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Material Experiments Term Paper Spring 2019

1. Introduction

Digital materials

I will be designing and building my own reversibly assembled cellular material. It will consist of 3 dimensionally tiled discrete cellular units that, when assembled, behave like a bulk material. These types of structures expand on the concept of what a material can be. The cellular units have both structural and fastener functionality. Similar to LEGOs, the units have consistent geometry and all fasten together in the same fashion. Unlike LEGOs, the base unit cells will have octahedral symmetry. The ability to assemble and disassemble the units from each other means that the structures are highly configurable, are recyclable, can be assembled into arbitrary shapes, and can be repaired if damaged. Structures like this are considered to be digital materials because each cell is either wholly populated with a part or is entirely empty.

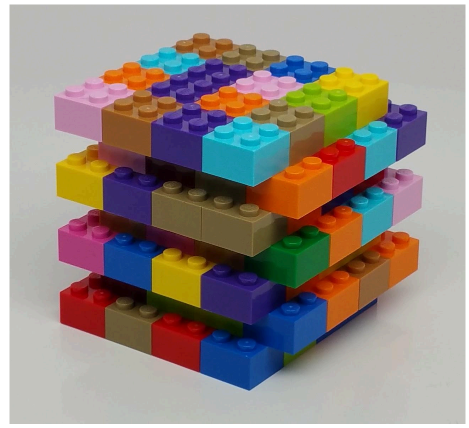

Figure 1 This assembly of LEGO bricks is made of a reversibly assembled cellular material. Note how each brick unit has the same shape.

Cellular lattice structures

Structures in the category of cellular lattice structures have recently become easier to fabricate due to advances in additive manufacturing. Cellular lattice structures are advantageous over traditional materials because they are strong and lightweight. Unfortunately, these processes usually create monolithic materials that cannot be reversibly constructed or repaired if damaged. Reversibly assembled cellular materials are assembled rather than printed, and so have the added benefit of both being able to be disassembled and also being able to be assembled to arbitrary sizes by assembler robots, unlike traditional additive manufacturing, which has strict limits on build volume because the printing must occur within a chamber.

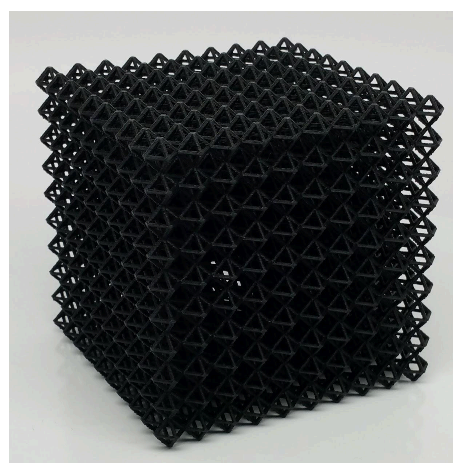

Figure 2 This 3d-printed lattice structure consists of repeated cells, but cannot be disassembled.

Properties

Reversibly assembled cellular materials lend themselves to robotic assembly. This is because they are highly structured and repeat in integer units. Robot assemblers can be relatively simple because they don't need the advanced sensing systems that robots in unstructured environments need.

The components that make a cellular unit can be flat-packed for easy transport. Assembly can be done at the site of installation. The assembly process can be performed by multiple assemblers in parallel, so the time it takes to build a structure is significantly faster than traditional serial gantry processes.

Reversibly assembled cellular materials can be assembled into almost any shape. Restrictions on this are based on the structural integrity of the shape and resolution based on the size of a cellular unit. Shapes are not limited in scale like traditional gantry based assembly process so this method can be used in truly large structures. Buildings, bridges, space structures, and vehicles like boats and planes, can potentially be constructed in a reversible fashion.

Cellular structures can be made of cells with different material properties. As long as all cells fit together, composites can be created. Traditional composites, like carbon fiber, cannot be recycled, but reversibly assembled cellular composite structures can.

Most functional objects can be broken down into a handful of material properties. Transistor-based computers consist almost exclusively of electrically insulating, electrically conductive, n-type, and p-type semiconductor materials arranged in specific ways. With the addition of flexible, rigid, and magnetic materials, all kinds of functional objects can be made. The structures that are created could themselves be robots. While the structures I am most interested in are too big to be useful for making transistors from semiconductor materials, I can embed sensors, actuators, batteries, and radios within cells to make them more functional. As this technology develops further, it is likely to shrink. The smaller it gets, the higher the resolution will become, and the more fundamental the unit functions can be.

Research motivation

Assembly-based manufacturing is likely to further the trends of personal fabrication. Democratization of manufacturing means that anyone can be empowered to make almost anything.

With enough development, assembler robots will eventually be made of the same materials that they use to assemble things. This means that assemblers could assemble more assemblers.

