Jamming Formations

Intuitive design and fabrication process through human-computer interaction

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This paper examines the potential of User Interfaces (UI) and sensor feedback to develop an intuitive design and fabrication process utilizing granular jamming. By taking advantage of the variable stiffness of granular jamming over time, an adaptive fabrication process is presented in which various structures are formed from individual jammed components which can weave or interlock in an overall system. A User Interface (UI) is developed as a design tool which would enable interactive design decisions and operations, based on pre-designed formal and tectonic strategies. The project has four research trajectories that are developed in parallel: (1) material system research; (2) development of an ad hoc digital recording system; (3) creation of a computational library that stores users` iterations; and (4) development of a User Interface (UI) that enables users' interaction with the computational library.

Keywords: *Granular Jamming, Human-computer Interaction, Adaptive Fabrication*

INTRODUCTION

While significant progress has been made on simulation technologies, such as finite element analysis, there are still material processes which are difficult to digitally represent, simulate and predict, such as granular and fibrous materials (Daviet 2016). In the past, materials with more complex behaviors than traditional engineering materials were intuitively used by pre-industrial craftsmen, who learned how to work with them through trial and error (Carpo 2017). Craftsmen had to take the complexity of matter into account because the available materials were heterogeneous (DeLanda 2001). Through direct interaction with them, humans evolved a heightened ability to sense and manipulate the physical world (Ishii et al. 2012), which led them to develop a strong connection with the nature of matter and behavior of material systems (Alexander 1999).

Today, human ability to intuitively manipulate materials can be enhanced by computational powers of iteration and intelligence, suggesting a new model of design and construction where “humans, devices

Figure 1
Assembly process for wall prototype using granular jamming.

and their shared environments might coexist in a mutually constructive relationship" (Haque 2007). Through digital recording of artistic processes and outcomes, a computational process might "learn" from human's inherent intuition with materials, and their fine motor control and cognitive abilities (Lafreniere et al. 2016). At the same time, a designer might benefit from the computational ability to calculate or generate infinite variations with speed. This bi-directional and reciprocal learning process, where the human learns from the computer, and vice versa, can lead to an understanding of how we can work iteratively between digital and physical tools and environments towards new materialities. The use of such workflow can result to the generation of unexpected designs, which may not have been able to be conceptualized or represented with a purely digital, or purely physical workflow alone.

To investigate these potentials, this research focuses on the development of an intuitive design and fabrication process for granular jamming, a material system with very complex, unpredictable and emergent behavior (Herman 2013), using a set of processes and tools for Human-computer Interaction (HCI). Jammed, discrete elements which are formed intuitively by hand are digitally analyzed, recorded and stored in a computational library.

BACKGROUND

Granular Jamming

Granular jamming is the physical process by which particles can transition between a liquid-like and a solid-like material state (Steltz et al. 2009). When the free volume between the particles is large enough to allow mobility (Jaeger 2015), the object feels soft and malleable. In this project, stiffness is achieved by applying vacuum into the membrane that contains the particles. The ability to switch between soft and rigid material states enables novel interactions for organic shape-changing interfaces and haptic feedback (Ou et al. 2013). An example is the ShapePhone by Tangible Media at MIT (2012), a mobile device that can be formed into different jammed shapes, which can transform from a phone to a watch, or a game controller (Follmer et al. 2012). Granular jamming is also broadly used in soft robotics and grippers because it enables soft robots to safely collaborate and interact with users. The Universal Robot Gripper by Cornell University (2012) is a single mass of granular material that can be pressed onto an object, conform to its shape and when vacuum is applied it shrinks, hardens and grips it (Amend et al. 2012). An effort to bring granular jamming to an architectural scale was conducted by Lucy McRae and Skylar Tibbits (2015). Their project Jamming Bodies demonstrates the ability of granular jamming to change states from solid to liquid and maintain shape in large scale (Tibbits 2015). However, the result exposes the design limitations of the system when working with large scale volumetric elements that do not allow big deformations.

