field (Diller et Al. 2013). However, the control of more than one magnetic agent hasn't been thoroughly explored yet. Therefore, the research will aim to investigate the use of magnetic fields to induce swarming and clustering behaviors in small passive magnetic agents.

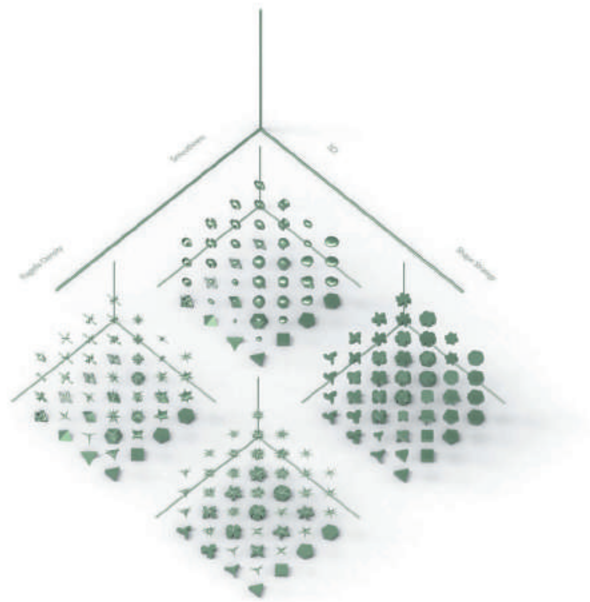
Physical Setup

The designed and constructed actuation platform is a 2D array of electromagnets (solenoids) that actuate the magnetic agents. Using this setup, a wide range of controlled movements could be generated (Pangaro et al. 2002; Hurak and Zemanek 2012). The platform consists of a 4 x 4 array of electromagnets under in a 16 *16 cm layer of clear acrylic with 2.5 mm thickness (Figure 2).

Four PCB milled boards are designed, soldered, and programmed to control the electromagnets. Each board consists of a micro-controller (ATtiny44), a regulator to regulate between the 12 V power and 5 V signal sent from the computer, and 4 H bridges that pass electricity in the 1.5 cm radius wound copper coils. The electromagnets have on average 25 Ω resistance (Figure 3). The polarity of the magnetic field on each electromagnet can be altered by changing the direction of the electric current in the corresponding H bridge, and the strength could be changed by using pulse width modulation. A computer interface was developed to control the strength and polarity of each solenoid in real time.

Digital Setup

As for the digital simulation, Unity 3D was chosen as a gaming and physics engine to calculate and visualize the collisions and forces applied on the agents. As for the electromagnetic forces calculations, the MagnetoDynamics package was used. This package simplifies the magnetic field forces calculations by discretizing the forces into infinitesimal dipoles, making it faster for a gaming engine to have a real-time simulation without compromising the accuracy of the calculations. The creation and behaviors of the objects in the system were all coded using C# scripts.



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2 Electromagnet Array.

3 Circuit Boards Design.

4 Finite Element Magnetic Simulation.

5 Agents' Shape Matrix.

Agents’ Design

In the process of designing a family of agents, influenced by the plankton anatomy described earlier, the agent system could be divided into three components for exploration: the nucleus as an analogy of the agent’s magnetic field, the flagella as an analogy of the surface friction, and the shell that describes the main geometric shape of the agent.

Shell Design: A parametric model was developed using Grasshopper and Rhinoceros 3D in order to design a wide range of objects. The performance of various objects can be tested later in terms of their effect on the global formations. In order to explore the different geometric shapes of the agents, full 3D as well as 2D extruded shapes were examined. Three-, four-, five-, and six-sided geometries were explored. For 2D extruded shapes, algorithms for generating different shape strategies (stellated, interlocking, directed) were developed. As for 3D shapes, or platonic solids, elongated and perforated polyhedra were explored. Different smoothness values were added to the shape to test the effects of smooth interactions.

Flagella Design: For the flagella explorations, an algorithm to add flagella at the corners of the shapes was developed, introducing different lengths, diameters, and end shapes to create objects that were more prone to having interlocking and tangling behaviors.