Due to advances in computer technology, anyone with an internet-connected mobile device has access to almost all of human knowledge. This has democratized access to information. If reversibly assembled cellular materials advance in a similar way, anyone with an assembler robot and materials could make almost anything.

Environmental and/or social benefits

Similar to the social issues that arose with the internet, there will be social issues related to this technology as well. We must not forget the importance of developing the social aspects of this technology alongside technological developments, especially when social developments move along at speeds far slower than technical developments.

In the upcycling reading, it was mentioned that our terrible environmental issues are a design problem. I agree. Reversibly assembled cellular materials are fundamentally recyclable. This may fix much of our poor landfill based practices.

The line between goods and services may be blurred by self-replicating assembler machines. If anything can be used to make anything, there is no reason to store things for later; everything exists only for as long as it is needed, whether that need is the service of a tool or machine, especially since services are automated, the machines that perform the services can be made by anyone.

2. Material qualities

Elements/components

Every digital material structure is made from repeating unit cells. The unit cells that I am working with will consist of two different components: struts and fasteners. Struts will be made of laser cut, CNC routed, or punched polycarbonate, and may be upgraded to carbon fiber in the future. Fasteners will be 3d printed out of polycarbonate, or a similar material.

Unit cell

Each cell is an octahedron with 6 fasteners, one at each of the vertices, and 12 struts, one along each edge. The faces and volume are left empty.

Each octahedral unit cell is preassembled before being placed and fastened to the structure. This will be a multistep process, and it may be done one of two ways. The first method is as follows:

1. Struts are manufactured from raw sheet stock, either CNC routing or laser cutting. They are stacked into strut dispensers.
2. Fasteners are made by 3d printing with two different filament materials. One is the build material and the other is a soluble support material. After the fasteners are printed, the soluble support material is dissolved in a bath of water. There is one fastener made for every two struts. The fasteners are then stacked into fastener dispensers.
3. Pyramids are assembled with one fastener from a fastener dispenser and four struts from a strut dispenser. The fastener rotates 90 degrees and then another strut is slid into place. After all four struts are added, the struts are locked in place. The pyramids are stacked into pyramid dispensers.
4. Squares are assembled with four fasteners from a fastener dispenser and four struts from a strut dispenser. Two fasteners are connected to one strut, and then two other fasteners are connected to another strut, then the two will be joined with two more struts to make a square. There is one square made for every two pyramids. The squares are stacked into square dispensers.
5. Two pyramids and one square are assembled into a single octahedron. This is done like a sandwich, then the unlocked struts are locked into place.

The second method is as follows:

1. Struts are manufactured from raw plastic sheet stock, either CNC routing or laser cutting. They are stacked into strut dispensers.
2. Fasteners are made by 3d printing with two different filament materials. One is the build material and the other is a soluble support material. After the fasteners are printed, the soluble support material is dissolved in a bath of water. There is one fastener made for every two struts. The fasteners are then stacked into fastener dispensers.
3. Octahedrons are assembled with 6 fasteners from a fastener dispenser and 12 struts from a strut dispenser. The octahedron assembler is a bit complicated. There is a gimbal mechanism that spins the octahedron carrier on two axes so that it can be lined up with a fastener placer, which places the fasteners in the right positions on the carrier, and a strut injector, which pushes the struts into the right positions on the carrier. After a fastener or strut is pushed into place, the gimbal moves to the position for the next part to be installed, since the fastener, placer, and strut injector stay in place. There will also be a backstop mechanism

to make sure the struts go into the right position, and a strut fastener activator mechanism, which will fasten the struts to the fastener. Lastly, there will be a mechanism to remove the finished octahedron from the assembler. This whole Octahedron assembly process is reversible, so octahedrons can be disassembled into a pile of fasteners and a pile of struts. The disassembled pieces would be stacked back into the dispensers. If this is too difficult, a bulk-to-dispenser converter would be necessary to reuse parts that have been removed.

Processes

Placer robots will grasp preassembled octahedrons one at a time and bring them to a location on the structure where they need to be placed. After placement, magnets may help them stay in place until a fastener robot comes along and fastens it to the structure. Placer robots locomote on the structure and fastener robots locomote in the structure. Fastener robots perform the fastening process by differentially driving two gears on the fasteners while pulling them together.

I am interested in seeing how uncoordinated behavior between these two types of robots can lead to the successful assembly of a structure.

Environmental Qualities

These components are made of plastics, and are designed to be reused many times. There are no one-time-use material consumables in the assembly process.