Human-computer Interaction (HCI) in Design and Fabrication

Human-computer Interaction (HCI) has been a fundamental element of Computer-aided Design (CAD) technologies since its foundations in the 1960s. In CAD, computer systems are used to assist designers and increase their productivity. One of the first examples is the Sketchpad, a system that uses line drawings to enable human-computer communication (Sutherland 1964). However, only recently computers achieved the goals that were set in the past, of augmenting the design process, instead of just executing mechanical and accounting tasks (Negroponte 1975). Today, with the use of User Interfaces (UI), the communication between humans and computers becomes intuitive and fast, enabling their direct collaboration in design decision making. The project Making Gestures explores the possibilities of design and fabrication through real-time HCI by using body gestures to establish a dialogue between the human and the fabrication machine (Pinochet 2015). In a different way, in the project HIVE human-robot collaboration is achieved through a wearable interface that provides fabrication and assembly instructions to non-expert users, enabling them to participate in the production and construction of a robotically fabricated structure (Vasey et al. 2016).

Research Aims

This research aims to investigate new protocols for interacting and designing with granular jamming using principals from HCI, in order to enhance the ability to design intuitively with a material system which is extremely difficult to simulate and predict. The ability of granular jamming to switch between soft and rigid material states allows an intuitive forming process and provides the possibility of generating various designs. This variability of designs coupled with sensing technology enables the recording and processing of multiple design iterations. The recorded information is stored in a computational library through a UI (Figure 2). The integration of material and software leads to a highly adaptable and open-ended construction system. This system offers easy fabrication and high variability of forms, taking advantage of both continuous and discrete design processes.

METHODS

Material System

In this research, a membrane filled with free aggregates is used for granular jamming. A series of experiments is conducted in order to determine the most performative membrane and aggregates. The criteria for choosing the materials are: (1) the ability to be formed easily and quickly by the user; (2) the stiffness transition between the soft (fluid-like) and the stiff (rigid-like) material states; (3) the ability of the system to achieve and maintain any given shape with small tolerance; (4) the ability to be sealed and remain stiff after stopping applying vacuum to the membrane; and (5) the sustainability and recyclability of the materials.

Thermoplastic materials such as Polypropylene (PP), High-density Polyethylene (HDPE), Ethylene Tetrafluoroethylene (ETFE) and Polyvinyl Chloride

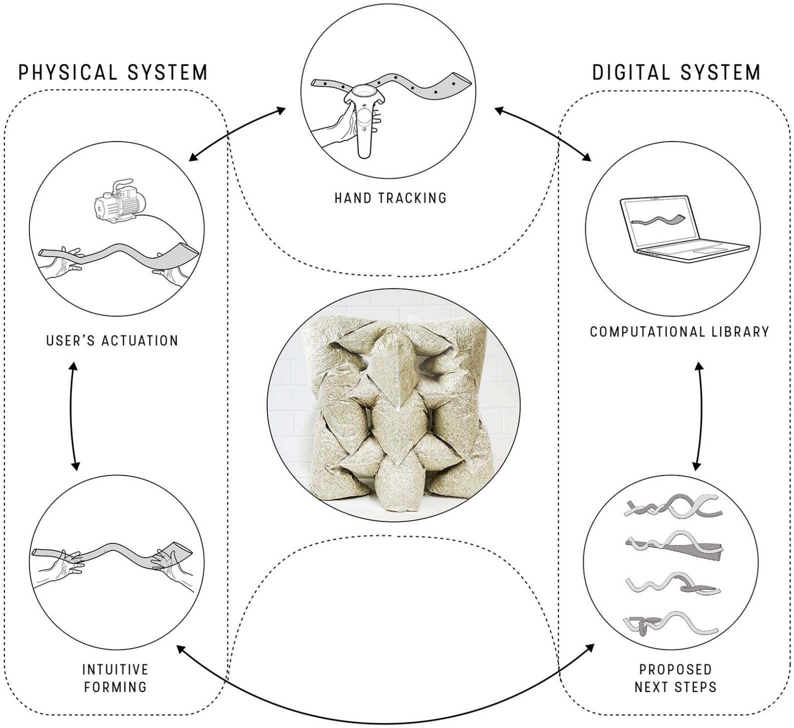


Figure 2
Design and fabrication process

(PVC), as well as rubber-like materials, such as Latex, are tested for their capacity to act as an outer membrane.