Nucleus Design: The last parameter was the most important one in the investigation, as designing the strength and polarity of the magnetic field around the agent could in some cases have a larger effect on the global formations than the shape and surface friction (Figure 5).

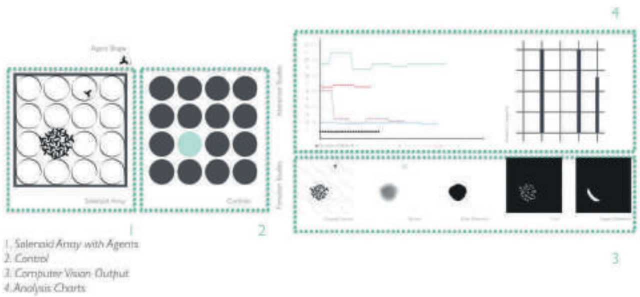
In order to study the effect of the external magnetic field on the agent, it is important to have the ability to isolate the agents from one another in order to maximize the external magnetic field effect. This will ensure maximum control over the agents. If the agents aren’t isolated, they will have a dominant clumping or repulsion behavior, and the external magnetic field would have a secondary effect in comparison. Using FEMM, finite element magnetic field simulation was implemented to study the effect of adding side magnetic shielding in an attempt to sculpt the magnetic field around the agent and minimize the agent-to-agent interactions (Figure 4). The agent design is an integrated multiphysics problem, where both the visible and invisible design factors should be rigorously crafted, as they have a great effect in the final multi-agent swarming behavior (Figure 18).

RESULTS

Digital Experimentation

To complement the physical experimentation, digital simulation environments were developed to mimic the physical setup and provide a platform where a larger number of explorations could be conducted and thoroughly analyzed.

For the 3D digital simulation setup, a replica of the physical experimental setup was first developed. The solenoids were put in a 2D array and the strength and polarity of each solenoid



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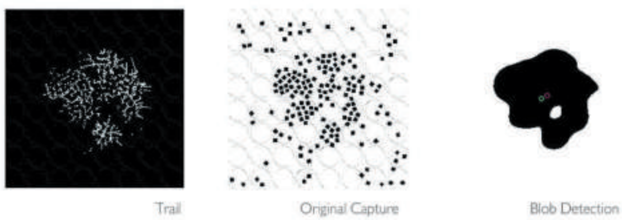

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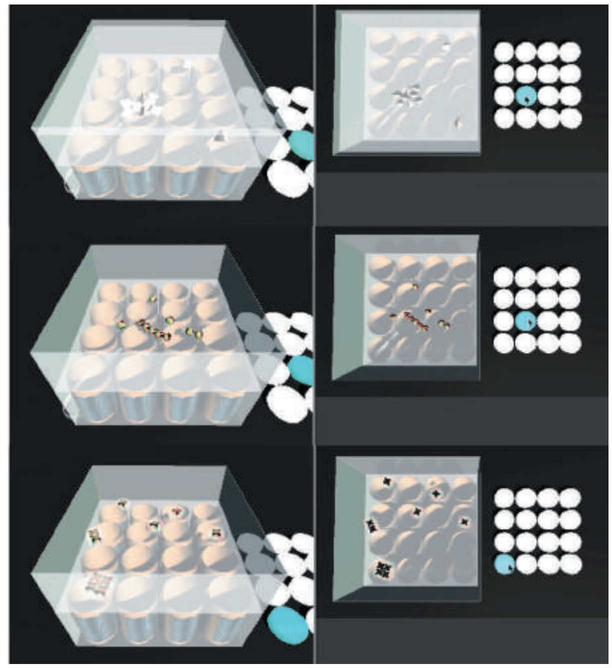

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could be controlled independently. The solenoids' magnetic fields were afterwards translated into forces applied on the magnetic agents. A large variety of agents were tested with different shapes and magnetic properties. In the 3D simulation environment, agents with magnetizable material with different strengths were tested. The magnetic field from the solenoids tended to cause the translation of the agents, and the 3D rotation and packing of the agents were a result of the collision forces between them. The change of the polarity of the solenoids had very little effect on the forces on the agents.

