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Parametric Biodigital Inspired Tessellation for Mass Customized Digital Fabrication

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Abstract. This paper researches the limits of repeating patterns that tesselate in a more artistic way for architectural application that is not limited to creating regular triangular, rectangular or hexagonal pieces with decorative purpose and sole material usage. Digitally parametric modeling and CAD-CAM paradigm with input-output sensorial microcontrollers, have brought the possibility to explore the limits of mixing up manual and automatized fabrication techniques with the infinite geometrical potential, implementing AI features. The applied research is being materialized into a mixed technique grayscale concrete floor-tiling prototype featuring concepts of passive flame-imitated indirect red light to enhance health benefits (Arduino microcontroller operated) and zero-waste manufacturing by carrying out CNC milling positive cast to a rubber mold to create an exact amount of geometrically matching pieces needed for the design.

Keywords: Arduino, CNC fabrication, mold-making, parametric tiling, patterns, polymers

Tiling patterns and the tessellation challenges

In search for available tiles in a retail market one would always find square and rectangular tiles first, some options in hexagonal or triangular shape and usually in a wide range of colors including textures that mimic or try to imitate natural materials like wood or various types of stones. That is about it when it comes to mass production due to the demand and some sales marketing research. The manufacturing quality sets the price range of such tiles from very cheap to luxurious designer styles that compete with real equivalent material costs like marble or hardwood. When it comes to practicality it is no doubt that ceramic tiles are good, durable and in general they are easy to install even by non-professionals. Sizes range from very small mosaic tiles to ones that are “oversize” or “jumbo”, measuring up to 1,8 meters or more in the longest dimension. The latter ones have become fashionable quite recently and they almost do not feature any joints meaning that in terms of decorative aspect they have a feel of an entire slab of the featured material. Only limitation is that these gigantic tiles are fragile in transportation, storage and installation. There is no such esthetical feature as aging patina in the tiles, so a dent, cracks or broken corners usually means that the whole tile needs to be replaced. Durability is questionable and one light damage can lead to severe visual defects.

Knowing this background information, we can see that the tile market is somehow limited both in the creativity and the lack of design qualities. Has this been addressed before? In art it has been done by a grand Dutch artist M.C. Escher in his entire lifelong career, trying to step out of the classic and standard geometry into the explorations of non-standard and extraordinary. Even more, Escher is known to have experimented with transitional shapes that have achieved to freeze the motion and morphing transitional forms that are on limits of the geometrical potential, also the dualities and mathematical surrealism. The work could be seen as “parametric” if he would have had computer modeling available in his time of the studies.

By the advent of computer modeling software, it has now become easier to explore the limits of tessellation and parametric modeling that just adds a whole new perspective to the possibilities. In the age of the digital parametric non-standard architecture, mathematics and geometry represent the core of the architectural design process [7]. A tool that plays a significant role for this aspect is the famous 3D modeling software Rhinoceros plugin “Grasshopper” that is a visual programming language. It is allowing the designers to build form generators from the simple to the awe-inspiring [4]. While the generative workflow seems very easy from the first look, it becomes clear with usage of these tools that good skills of geometry are still very much needed.

CAD-CAM paradigm meets sensorial microcontrollers (and AI)

Having the digital designs straightly available for digital manufacturing has changed how we understand the workflow of a designer in the 21st century. Let it be any shape and form in two or three dimensions, the only thing that limits the materialization is the manufacturing equipment and its operator's skillset and experience. Literally anything can be made physical and we have started to take it as a norm, so with the economy of time we can focus on more creative aspects and exploration of previously unseen complexity. Why designers always strive for the more innovation proves that we still have the thirst for the novel, for surprise and admiration of the beauty. Friedrich Nietzsche confirms it in a more philosophical way [3]:

"Admiration for a quality or an art can be so strong that it deters us from striving to possess it."