Latex achieves the largest range from soft to stiff material states, with the capability of becoming a stiff and stable structure. However, because Latex is not a thermoplastic material it is difficult to seal and thus requires a constant vacuum to maintain a stiff state. Among the thermoplastic materials, the most performative is the PP vacuum membrane, because it can be easily sealed avoiding any leaks and it can maintain its shape after forming. PP has the additional ecological benefit of recyclability.

Aggregates play a critical role in the performance of granular jamming because their material properties influence the degree of stiffness and stability that the system can achieve. Aggregates of different shapes, sizes and textures are tested, such as salt, wood shavings, straw and wood sticks. The most effective material in terms of strength, weight and formal stability are the wood shavings. The small size and the rough edges of the wood shavings provide big contact area among the aggregates which leads to stiff results. The lightweight properties of wood shavings allow users to easily form large components and the system to be scaled up and create bigger

Figure 3
Family of components: (A) rectangular, (B) linear, (C) "Y" shape, (D) "H" shape and (E) "U" shape.

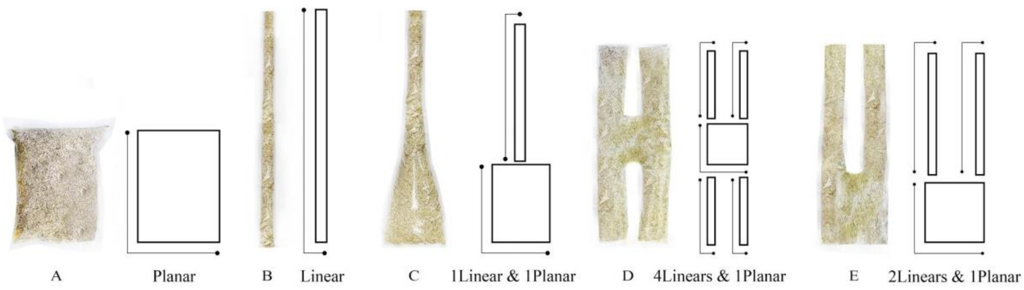
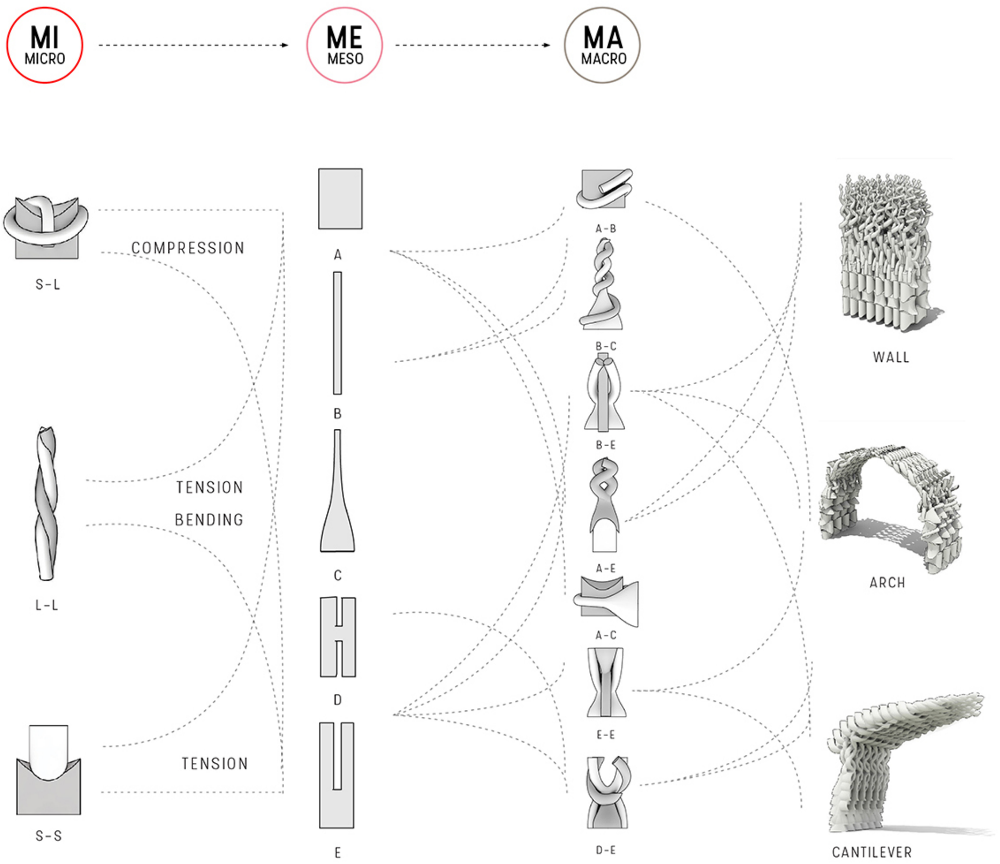