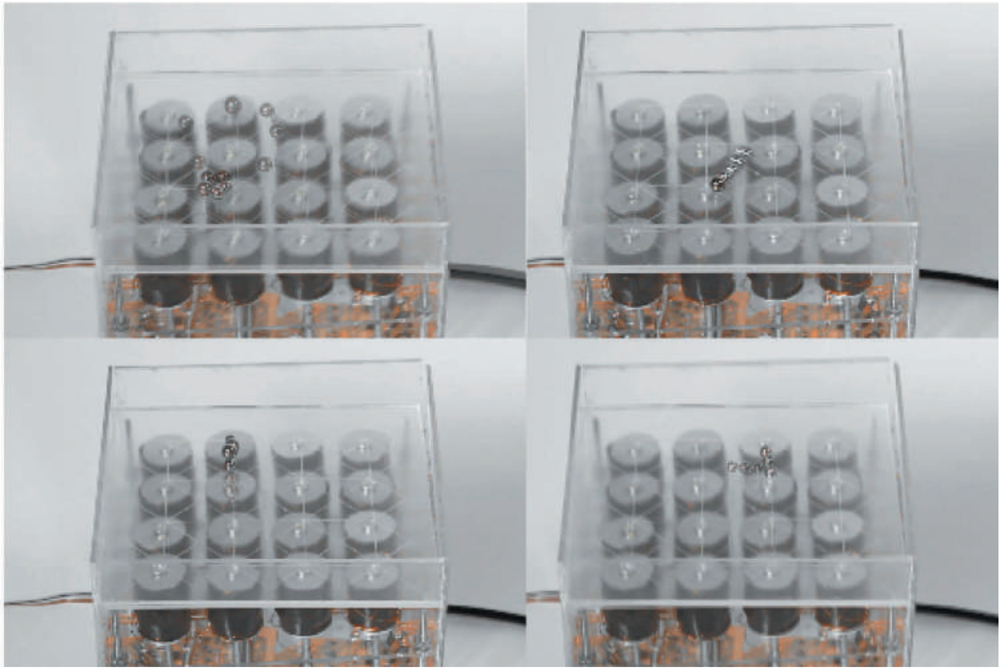
The second set of experiments were with agents with one centralized magnetic dipole to evaluate how the agents behave with and without the external magnetic field. In these experiments the external solenoid's strength is set to be higher than the dipole magnetic strength in order for it to be strong enough to obstruct the interaction between the agents. In this case, the solenoids' polarity had a great effect on the torque and forces applied on the agents. The agents were set to be in random positions at the beginning, and the ones that were close enough clumped together, creating linear and circular anisotropic formations. When the external magnetic field was on, the agents rotated and moved to reach the most stable state. The collision between the agents was minimal, because neighboring agents have repulsion forces between each other as they tend to have the same orientation and polarity. Once the external field was turned off, the agents returned to the initial clumping behaviors.

The last set of experiments was with agents that had multiple distributed magnetic dipoles. When the external field was on, the agents tried to clump together, and the different clusters had in-plane rotation behavior. Once the external field wa off, the rotation stopped.

A notable problem with the 3D agents' simulation is that when the number of agents increases, so does the time needed to calculate the heavy 3D physics collisions calculations, making it hard to have an interactive real-time simulation of the agents' behavior. Therefore, in order to study the formations of a larger number of agents, another 2D digital simulation environment for 2D extruded shapes was developed. All the magnetic forces and torques were transformed into 2D forces and in-plane rotations. The weight of the agents was translated into surface friction between the agents and ground plane.

The 2D simulation tested a large number of 2D agents with magnetic material (Figure 8). For the simulation to be similar to the physical setup, the solenoids were only strong enough to move agents that were in a radius equal to the solenoids' spacing. A clustering/packing algorithm for the solenoids' control was generated. Since the simulations always started with a random scattering of agents, at the beginning all the solenoids were turned on, and at each time-step (dependent on the agents' strength, weight, and size), one of the outer open solenoids will be turned off until only one central solenoid is on.

In order to analyze the clustering and formations behavior, different evaluation criteria were calculated. The first set of



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6 2D Digital Experimental Setup.

7 Clustering and Reconfiguration Analysis.

8 3D Digital Experimentation and Setup.

