Digital materials for digital printing

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Abstract

Conventional three-dimensional printing processes are material-dependent, and are irreversible. We present an alternative approach based on three-dimensional assembly of mass-produced two-dimensional components of digital material. This significantly enlarges the available material set, allows reversible disassembly, and imposes constraints that reduce the accumulation of local positioning errors in constructing a global shape. Experimental work on material properties and dimensional scaling of the digital material will be presented, with application in assembling functional structures. We propose that assembling digital material will be the future of 3-dimensional free-form fabrication of functional materials.

Most existing commercial free-form fabrication printers build by putting together small quantities of no more than a few expensive materials. In order to make high-resolution objects they need to be very precise and therefore cost between tens and hundreds of thousands of dollars and are operated by skilled technicians. On the other hand young children build 3-dimensional structures out of LEGO with their hands. LEGO structures are cheap, quick and easy to make, reversible and most importantly they are more precise than the kids who build them. However, they are big and are only made out of ABS plastic. We believe that digital materials bring reversibility, simplicity, low cost and speed to free form fabrication in addition to a larger material set.

Previous research on structures built out of many discrete parts involved self assembly [1], error correction self assembly [2], programmable self-assembly [3] and folding[4]. We rely on a digital printer, as presented in [5] which will assemble the structure by picking and placing the bricks forming the digital material.

We define a digital material as a discrete set of components that can be of any sizes and shape, made out of various materials and that can fit together in various ways (press fit, friction fit, snap fit, reflow binding, etc.). However the components of a digital material must satisfy the following properties which are familiar to many toy assembly kits:

1. All components can be decomposed into smaller elementary geometrical shapes.
2. Two components can form a finite number of links.
3. The links between two components are reversible.

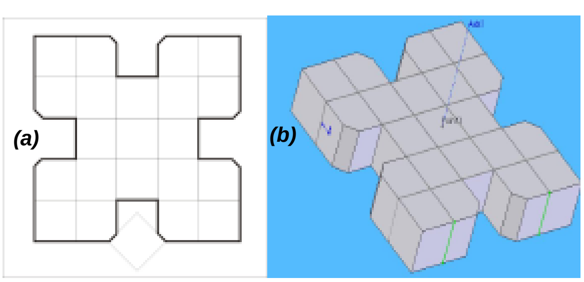


Figure 1 ***A drawing (a) and a 3D model (b) of a square GIK part. A square GIK is made out of 21 cubes among which 8 have chamfers. Many other geometries (triangle, rectangles, …) are possible.***

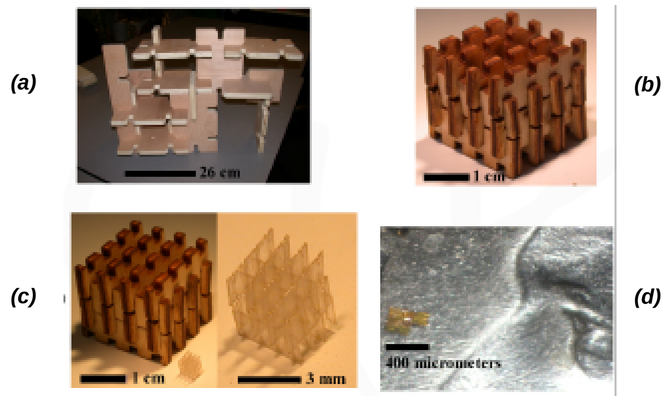


Figure 2 ***GIK structures of different sizes & shapes: (a) meter (in plywood) , (b) centimeter (plywood), (c) millimeter (celluloid) , (d) µm (Kepton). You can see the mm and cm scale structures side by side in (c). The µm structure is on top of a dime for scale purposes.***

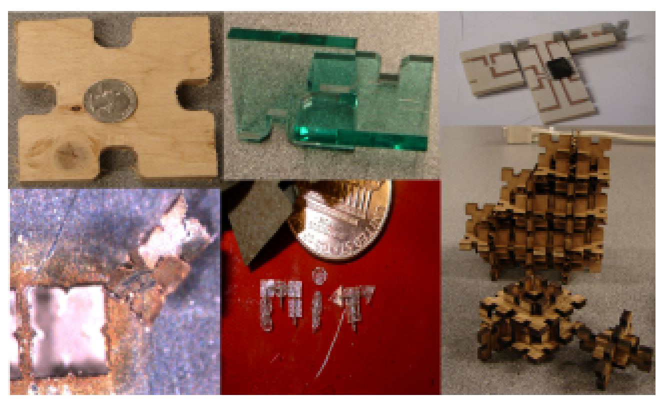


Figure 3 ***GIK parts made out of different material: plywood, Plexiglas, aluminum and fiberglass composite material, stainless steel, transparency (celluloid) and cardboard.***