Going further with a design and searching what else could make it more complete takes us to artificial intelligence. Market of gadgets offers several integrated AI assistants like Siri or Google Assistant, or Alexa to automatize your home, control the lights and play music, take online shopping orders, just to name few of the functions. While these smart tools or "toys" seem to make our lives more comfortable, they are definitely also showing us what trends are being implemented into the everyday things around us. Still for the compatibility issues one would need adapters and special compatible accessories and most of all – electricity and an internet connection.

Author proposes that it is more feasible to work with a simpler alternative to imitate the AI with the usage of Arduino microcontrollers. These little and affordable devices can be running very complex tasks, and they have a huge potential in terms of interaction with the environment around us, wide range of input sensors and output reactions. The electronical components of Arduino are small enough to be integrated into the designable objects and the added value of the interactivity definitely can improve the user experience. For the theory of a complex behavior brought into the world and applied into a real design one would need to look for a possible physical space and a location, adding the factor that the design could be replicated easily – leading us to an integrated project-based research.

The design preconditions and conceptualization

Author did several extended brainstorming sessions to crystalize the possible design and find the innovation for a practical necessity. Since December 2018 author has been designing the first Net Zero Energy House in Mexico for his family residence, and at the moment of making this research there were three major opportunities of the design that were still in the to-do list to be built: hybrid wind and solar energy farm for off-grid energy production, automatic curtain shading system for the main façade and the Sauna design.

As every of these designs would be a great platform to experiment, author summed up the design task as following exercises:

- design has to explore advanced 2D tessellation;
- is easy to materialize with a laser cutting or CNC router;
- can be replicable addressing zero waste manufacturing principles;
- has a "feature" that involves programming certain intelligent behavior;
- possibly gives additional qualities like health benefits etc.

With this list of information, the decision was on behalf of a sauna – a central piece in a Scandinavian style home with presence of high temperatures and humidity, as there is a huge potential for almost every of the abovementioned aspects to be solved. As the space and its dimensions were already fixed and the metal framing partly built and the necessary insulation in the place, the designing exercises were narrowed down to solve somehow the least important element - floor. The sauna of this house features 2,6 x 1,5 meters of floor surface and the sauna room's height is 2,2 meters – an ideal dimension according to traditional Finnish Sauna design guidelines [6].

Development of the geometrical setup and the "maker" movement

First step in designing the tessellation started off with 2D formal exploration to see what geometries best adapt to the bounding box limits of the floor x and y dimension limits. Apparently by scaling up and down various simple polygons into this space, in particular the triangle had almost perfect dimension in a multiplication of its grid to accommodate the base figure in the given space 2x3 times. The full height fits in exactly twice and the width would occupy three full triangles by leaving only 1,92 centimeters of space unused in the total width dimension of 2,6 meters.

Roughly analyzing the formal proposal, it can be clearly seen that if this space would be tiled with pure triangles, it would cover an area of 12 triangles – where 10 would remain whole and two would be cut in halves, leaving zero leftovers of the triangles. This step followed several developments of rationalizing the shape to include absolute mirroring properties in any applied rotation, in order to eliminate the need of having too many different elements in the design. Adding complexity in an early stage of this design gave a great leverage further to simplify it back in both the proliferation and the fabrication processes. As the base figure is an equilateral triangle, its three outer edges were halved and substituted with two centrally oriented back-facing and mirrored rhombs that underline more of the previously discussed repeatability qualities. The final development of the form was based on having only three individually designed elements that would populate the entire floor design - one triangular, one four-edged and one five-edged modulation.

Ultimate designing phase implemented an intelligent curvature where the straight segments of the line become curved by weighted attraction in random direction, always pulling another coinciding edge of bordering geometries along with the same move vector, keeping all of it simple and always displaced at 120 degrees rotation. While this design seemingly has a complex appearance, it is also giving a false mirror effect while in the reality nothing is ever mirrored. The result gives a total mosaic piece count limited to just 84 pieces to cover