9 Initial Physical Experimentation.

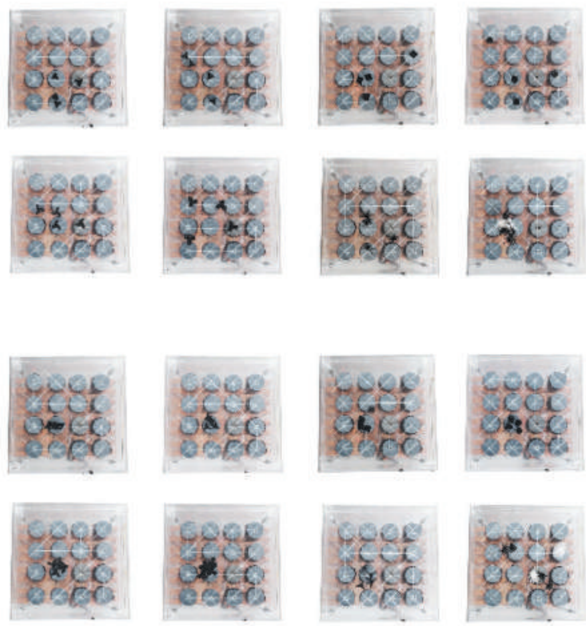
evaluation criteria to describe the agents is the pre-jamming state (Figure 6). Firstly, the rotation category R is defined as the number of dominant relative rotations between the agents. For example, for 4- and 6-sided symmetric agents there is mainly 1 dominant rotation where all agents have the same relative in-plane rotation. By contrast, 3- and 5-sided shapes have 2 dominant rotations. Secondly, the agents' trails are drawn and analyzed to deduce the speed and type of movement of the agents. Each vertex of the trail curve is added at a fixed distance (2 mm) from the vertex preceding it and stays for a fixed amount of time (5 seconds) before it is removed. This setup helps in the calculation of the average speed of the agents by getting the average length of the trails, and the type of agent movement is calculated by analyzing the curvature of the trail curve. When the average curvature of the agent trail curve is high, it means that the agent's movement is a rotational movement, and when it is low, it means that the movement is a linear translation movement (Figure 7).

Using OpenCV (Bradski 2000), at each simulation frame, a blob detection algorithm is implemented. The blobs are the first representation of the system in a fluid state where concepts like flow, viscosity, and ease of reconfiguration could be described. At each frame rate, the number, area, and inertia of the blobs is calculated.

The jamming of the system could have been detected by using some of the evaluation criteria discussed earlier. When the agents are in the solid state, they have slow rotational movements and all blobs converge into one circular blob. Once jammed, other criteria like the packing fraction and contact number, which are often used to described jammed granular materials, are computed. The packing fraction is calculated by dividing the total area of the agents over the area of the blob. The contact number is deduced using Unity3D's collision detection and the average number of agents in contact at a certain time is calculated.

Table 1: Clustering Analysis Examples

Number of Sides	Shape Type	Rotation Category	Packing Fraction	Contact Number	Reconf-igutaion
3	Basic	2	0.72	4.1	0.80
4	Basic	1	0,72	4.5	0.71
5	Basic	2	0.73	5.2	0.68
6	Basic	1	0.70	6.1	0.65
3	Stellated	More	0.64	5.1	0.60
3	Chiral	More	0.67	4.1	0.55
4	Smooth Interlock	1	0.68	4.8	0.69



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10 Clustering Experimentation.

11 3D Printed and Casted Agents.

12 Magnetic Shielding.

Physical Experimentation

The physical setup was first tested to see the solenoids' control over the movement of a single element and a cluster of 5 mm sphere magnets. The ability to create translation, as well as in-plane and out-of-plane rotation using a different number of ball magnets. In addition, a solenoid set-of-actions was achieved (Figure 9). Two methods of mass production to fabricate custom agents' designs were then explored: 3D printing and casting.