Figure 4
Interscalar design strategy for micro, meso and macro scale



can be found as a byproduct.

Thus, the material system consists of a Polypropylene vacuum membrane filled with wood shavings. Four main processes need to take place for the fabrication of the system: (1) cutting the membrane into the desired shape using a knife or cut plotter; (2) sealing the edges of the cut membrane with a flat iron to form a cushion; (3) filling the membrane with aggregates; and (4) sealing the membrane after the system is vacuumed.

Design of Components

Human scale and lightweight components are designed to enable the fabrication of intuitive and fast formations. These components vary in sizes and shapes offering different performances, form variations and tectonic connections after shaping. More specifically, they consist of linear and planar parts, arranged in different configurations. The thin, linear parts of the components are light, easy to form and have many form variations. On the other hand, the wide, planar parts of the components can adapt and mold in any shape and provide very stiff results. Although this family can be extended indefinitely, for the scope of this project five geometric patterns are chosen: the rectangular, the linear, the "Y," the "H" and the "U" shapes. These components create a tectonic system for granular jamming and showcase the variety of designs and performances that can be achieved (Figure 3).

Interscalar Design Strategy

An interscalar design strategy for granular jamming is developed to assemble the components into larger structures (Figure 4). This strategy is not a fixed design proposal, but rather an open system that keeps being developed when more users utilize it. The design system runs at different scales, starting from the micro scale of the connections between components, going to the meso scale of forming typologies and the macro scale of assembly techniques.

Adaptive Connections. In the local scale, three types of connections are developed based on the properties of the material system. These connections depend on the size of the connected parts and can be divided in these categories: (1) thin-with-wide part, the wide part acts as a mold for the thin one, surrounds it and locks it in place; (2) wide-with-wide part, the two parts mold into each other; and (3) thin-with-thin part, the parts are intertwined and interlock with themselves (Figure 5).

Figure 5
Physical prototypes of adaptive connections: (A) thin-with-wide part, (B) wide-with-wide part and (C) thin-with-thin part

Forming Typologies. The malleable components can be formed and assembled in three ways: (1) a one-dimensional linear assembly; (2) a two-dimensional planar assembly; and (3) a three-dimensional volumetric assembly. In the meso scale, the investigation focuses on how these typologies can form linear, planar and spatial structures (Figure 6). These forming typologies indicate the growing behavior of the structures and imply global design possibilities.

Assembly Techniques. Three assembly techniques are implemented, by combining the forming typologies in various manners. The first technique is weaving, which consists of linear and volumetric elements and has a horizontal growth logic. Each volumetric element is interlocked with its neighboring one while the horizontal linear elements run through them (Figure 7A). The second technique is interlocking, which consists of planar and volumetric components that lock themselves in all directions. The fabrication process follows a bottom to top sequence (Figure 7B). The third technique is intertwining, which combines linear and planar elements and has a vertical development. This technique requires that linear elements are intertwined with themselves and then planar elements bring them together by forming loops around them (Figure 7C).