Benefits

Components- Can be flat packed
Assembly process- Does not require gravity
Structure- Lightweight and strong
Assembly method- Can be easily reconfigured
Parallel process is quick
Only two different parts to create one unit- can be mass produced
Assembly process- No inherent size limit

3. Precedents

Bill-e - Robot climbs on cuboct lattice structures, unclear how assembly process actually works

Bitblox - PCB pogo pins based, components must face upward, assembly done by gantry, relies on layer-by-layer assembly method, replacing parts requires significant disassembly

Digital material fabricator - sphere-based, assembly done by gantry, with adhesive, not disassemblable, relies on layer-by-layer assembly method

M-blocks - Jumping Cubes that self assemble, magnet-based, assembly force is opposed during loading

Vacuubes - requires constant vacuum, selective disassembly is unclear, not robotically assembled

Cuboct - woven carbon fiber x structures, very strong, but difficult to assemble. Dedicated fastener pieces are added in fastening process and have an orientation.

GIK - vertically stacked and laser cut, assembly of overhangs are difficult, relies on layer-by-layer assembly method, replacing parts requires significant disassembly Removing or adding parts to the side of the structure requires large amounts of disassembly, currently gantry based assembly

Truss reconfiguring robot - seems very fragile. Very limited in part transport

Termes bots - pick up and stack tiles, relies on gravity, components must face upward, successive layers, bridging is not an option, tall structures unstable, replacing parts requires significant disassembly

Soldercubes

Molecubes

Mori

4. Proposed experimentation or project

Proving concepts

I am most interested if the parts can be assembled and fit together, and so my primary goal is to prove that the parts I have in mind do indeed fit together in a way that can be repeated. Do compound errors arise as the structure becomes large? Once I prove that hand assembly is possible, I want to eventually figure out robotic assembly. What issues will arise for robotic assembly?

Testing strength

Once I have robotic assembly working, I'll be more inclined to do strength characterisation testing, but right now, I am less interested in destroying and more interested in building. Proper strength tests are out of the scope of the current semester, but I might do some rudimentary strength tests. I am interested in eventually taking a rigorous approach to these types of tests.

Future developments:

-Strength, eventually
-Robotic assembly of cellular unit
-Robotic assembly of structure, including placer robots and fastener robots
-Different material cellular units, flexible and rigid parts, and actuators
-Embedding of robots to make assemblies into robots
-Sheet cover facade system to enclose spaces
-Dynamic people-based benches and pavilions for landscape applications

5. Sources

http://cba.mit.edu/docs/theses/16.08.Ghassaei.pdf
http://cba.mit.edu/docs/theses/15.09.Carney.pdf
http://cba.mit.edu/docs/theses/14.08.Langford.pdf
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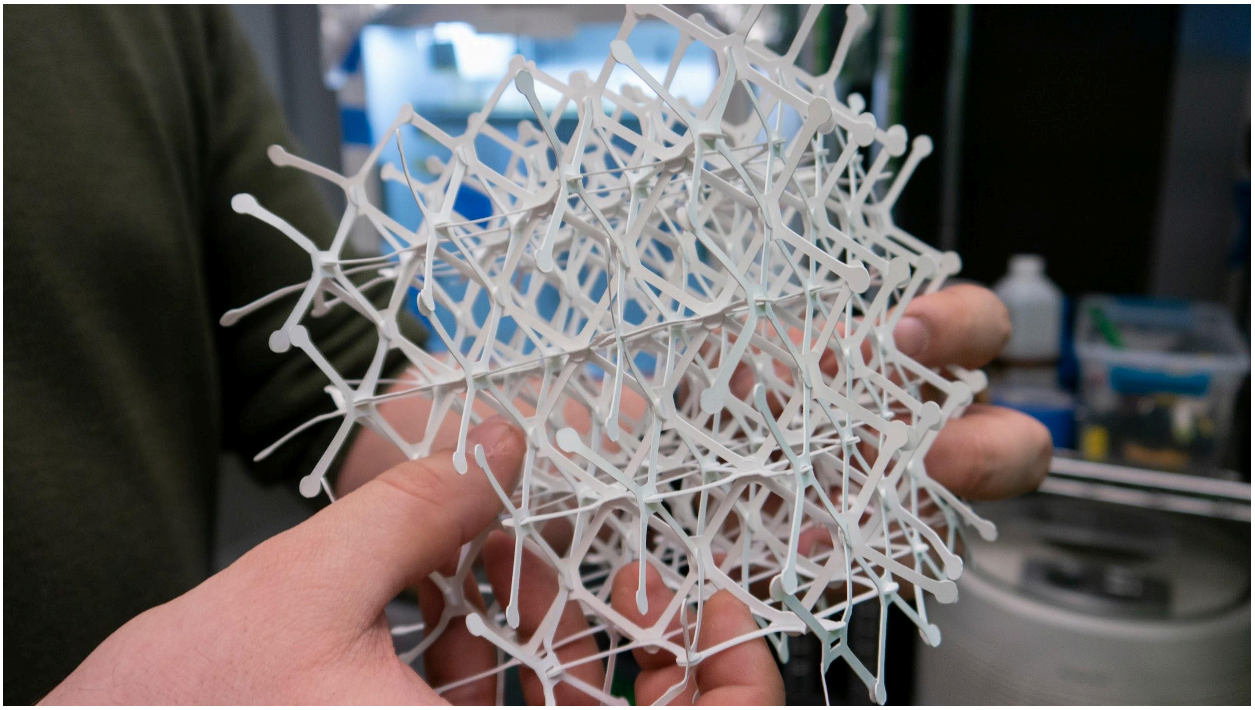
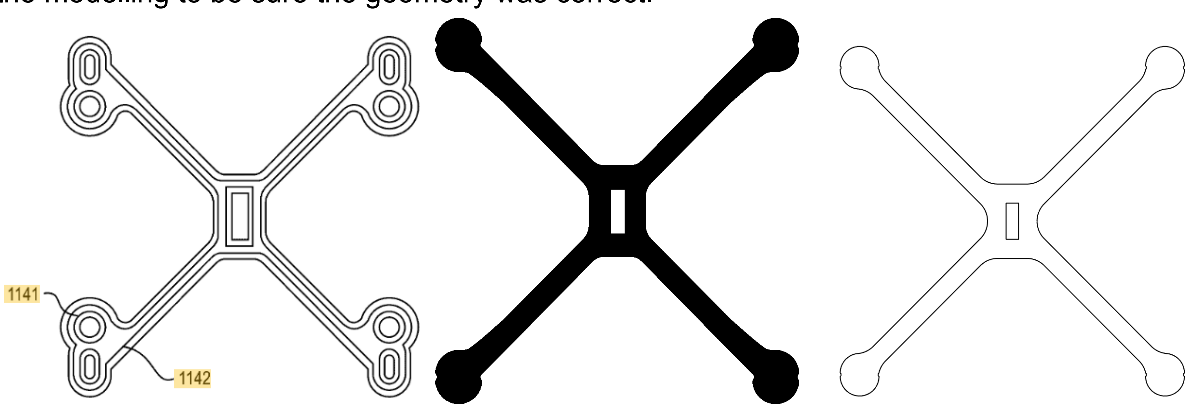
Process Documentation