In order to test the family of agents modeled earlier, a number of agents were 3D printed using iron-based PLA filaments, however, the solenoids didn't have enough strength to move them (Figure 11). Therefore, the next set of 3D printed agents were fabricated with a non-fixed 3 mm diameter sphere magnet embedded inside (Figure 12). Eight layers of 0.025 mm low carbon steel sheets were inserted to decrease the agent-to-agent interaction and make them move independently from each other. A set of agents with different shape strategies and different flagella densities were fabricated, and the clustering algorithm for the solenoid array was implemented to test how closely aligned the physical clustering of the agents was to the digital ones. The clustering behavior was to a great extent aligned with the physical experiments, validating the digital experimentation results.

In order to visualize and understand the agent-to-agent jamming stresses, soft agents with magnetic cores were cast with different sizes. Clear polyurethane was used as a casting material because of its photoelastic property, wherein the stresses can be visualized using polarized film (Figure 13). These agents, however, were relatively heavy and had too much friction with the acrylic base. Therefore, they couldn't be actuated using the constructed solenoid array. The stresses between the magnets could nevertheless still be seen. A new set of soft agents were fabricated afterwards with with the goal of investigating the potential of soft coupling between the agents (Figure 14). Two prototypes were designed and fabricated: a grid and a star soft network of agents. The external magnetic field caused a wide variety of subtle movements. Twisting, rotation, and elongation movements were amplified by the stress visualization (Figure 15). These explorations have a high potential for the future investigation of external actuation in different networked surfaces.

REFLECTION

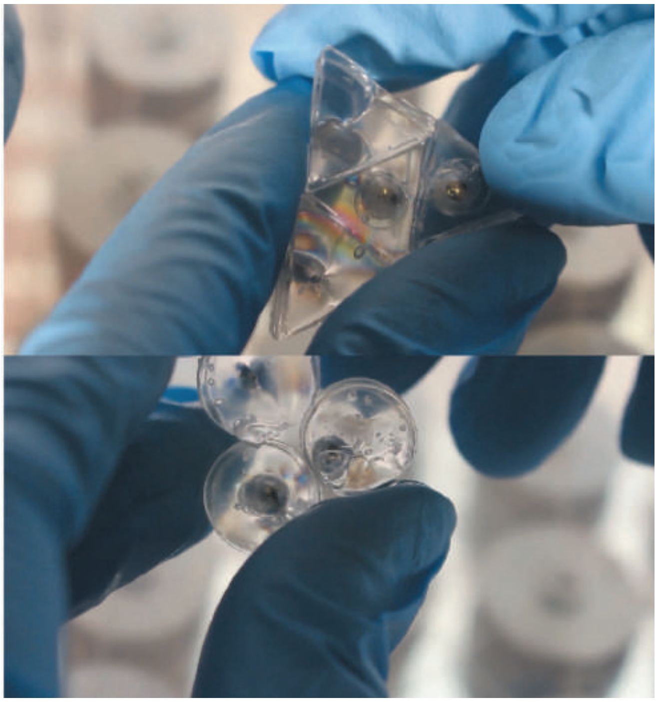
As a reflection of the various physical and digital experiments conducted, a taxonomy of the different agent design parameters and their effect on the global clustering and formations behaviors was developed.

Parameters

The main three parameter categories as discussed earlier are the nucleus, flagella, and the shell. Firstly, the nucleus parameters are the strength, polarity (fixed, free and metal), magnetic shielding, and distribution the magnetic dipoles. The flagella parameters are the density, length, range, and shape. Finally, for the shell, the relative size of the nucleus in relation to the shell, its weight, shape, and chirality were the final variables explored (Figure 16).

Effects

In terms of nucleus parameters, the magnetic field strength has a large effect on the speed of the agents, as well as their flow (liquid state), their deceleration, and the effect range of the solenoids. The polarity of the agents, if fixed, could cause



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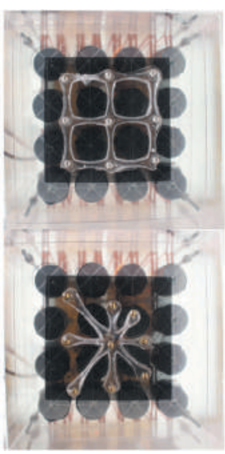

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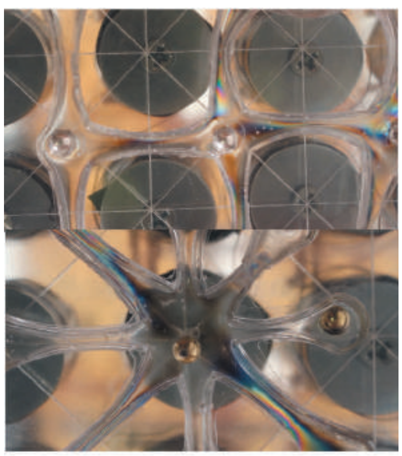

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13 Soft Agents.