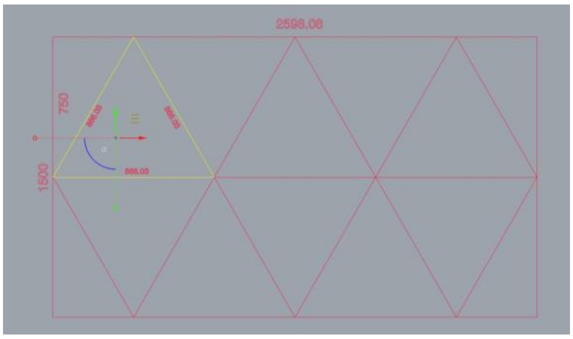

Fig. 1. Tessellation of 2x3 triangles along the floor plan's maximum bounding box of 2,6 x 1,5 meters left only 0,0192 meters (1,92 cm) of unused space [created by the author, 2021]

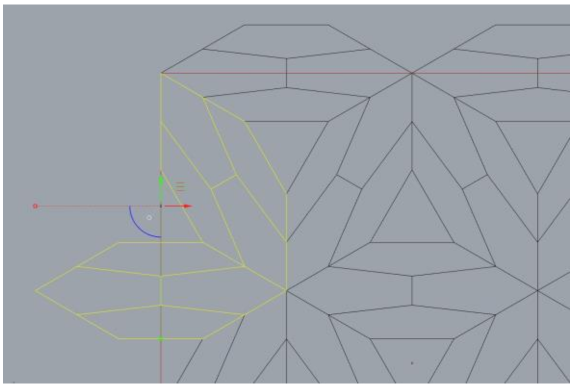

Fig. 2. Three element design to build the proliferation on a single 120-degree rotation [created by the author, 2021]

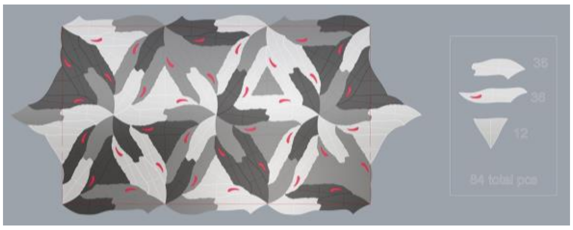

Fig. 3. Concrete shades at their best natural grayscale palette, ranging from white concrete made with white Portland cement and marble sand aggregate to natural gray concrete and lastly the usage of naturally black pigment additive to obtain black concrete. Additional red inlay is added to every third piece for more dynamic look and special features [created by the author, 2021]

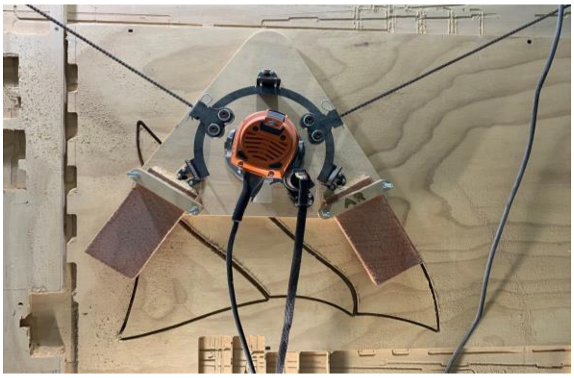

Fig. 4. Author's built Maslow CNC router in process of cutting out three main geometries from a 19 mm thick plywood sheet [photo Arne Riekstins, 2021]

the entire floor, all of it with just three types of modulated elements.

Material choice fell on the most malleable classic – pure concrete, that can take literally any shape and is the utmost durable to heavy temperature changes and extreme amount of humidity. Concrete could undergo the metamorphosis as it is freed from its untreated state and mechanical properties, becoming highly expressive, almost like it was done by artists of Lombardy back in the age of Art Nouveau [8]. As the plan was to cast these pieces only in the necessary amount, the game element to make it more graphical and vivid was the introduction of the variation of concrete tonalities. Three tones were chosen to keep the greyscale palette and underline the real shades what this natural material could feature. First color of this trio is the raw gray cement color unaltered, the second color has a natural black cement pigment that is mixed into the concrete and the third color is almost paperwhite using the same quality and strength white Portland cement with white marble sand and marble gravel aggregate. Before going to the design and making of the molds, author added to one of the modulated pieces a decorative droplet shape inlay, further discussed later in the making steps.