GIK[*] as described in figure 1 is as an example of digital material. GIK bricks (see Fig. 1, 2, 3) can be cut in 2-dimensions which makes them very easy to make at any scale (Fig. 2). They can be press fit together to form space filling voxels that can be connected and disconnected at will making the construction reversible. In addition, as seen in Fig. 3 they can be made out of a variety of materials. Below eye resolution GIK parts (1µm and smaller) will have macro-scale behavior but will form high resolution objects which will seem continuous. GIK building blocks can be compared to an atom that assembles to form a

[*] GIK, initially Grace's Invention Kit after its inventor Grace Gershenfeld, became the Great Invention Kit after Eli Gershenfeld contributed, than simply GIK.

crystalline lattice. Similarly, a combination of GIK materials can be assembled within one structure to create components with unique properties.

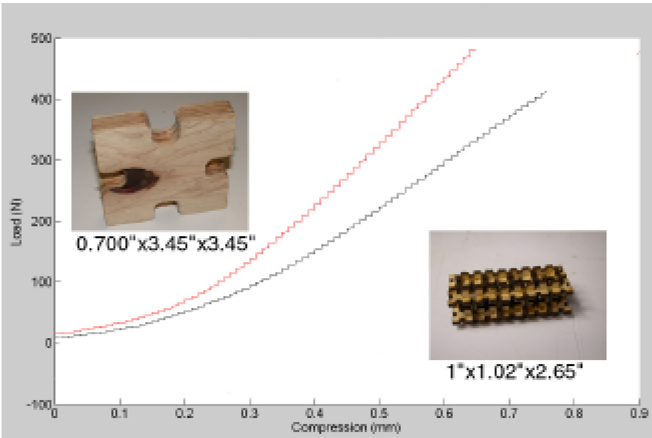


Figure 4 ***Load compression diagram for a piece of bulk plywood and a GIK structure. The compression modulus is 309 N/mm/square inch for Bulk and 223 N/mm/square for the GIK structure.***

All the material testing measurements were done on GIK parts cut on a laser cutter. The material used for materials testing was white birch plywood of thickness 95 mils +/- 5 mils. The material testing machine was a commercial Instron 4411 (time resolution: 5ms, force resolution: 0.01 N and position resolution: 0.01 mm). GIK part connection and disconnection hysteresis cycles where recorded using the Instron's GPIB interface and processed (Fig, 5). To record such a cycle, two GIK parts were assembled by hand, then mounted in the Instron material testing machine. The parts were pulled apart at a constant speed of 1mm/min. and the pulling force was recorded. When the extension reached 2mm (and the GIK parts are totally separated) the cycle was reversed until the parts were back to their original position.

We compared the behaviors of an individual GIK building block and a lattice structure that it was assembled into. A single GIK brick and a structure assembled from GIK were individually subjected to longitudinal compression. As expected and seen in figure 4, the two specimens behaved almost identically and exhibit

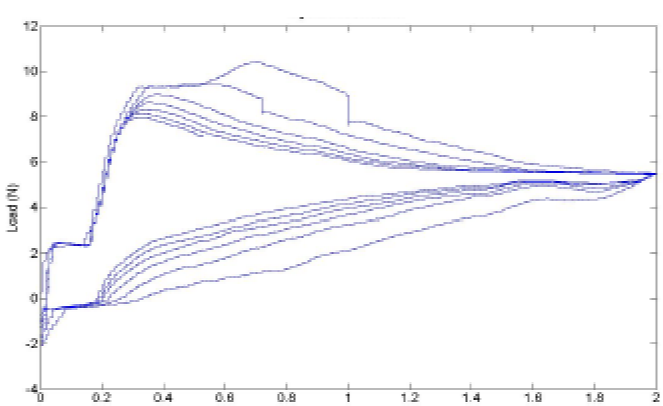


Figure 5 ***About 6 hysteresis cycles of the connection and disconnection of 2 GIK parts. One can notice the 2 "earthquakes". Once can also notice that less and less force is necessary to part the parts with time. However the force needed to do so doesn't seem to converge toward 0 but rather towards 8N.***

similar Young's modulus. A compression stress pattern analysis was also conducted and is seen in Fig. 8.

When submitted to a longitudinal tension test, we were able to measure the force that was needed to break a press fit connection as a function of the slot size (Fig. 6), the number of links taken apart simultaneously (Fig. 7) and the history of the press fit connection (Fig. 5). For the specific range of slot widths, there seems to be a linear relationship between the breaking force and the slot width (Fig. 6). For all practical purposes, this data can be used for designing GIKs for a particular joint strength.