14 Networked Agents

15 Closeup of the photo-elastic effect due to stress and strain.

the individual elements to flip, or could cause cluster to have in-plane or out-of-plane rotations or hovering behaviors. The shielding of the agents' nucleus minimizes the agent-to-agent interaction, which reduces the ability of the agents to reconfigure/move when the external actuation field is turned off. When the agents have a centralized magnetic dipole, the dominant external forces on the agent are linear, and the packing is mostly based on the shape of the agent. If the dipoles are on the other hand distributed and non-centralized, there are more complex forces applied on the agent because of the different dipole polarization, causing torque. Moreover, when the dipoles are near the edges, the agent-to-agent attraction and repulsion forces have a higher impact during the agents' packing.

The flagella variations have a large effect on the ability of the cluster to reconfigure from one shape to another. Having higher flagella density increases the surface friction, causing a more difficult reconfiguration. If the flagella have an "arrow" interlocking shape the ability to reconfigure is very low. Moreover, the number of flagella in contact with the bottom side of the agents could increase or decrease the friction between the agent and ground layer, thus decreasing the speed of the agents.

Lastly, analyzing the parameters under the shell category, the relative size of the shell in relation to the nucleus distances the nucleus from the effect of the external solenoids, which has the same effect on the agents as changing the nucleus strength. The weight of the shell impacts the range and time needed for the solenoids to move the agents. The shape of the agents, as discussed earlier, has a great impact on the rotation category, contact number, and packing fraction. Lastly, introducing agents with different chiralities could cause selective clustering (Figure 17).

CONCLUSION

In conclusion, the project offers a systemic investigation of the effect of shape, interparticle forces, and surface friction on the packing and reconfiguration of granular systems. Using advancements in nanofabrication technologies, one will be able to fabricate a large number of nanoagents, which will facilitate the ability to change system states from gaseous to liquid to solid state. This will in turn offer new possibilities in the field of material computation, where one can design a "material" and change its properties on demand. Using the deducted reconfiguration principles to design desired distributions is part of the forthcoming research.

The next steps also will be to explore the three-dimensional control of the agents to reach 3D formations. The use of more passive environmental actuation techniques like temperature and humidity could also be explored to increase the applicability of the system. The applications of having shape-morphing objects are endless and could be applied in different fields like medicine, material science, and even architecture, causing a paradigm shift in the manufacturing industry into a bottom-up production process.

REFERENCES

Athanassiadis, Athanasios G., Marc Z. Miskin, Paul Kaplan, Nicholas Rodenberg, Seung Hwan Lee, Jason Merritt, Eric Brown, John Amend, Hod Lipson, and Heinrich M. Jaeger. 2014. "Particle Shape Effects on the Stress Response of Granular Packings." *Soft Matter* 10 (1): 48–59.

Bradski, Gary. 2000. "The OpenCV Library." *Dr. Dobb's World of Software Development*, online at http://www.drdobbs.com/open-source/the-opencv-library/184404319.

Cox, Meredith, Dong Wang, Jonathan Barés, and Robert P. Behringer. 2016. "Self-Organized Magnetic Particles to Tune the Mechanical Behavior of a Granular System." *EPL (Europhysics Letters)* 115 (6): 64003.

Dierichs, Karola and Achim Menges. 2012. "Aggregate Structures: Material and Machine Computation of Designed Granular Substances". *Architectural Design* 82 (2): 74–81.

Diller, Eric, Joshua Giltinan, Prakjit Jena, and Metin Sitti. 2013. "Three Dimensional Independent Control of Multiple Magnetic Microrobots." In *Proceedings of the 2013 IEEE International Conference on Robotics and Automation*. Karlsruhe, Germany: ICRA. 2576–2581.