I had a change in direction; I made a different structure from what was originally planned. Instead of the strut-and-fastener design, I made a scaled up version of the paper structure I had made previously out of small paper Xs.



Paper structure made last year out of tiny paper Xs

I started by modeling the Xs in OnShape. I originally made the small paper Xs with a vinyl cutter. The file that the vinyl cutter cut out is the black X shown below, which I created by adapting figure 11 of [US patent US9566758B2](). I used Onshape to trace the black X and do the rest of the modelling to be sure the geometry was correct.

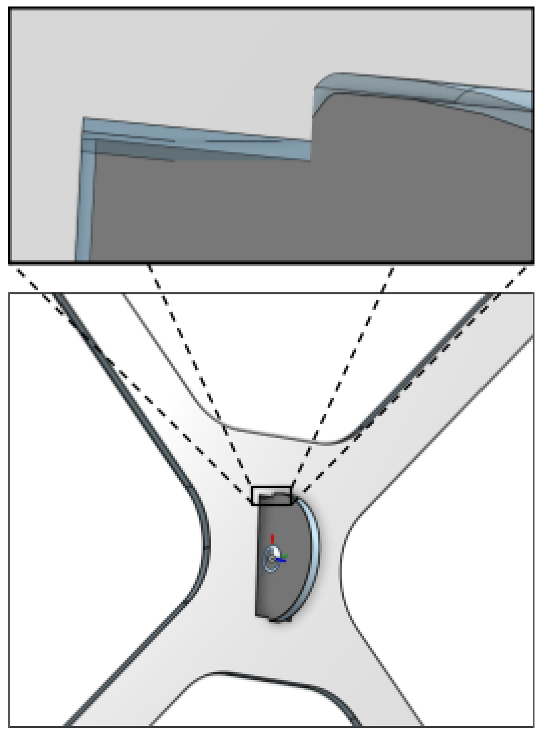


From left to right: Figure 11 of US patent US9566758B2, the black X design I used to cut out the paper Xs, the new CAD model used for laser cutting this semester.

I modeled it parametrically based on the thickness of the sheet stock.