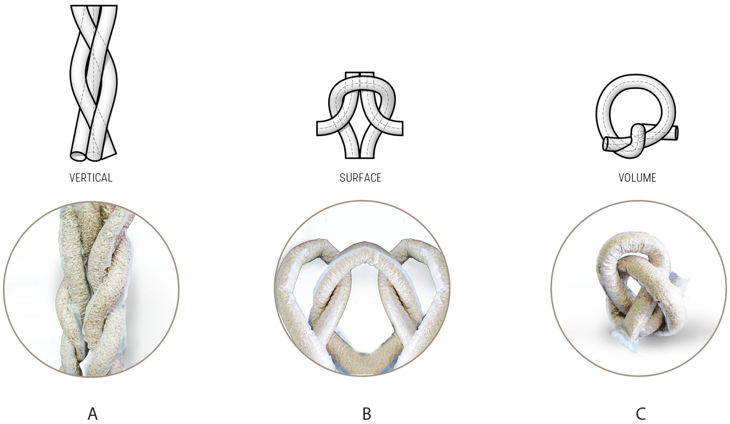


Figure 6
Physical prototypes of forming typologies: (A) one dimensional linear assembly, (B) two dimensional planar assembly and (C) three dimensional volumetric assembly.

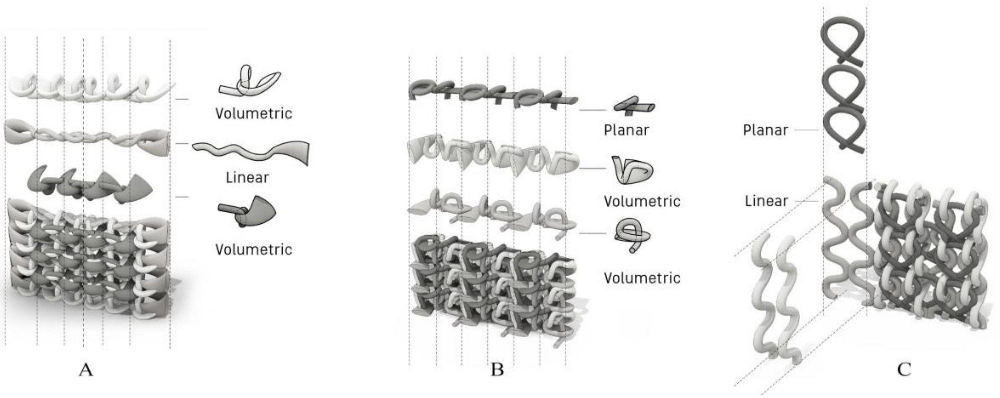


Figure 7
Digital models of assembly techniques: (A) Weaving, (B) Interlocking and (C) Intertwining.

Bending and Compression Tests

Various components and connections behave differently under specific structural loads. A series of structural tests are conducted to explore the possibility of creating larger structures with granular jamming. Each connection type is tested under specific loads, according to their expected best performance in bending and compression. A linear component and a thin-with-thin connection are tested in bending, while a rectangular component and a wide-with-wide connection are tested in compression (Figure 8).

For the three-point bend test, specimens of 30 cm x 10 cm x 2 cm are prepared and the maximum load is 60 N. For the compression tests, the specimens' size is10 cm x 10 cm x 6 cm, reaching a maximum load of 10.000 N. In all of these tests, there is a fast and large deformation of the components. However, because of the elasticity of the membrane, the material system does not fail through ripping.