Duran, Jacques. 2012. *Sands, Powders, and Grains: An Introduction to the Physics of Granular Materials*. Cham, Switzerland: Springer.

Haeckel, Ernst. 1998. *Art Forms in Nature: The Prints of Ernst Haeckel.* Munich: Prestel.

Honda, T., K.i. Arai, and K. Ishiyama. 1996. "Micro Swimming Mechanisms Propelled by External Magnetic Fields." *IEEE Transactions on Magnetics* 32 (5): 5085–5087.

Hurák, Zdeněk and Jiří Zemánek. 2012. "Feedback linearization approach to distributed feedback manipulation." In *Proceedings of the 2012 American Control Conference*. Montreal, QC: ACC. 991–996.

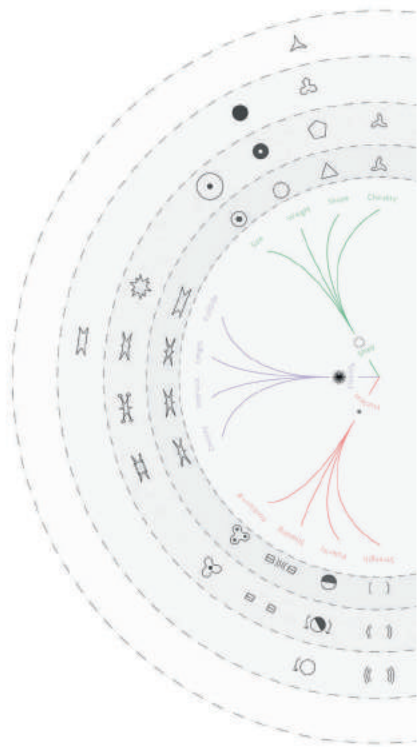
Jenny, Hans. 2007. *Cymatics: A Study of Wave Phenomena and Vibration*. Epping, NH: MACROmedia.

Lee, Jinha, Rehmi Post, and Hiroshi Ishii. 2011. "ZeroN." In *Proceedings of the 24th Annual ACM Symposium on User Interface Software and Technology.* Santa Barbara, CA: UIST. 327–336.

Cademartiri, Ludovico, Kyle J. M. Bishop, Phillip W. Snyder, Geoffrey A. Ozin. 2012. "Using Shape for Self-Assembly". *Philosophical Transactions of the Royal Society* 370 (1969): 2824–2847.

Miki, N., and I. Shimoyama. 2002. "Dynamics of a Microflight Mechanism with Magnetic Rotational Wings in an Alternating Magnetic Field." *Journal of Microelectromechanical Systems* 11 (5): 584–591.

Miyashita, Shuhei, Steven Guitron, Marvin Ludersdorfer, Cynthia R. Sung, and Daniela Rus. 2015. "An Untethered Miniature Origami Robot that Self-Folds, Walks, Swims, and Degrades." In *Proceedings of the 2015 IEEE International Conference on Robotics and Automation.* Seattle, WA: ICRA. 1490–1496.



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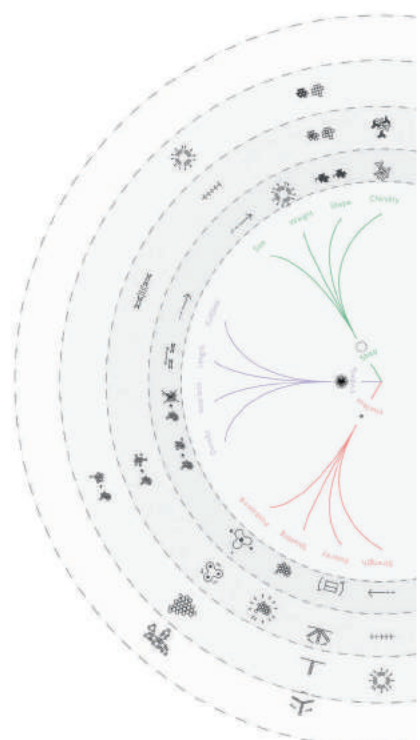