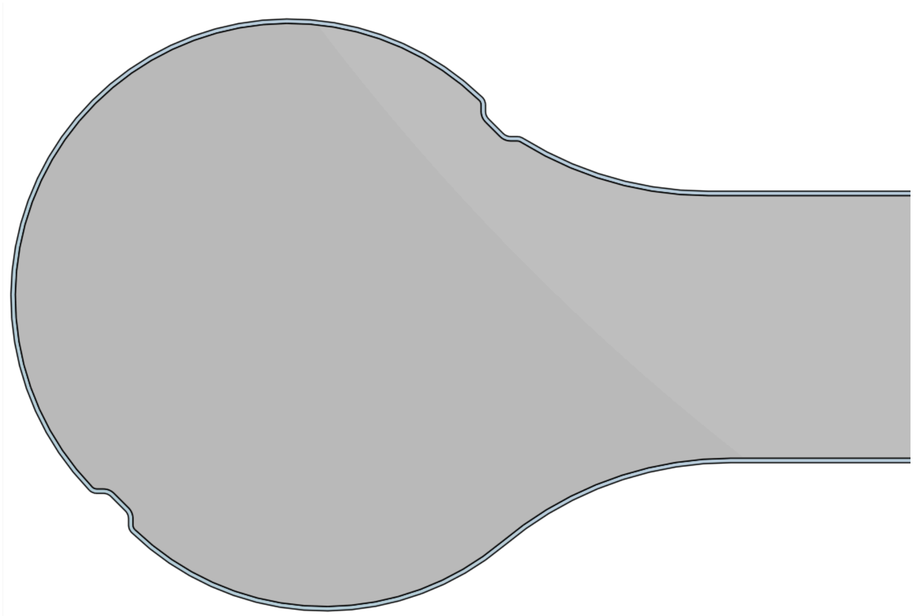
I cut a test piece out of some scrap chipboard and found that it was cut to the wrong size. The drawing that OnShape was exporting was not getting imported into Adobe Illustrator properly. So after a bunch of testing, I figured out that if I import the drawing it to AutoCAD and save it there, Adobe Illustrator will be able to import the file scaled properly. Here is the procedure:

1. Export Onshape drawing as DWG 2010
2. Open file in AutoCAD
3. Copy from paper space to model space
4. Save as DWG 2010
4. Open file in Illustrator
5. Move part onto the cutting bed
5. Combine paths as necessary
6. Change stroke weight to 0.025
7. Change color to RGB[255,0,0]
8. Print. For 1/16 chipboard: speed=8/100,
   power=90/100, frequency=100/100



This process fixed the scaling, but I hadn't accounted for the kerf. So I measured the kerf and added kerf as a new parameter to the CAD and then simulated the fit of the parts in order to tweak the right size. See the image to the right for a visual of this. The kerf is modeled in transparent blue, and can be seen intersecting the models in the zoomed in portion on top. After another few test cuts, I tried the snap-fit and liked how the pieces fit together.

Here is a close-up of one of the ends of the x for more context. Note how there are two notches opposite each other. These create the 'snap-fit'
Also note the thin transparent blue border is the amount of material removed by the laser. It might not seem like much, but I did have to account for it to get the fit that I wanted.



Then I ordered 64 quantity of this chipboard from Blick art supplies: Item number [13115-2226](), Chipboard, 28" × 44" x 14-ply.

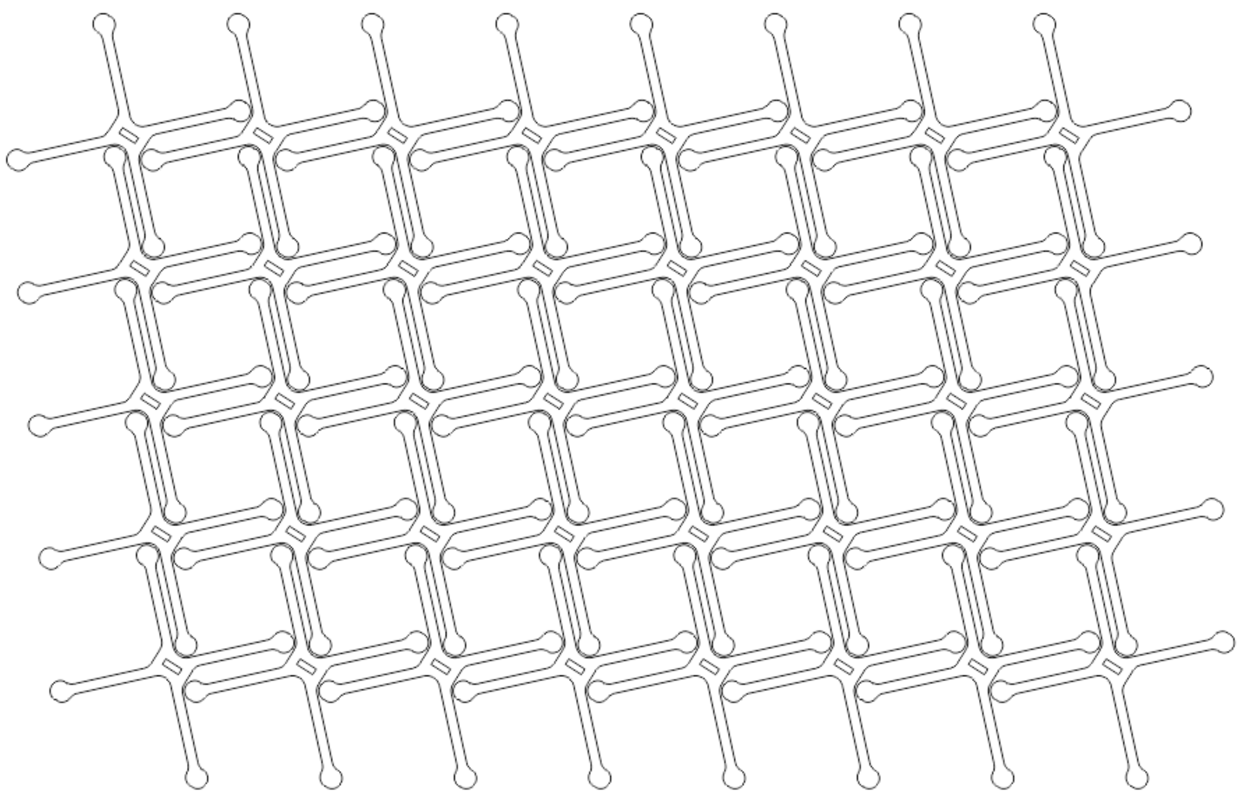
The chipboard that I got was 1.22mm, which was thinner than the 1.58mm chipboard that I was using in my test cuts with the laser in the design building. The thickness of the material had an effect on the design, but luckily the CAD model is parametric. I was able to put in the new material thickness and the rest of the geometries automatically adjusted.