The need for an economic mold

At this level of complexity there must be a very simple and economical way to materialize the repeating pieces and fabricate the moldable original geometries in the 1:1 scale. As this step represents a true mass customization, the most economical way to quickly materialize the digital file to a physical piece was by a home-built CNC router built by author and based on the open source project Maslow CNC [5]. This particular engineering piece features a chain-hung Ridgid-branded hand router that operates in 3 axis with stepper motors and is run with an Arduino Mega microcontroller and a special proprietary prototype shield for the motors. The router is semi-automatic and relatively slow, but features quite high precision and massive full-sized plywood 1,22x2,44 meters of routing bed. The router reads standard ".nc" extension files and it operates directly from a proprietary software on a MacBook via an USB cable connection to Arduino. The total costs of such a router do not exceed 500 USD/EUR mark, including all the wood necessary for the frame, the hardware and the hand router tool itself. Running and maintenance costs are a fraction to any comparable industrial degree router of this size.

The typical problem is the customized mold making cost, so being effective in reproducing many identical cast pieces afterwards would be possible by usage of a rubber mold. It features a large lifespan, it is easy to take the finished pieces out nevertheless of the material stickiness or its geometrical complexity

Fig. 5. Plywood geometries are being almost totally covered with a liquid rubber molding agent. Pigment is just added before stirring it up so that it could be seen if the rubber mix has become uniform with the catalyzer. The cast is being made in seven batches of 200-300 grams each time and as it is quite heavy substance and has a working time of about two minutes from preparation to solidification. The edges of the mold are made of 5 mm foamboard to support the 2 cm side offset, and the backing thickness is less than a 1 cm just to keep the geometries together. In casting thin concrete pieces this is the most economical and reusable way of having an economical mold [photo Arne Riekstins, 2021]

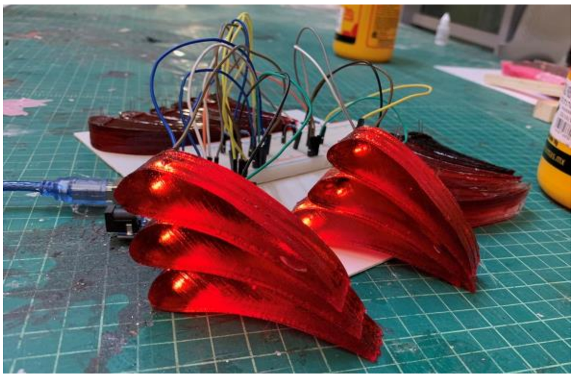

Fig. 6. Red resin droplets running a test pattern to imitate a burning fire effect - trios of LED lights randomly are being turned on with variable intensity, running a small up to 300 ms random time delay between another random value run, looped in 10 cycles. LED lights are bent 90 degrees and submerged in the middle of the 19 mm depth of the piece to shine sideways into the longitudinal axis of the translucent volume, illuminating the entire contour of the geometry [photo Arne Riekstins, 2021]

and can copy every detail of the original texture as well. From the three plywood pieces author casted total of five negative rubber molds, one for the triangular geometry that needs 12 final pieces and two per each four and five-edged geometries that both need 36 final pieces. By this the casting of concrete would be speed up double to total of 18 casting and demolding days. Meanwhile it was also clarified what material will be the little droplet featured in the design, so that became made into 6 mini molds to speed up the making of those 36 final pieces in six casting attempts. These aspects of saving time while still having a mass customization feature are essential for complex projects like this.

Being economic and maintaining an option for a special esthetical feature, the decorative droplet inlay became designed into a central element of the interactive lighting of the floor. As it can be totally incrusted to the concrete, a low voltage LED light can be embedded into a transparent or toned resin mass, keeping the wiring protected and intact forever under the floor. Here author did six trials with different red pigment intensities for obtaining a specific fire-imitating color shade when LED lights are being lit in series of three simultaneous lights at a time. Also, the angle of the LED projection played an essential role to illuminate 90 degrees sideways into the piece and bringing out all of its contour rather than shining straight upwards. The control of these lights is done by another Arduino Mega microcontroller that easily features 36 output connections at a time. Besides the system can be expanded to react to numerous external environmental factors.