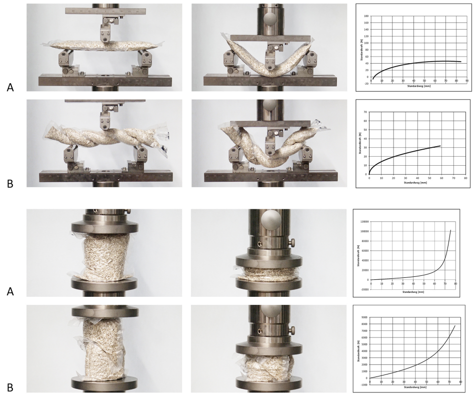


Figure 8
Bending tests: (A) linear component, (B) thin-with-with connection. Compression tests. (A) volumetric component, (B) wide-with-wide connection

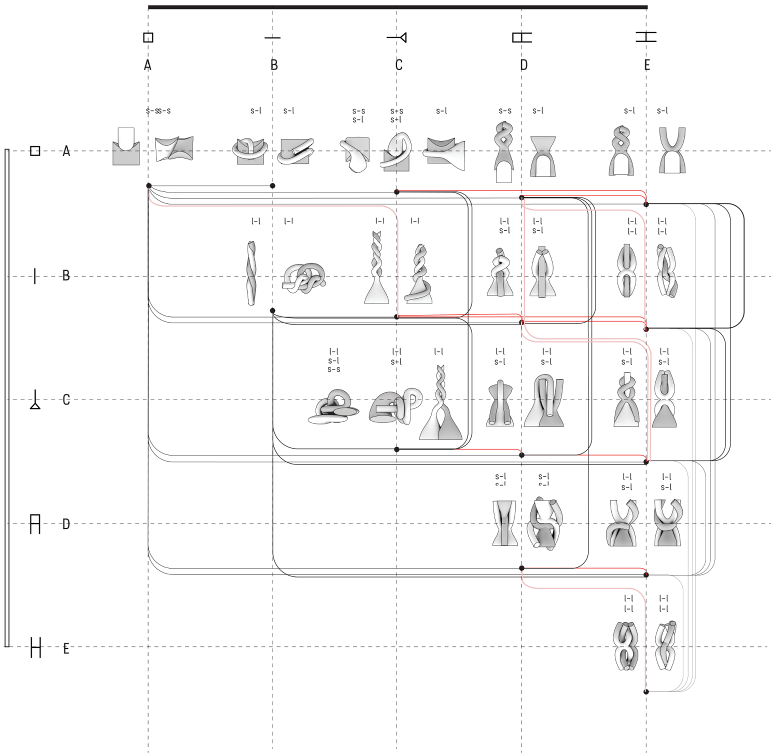


Figure 9
Matrix of all possible aggregations

Global Design Possibilities

The results from bending and compression tests and our design strategies are compiled into a matrix to showcase all possible aggregations and connections within these variables (Figure 9). This matrix is used for a series of digital and physical models that examine the potential of the system to create various structures with different architectural and structural qualities. These typology studies include a wall, an arch, a cantilever (Figure 10) and they also examine the possibility of these typologies to adapt to an existing context. For these typologies, volumetric rectangular components are placed at the bottom with wide-to-wide connection because of their compression strength. On top of them, the "H," "Y," or "U" shape components are used because they are able to take bending moments and make a transition to the linear components which are placed on top. Linear components are placed on top because they are the lightest and can create a gradient of porosity. In cases in which the overall form of the structure creates high tension, such as in the cantilever, linear elements are tightly intertwined. Finally, granular jamming allows the structures to adapt to different existing environments and boundary conditions. The linear parts of the components are easily attached to existing elements, while the volumetric ones are molded on uneven terrains.

Prototypes

Two medium-scale prototypes are developed to showcase the various design potentials of the system. The first prototype is a vertical wall (Figure 11A). The design is simple since only the rectangular block component is used. The components are molded sequentially into each other, using wide-with-wide connections. The size of the blocks is 0.40 m x 0.60 m x 0.20 m, while the total size of the model is 1.00 m width x 0.40 m depth x 1.20 m tall. This structure shows the structural potential of the system and its ability to quickly construct large structures with adaptive bricks.

The second prototype is an adaptive structure that grows into an existing frame (Figure 11B). The dimensions are 1.00 m width x 0.80 m depth x 1.60 m height. The used components have a maximum length of 1.50 m and 0.40 m width, which allows them to be easily formed by the user. All the five types of components are used and they are connected in various ways with each other. The structure adapts and molds on the top part of the frame.