Then I got access to the laser cutter in the life sciences building in the AddFab lab, since it didn't seem wise to rely on the one in the design building towards the end of the semester.

The chipboard was too big to fit in the laser cutter so I had to cut it down to fit. The laser bed is roughly 24.4in x 37.8in and the chipboard was roughly 28in x 44in, so the plan was to use the table saw in the M5 makerspace to cut them to size. 6.2in was removed from the long dimension and 3.6in was removed from the short dimension.

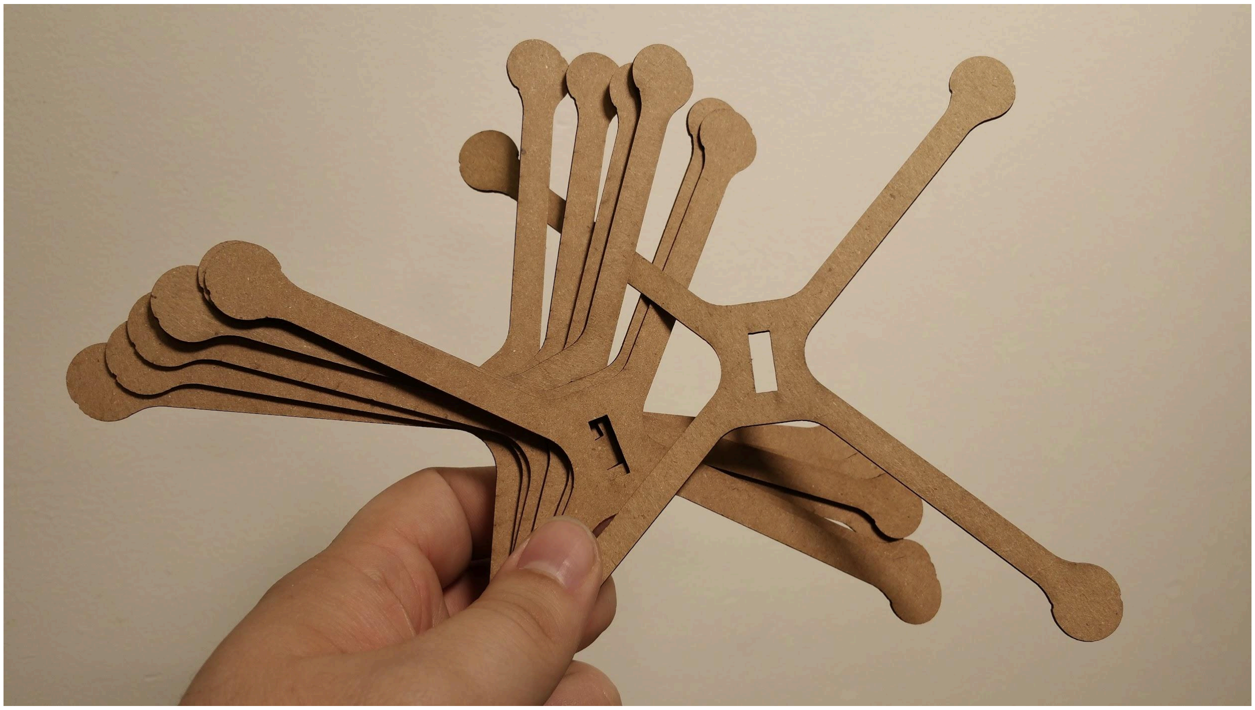
After testing, I came to the conclusion that 100% power and 2.8% speed was the best setting. But then the lenses were cleaned, and I was able to increase to 8.8% speed.