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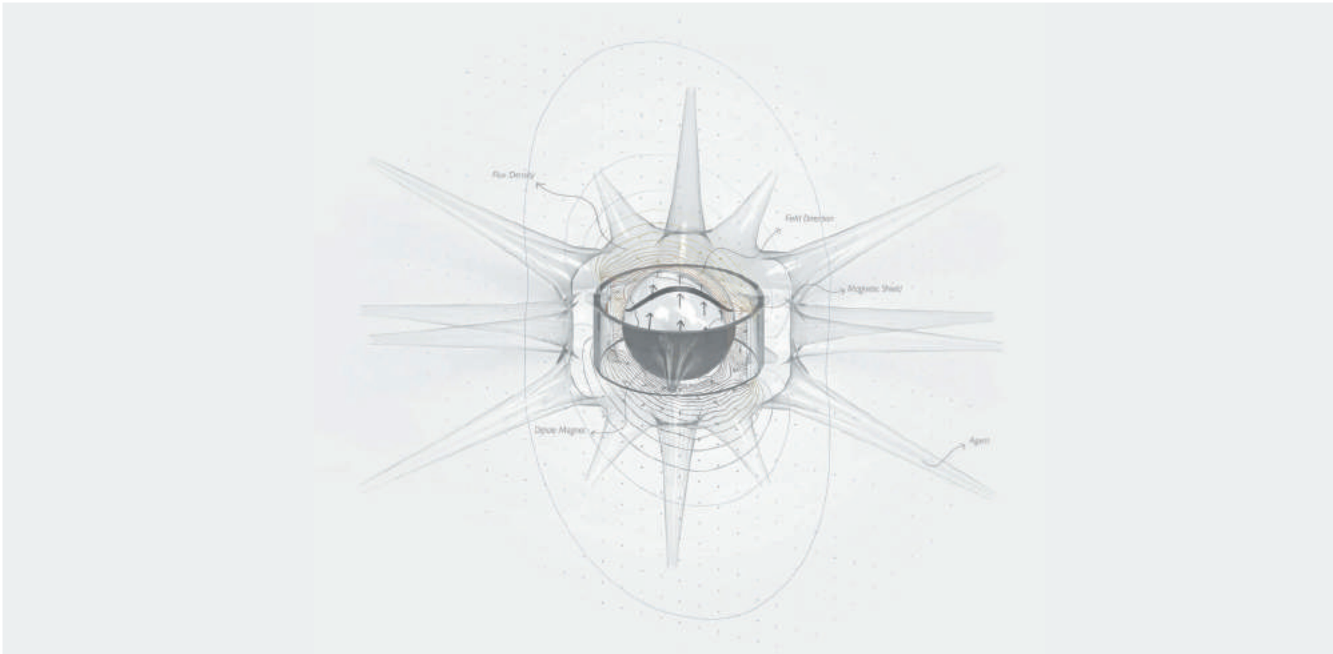
16 Parameters Taxonomy.

17 Effects Taxonomy.



18 Agent Anatomy.

Ou, Jifei, Gershon Dublon, Chin-Yi Cheng, Felix Heibeck, Karl Willis, and Hiroshi Ishii. 2016. "Cilllia: 3D Printed Micro-Pillar Structures for Surface Texture, Actuation and Sensing." In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*. San Jose, CA: CHI. 5753–5764.

Pangaro, Gian, Dan Maynes-Aminzade, and Hiroshi Ishii. 2002. "The Actuated Workbench.: Computer-Controlled Actuation in Tabletop Tangible Interfaces." In *Proceedings of the 15th Annual ACM Symposium on User Interface Software and Technology.* Paris: UIST. 181–190.

Pöschel, Thorsten, and Thomas Schwager. 2010. *Computational Granular Dynamics: Models and Algorithms*. Berlin: Springer.

Rubenstein, Michael, Alejandro Cornejo, and Radhika Nagpal. 2014. "Programmable Self-Assembly in a Thousand Robot Swarm." *Science* 345 (6198): 795–799.

Sardet, Christian. 2015. *Plankton: Wonders of the Drifting World*. Chicago: University of Chicago Press.

IMAGE CREDITS

All drawings and images by the authors.

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