Figure 10
Physical prototypes of (A) an adaptive arch, (B) an adaptive wall

Figure 11
Final prototypes; a vertical wall (A) and an adaptive free form structure (B)

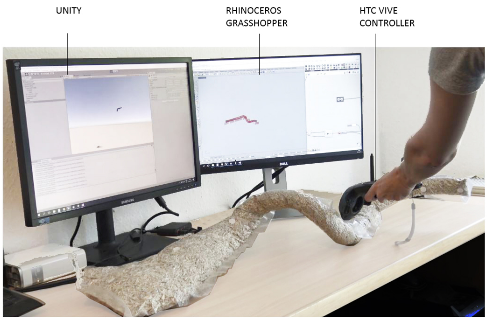


Figure 12
Physical setup for digital recording

Digital Recording

The previous design studies verified that granular jamming offers a vast amount of design possibilities because it takes advantage of both the malleable characteristics of a continuous system and the combinatorial characteristics of a discrete system. Thus, it produces a very large amount of design iterations by forming and assembling the components in different ways. By recording and storing the iterations that multiple users produce, an expanding computational library is created.

A digital recording system is developed to record every unique piece formed by the user. An HTC VIVE is used to track the user's hand when moving along the piece and encode this information from the physical to the digital environment. Although there are many recording systems that can be used, such as machine vision and positioning systems, the HTC VIVE handset is preferred because it is very easy to use, it is accurate and fast.

The components are marked with key-points on their boundaries. The user has to hold the handset and follow the piece that was just formed, pressing the handset button in every key-point. The recording happens in real-time, digitizing the position of the predefined key-points from the physical environment to Unity - the game engine platform that is compatible with HTC VIVE-. From Unity, the position of the points is transferred to the Grasshopper interface - the parametric plugin of Rhinoceros 3D modelling software - through the User Datagram Protocol (UDP) (Figure 12). These points are used by a custom computational tool to create an abstract digital model of the physical component. This tool is developed in Grasshopper using a shape matching goal algorithm. This tool requires the form of the initial unformed component as an input, imported as a mesh, and the key points of this component imported as 3d points. After receiving the new key-points from the HTC VIVE tracking method, the tool matches the initial points to the recorded ones. This process results in a digital geometrical approximation of the physical formed component.

Computational Library

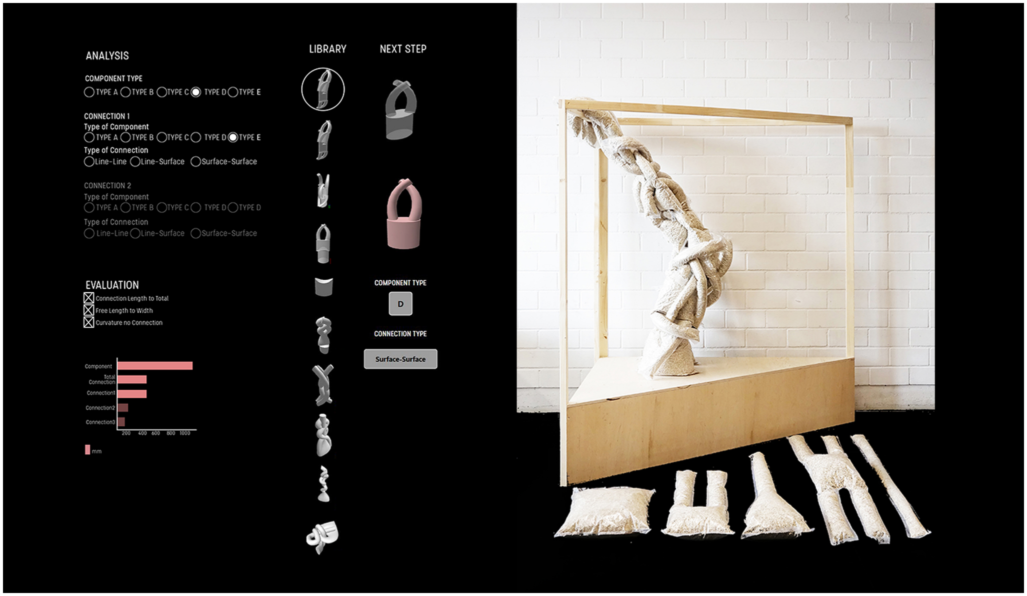
After each digital recording, the computational library analyzes, evaluates and stores the geometry of each component that is produced (Figure 13). When the recorded mesh is saved, the library runs an analysis, in which the geometry is examined according to the interscalar approach that was described before. The code identifies the location of the component in the structure at a global level, the type of component (rectangular, linear, "Y," ,"H" or "U" shape) at a meso level, and finally the types of connections (thin-with-wide, thin-with-thin, wide-with-wide) at a local scale.