I ended up using 40 sheets of chipboard. I was able to fit 40 Xs per sheet in a 5x8 grid. That is 1600 Xs in total.



This was the bed arrangement for cutting 40 Xs out of each sheet of chipboard.

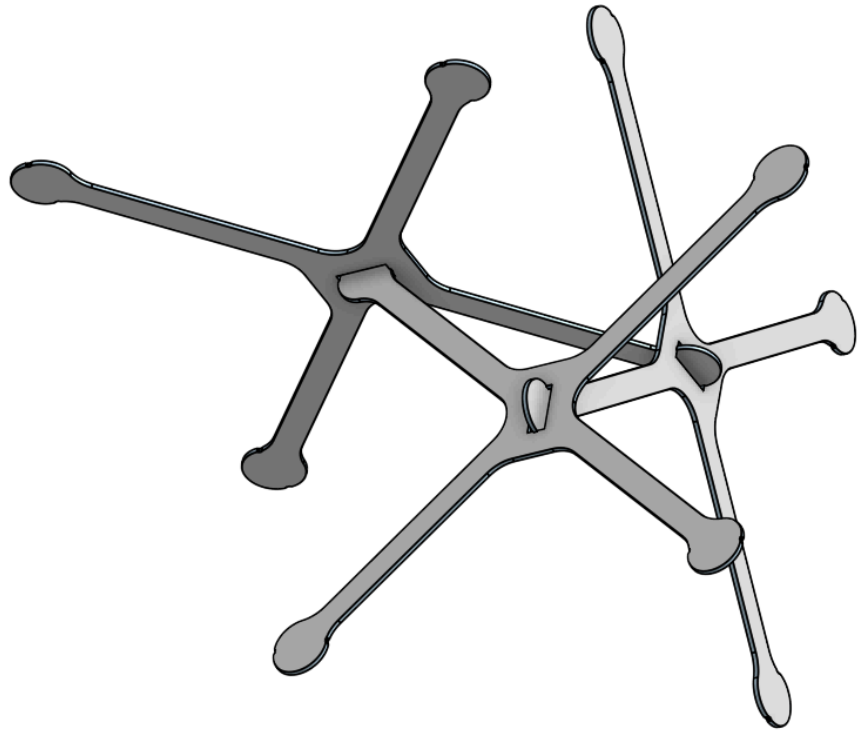
It took 18 minutes to laser cut one sheet and remove the parts from the bed. 40 sheets would take 12 hours. Overall, the fabrication process took 20 hours, which included sizing the stock and testing the settings.



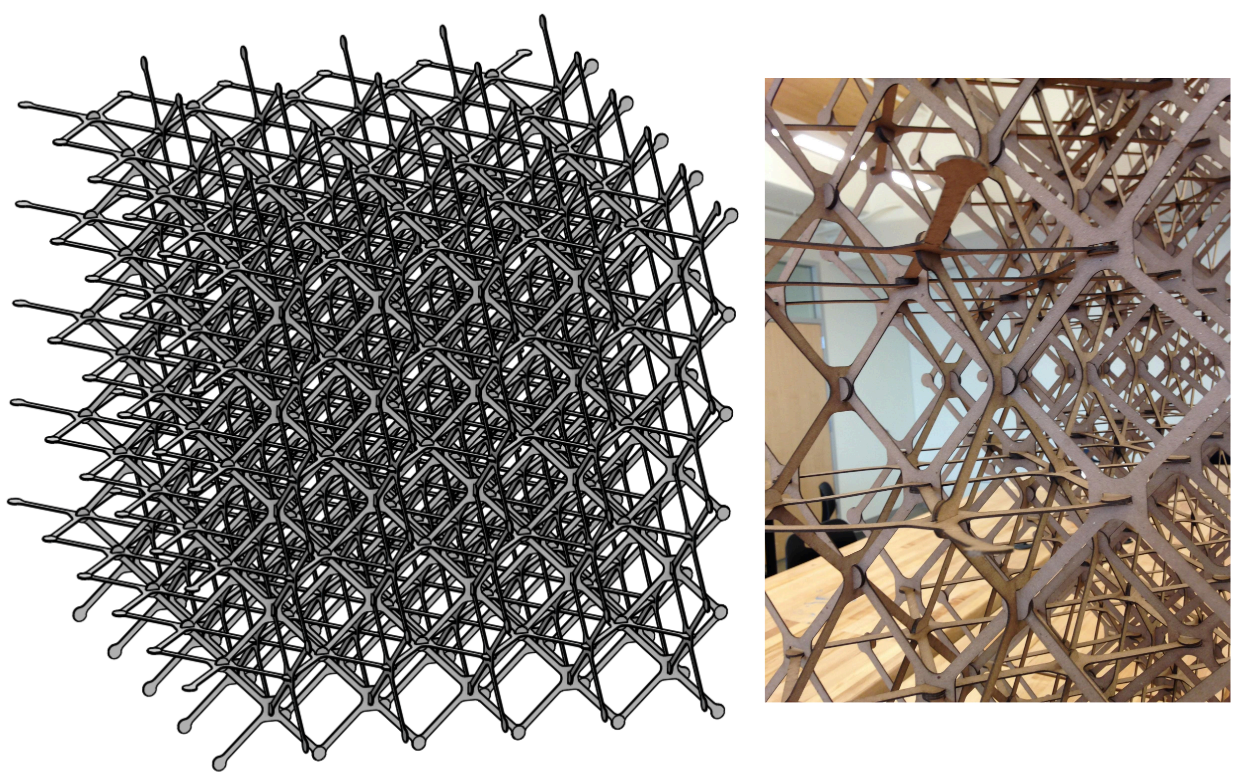
A handful of laser cut parts made out of chipboard