Pieces coming together in a zero-waste fabrication for low carbon footprint

Last step was the most laborious as it involved actual casting of the pieces in the molds. The process relies on a concept of making only the necessary amount of concrete mix that can be measured and weighed beforehand to have the concrete resistance of 250 kg/cm2. Having two molds speeded up the process to total of 18 casts – 1/3 with grey, 1/3 with black and 1/3 with white concrete tonality. First pieces seemed to have too little of the rough aggregate and did not feature any metal reinforcement inside, so a fine "rabbit" mesh was cut to fit the entire pieces and hold them together as it became an issue of fragility especially with the biggest element that is 57,7 cm long and has the thickness of mere 1,9 cm.

The entire process lead to a profound application of the zero-waste fabrication from beginning to the end, featuring low carbon footprint and keeping costs to just the simple basic ingredients of this design, most of them sourced locally from Monterrey, Mexico: cement – 50 kg standard and 25 kg white, sand and gravel aggregate - 6 buckets in total, fine "rabbit" mesh 4 m2, thin electric cable 20 AWG – spool of 100 m, open source Arduino Mega microcontroller, 5V transformer, some plywood, 3 kg of rubber molding material and 1 kg of resin with 10 ml of red pigment. Everything else counts as total of 40 hours of design and 80 hours of physical labor, including some programming and adapting of the Arduino code.

Additional health benefits and further research

In the process of doing the research for the best ever Finnish sauna, most of the decisions were made

Fig. 7. Casting first floor pieces in standard gray concrete [photo Arne Riekstins, 2021]

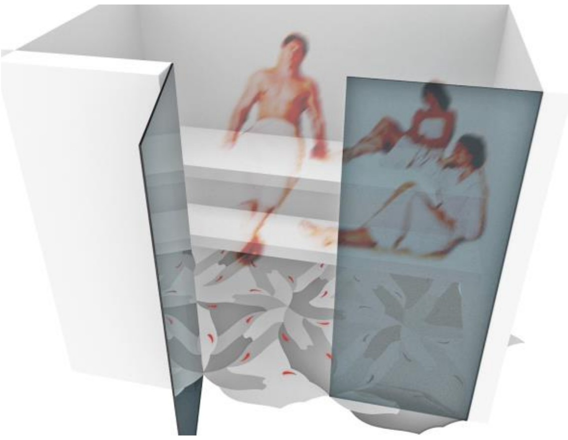

Fig. 8. Rendered architectural image of the parametric tiling pattern applied to the sauna floor [created by the author, 2021]

to improve its experience with any feature that could be related to the field. Red light apparently belongs to a category that gives notable health benefits. As it is a merely design feature, there still exist lot of research [2] about red light wavelengths in general. They are considered to increase the mitochondrial function of the cells, therefore producing more energy to the human body. Also, there is a long list of skin benefits – it repairs all sorts of damage caused from sunburns, scars etc. it also should reduce wrinkles, build collagen, perform detox and improve the blood flowing in veins. There are some studies of red light healing the age-related degeneration of the eyes [1], hormone benefits ... The list of the benefits goes on and on, where paired with a sauna experience they could be backing up each other's positive effects. As the research of health issues belongs already to other field, author sees it probable to link it to his future research, observing the best real-life practices and documenting the outcomes in an empiric way.

Further research could also be related to expanding the interaction of the Arduino microcontroller to more advanced AI behavior, linking the setup via wi-fi connection to an interface that could monitor the user's smart wearables like health-watches and make a connection with numerous available input sensors to set the red light illumination patterns to the equation of the sauna temperature, humidity, occupancy or mood (entertainment mode vs. healing mode). That would be the departure point of the possible scenario options for this research of Biodigital parametric tiling patterns for architecture.

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