The data gathered from the analysis is used to evaluate the components that are produced. There are three criteria that each iteration should ideally fulfil in order to be stored in the library: (1) the ratio of connection area with other components to the total area of the component; (2) the type of the component in relation to the structural needs of the structure at that area ; and (3) the type of connection in relation to the structural needs of the structure at that area. If these criteria are fulfilled then the iteration is stored in the library. The information that is stored in the library is the mesh geometry and all the data produced during the analysis and evaluation describing the component from global to local scale.

Development of a User Interface (UI)

A User Interface (UI) is developed which enables intuitive interaction with a computational library. Through this interface, the data that is collected from previous iterations becomes accessible to the current users. More specifically, the interface visualizes the previous design iterations and gives the user the opportunity to explore the interscalar analysis that is conducted by the computational library. In the macro scale, the user defines the typology of the structure that wants to be built, for example, a wall or an arch. The interface visualizes all the previous structures of this typology that were built before and analyzes what types of components and connections were used. According to this data, the user is free to follow some of the previous designs or to experiment with new designs that will further expand the computational library. The interface was developed entirely in Grasshopper, using the Human UI plug-in.

Figure 13
Structure of the computational library



RESULTS AND REFLECTION

The research succeeds in developing an intuitive design and construction process for granular jamming, utilizing data collection methods. Two medium-scale prototypes are fabricated, showcasing the design potentials of the material system. These structures are intuitively and rapidly fabricated while remaining low-cost and recyclable. A tracking system is developed to digitize the human creations into the digital system, as well as a computational library which is able to store these designs, and then compare and analyze them. Finally, a User Interface (UI) is developed to facilitate interaction with the background computational library during fabrication.

Regarding the material system, leaks that are caused either from inefficient sealing or tearing of the membrane damage the jammed components. In this case, although the aggregates can be reused, the membrane has to be replaced. An interesting aspect of the material system that is out of the scope of this research, is its potential reversibility. By embedding non-leaking valves on the membranes, the components could be removed, reshaped and reused at any time.

In terms of the digital recording system, the geometry generation tool is created specifically for the five components that are used. A more generalizable tool could be further developed for the simulation of more complex component geometries. Moreover, for faster and more efficient interface visualization, other programming languages such as Visual Basic or Java should be considered.

Finally, an aspect which is outside of the realm of this project is to test the success of the User Interface (UI) in transferring knowledge to users unfamiliar with the material system and fabrication process. Further research could also investigate the integration of more advanced methods of data analysis. Machine learning and artificial intelligence based on observation of the physical world can lead to an advanced bi-directional learning process between the human and the computer. Generative design tools could be implemented to suggest new unexpected designs to the users based on the data gathered from previous design iterations.

CONCLUSION

This study provides a proof of concept for an HCI system that enables new ways of intuitive design and construction with granular jamming. The broader vision of this project is to enhance architects' ability to work intuitively with unpredictable material, where intuition is not only understood as a single user's material intuition shaped by singular experiences. The recording of multiple users' experiences might enable knowledge and intuition to be crowdsourced, digitally stored, processed, and subsequently transferred. Accessibility and crowdsourcing in design processes can allow a dynamic pool of unspecified users (Lasecki et al. 2011) to contribute design iterations to a computational database. This leads to an acceleration of democratization of knowledge and craft to anyone willing to teach and learn (Lafreniere et al. 2016).

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