The chipboard contained small pieces of metal and glass that the laser could not cut through. I suspect this is left over from the recycling process. This made removing the laser-cut pieces a little bit more difficult because they were stuck and had to be broken off at multiple points.

As the laser was cutting, I started assembling. It wasn't easy at first, but I got used to the process by coming up with some techniques based on how the next part needs to be installed. This particular structure does not lend itself to robotic assembly. There was too much bending required to fit the next piece in. The pieces often creased during the assembly process, which decreased their structural integrity.



A render of three pieces assembled together, all perpendicular to each other in space.



Render of 375 parts in a 5x5x5 cube, compared to a photo of the real assembled lattice

I built up the final structure in 3 smaller structures, and put them together so that two of the pieces support the suspended third piece. This was difficult because adding the pieces involved very complex hand-eye coordination and finger strength. Connecting two large pieces created internal stresses that also tended to cause creasing of the parts. I carried on, and it ended up working out fine. I asked a friend to help me stand it up. We got it in place without too much additional damage.

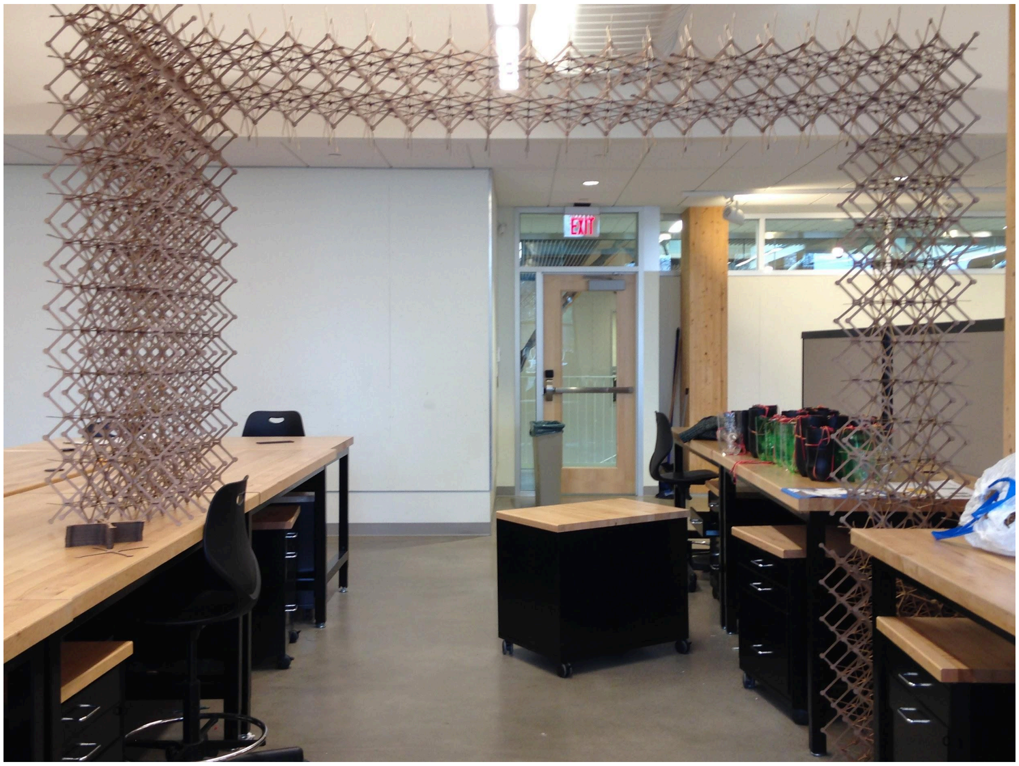


Photo of the final structure assembly

I wish I had time before assembly to paint each of the 6 sides of the 3 different parallel planes different colors so that the color of the structure would change as you move around it.