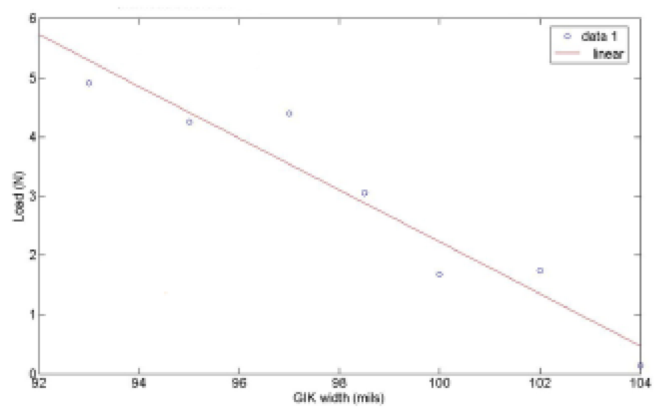


Figure 6 ***Maximum load a connection between 2 GIK parts can sustain before breaking by pulling as a function of the GIK width. The GIK parts used were square and made out of white birch plywood 95 mils thick.***

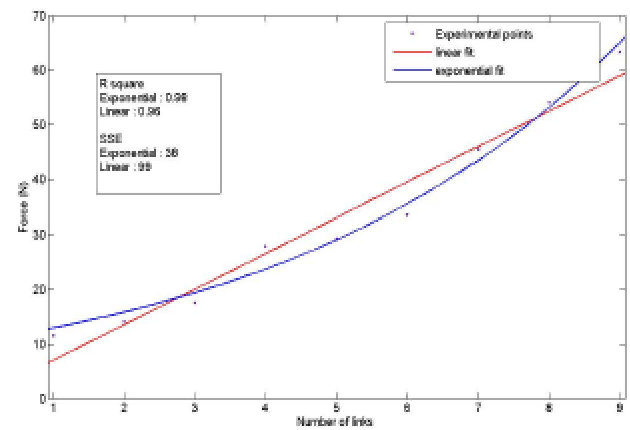


Figure 7 ***The force necessary to break simultaneously a given number of GIK links by pulling.***

As shown in figure 7, the force necessary to disconnect an increasing number of GIK parts grows faster than linear. The press fit connection between GIK parts has a stick/slip behavior and the passage from the stick state to the slip state is also non-linear. The faster-than-linear increase in the link strength with the number of parts would account for a high joint strength.

Properties unique to digital materials are *error tolerance, error reduction, error detection* and *material tuning*

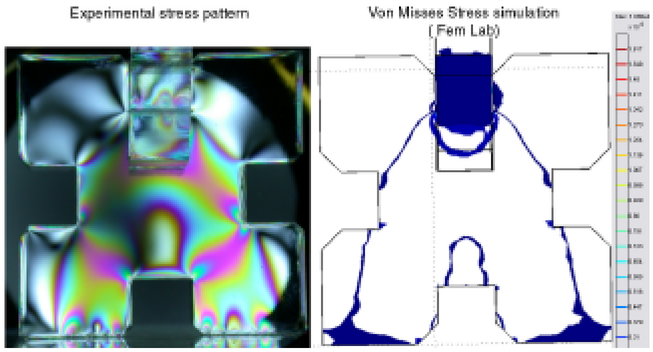
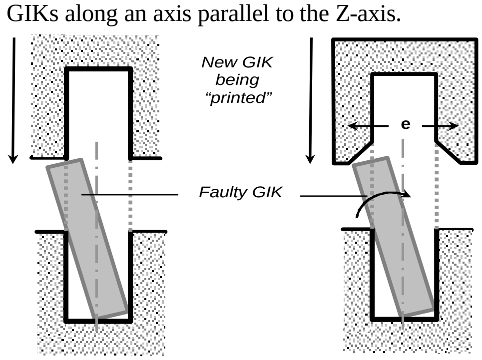


Figure 8 ***The experimental and simulated (using Femlab finite element simulation software) stress pattern in a square GIK. A force of 500 N was applied and locally the stress can reach up to 16000 N.***

Error tolerance: GIK parts are connected through layer-wise printing onto an XY grid. If the assembling mechanism is successful in accurately dropping the GIK parts in the designated positions on the 2D grid (XY), the basis of assembly error would be faulty GIKs or the deviation of the GIK from its designated 3D position. The second type of error can further be divided into two types: incomplete placement of the GIK along the Z-axis due to a severe interference fit & swiveling of the GIK at the joint due to a clearance fit. The swiveling of the GIKs can occur along an axis parallel to all 3 major axis. For now we shall ignore the swiveling of the GIKs along an axis parallel to the Z-axis.



GIK without error correction allowance Fig. 9a

GIK with error correction allowance Fig. 9b

Figure. 9 ***Shows a GIK that has swiveled due to a clearance fit. The angle at which the GIK collapses can create an obstruction for the placement of the next GIK (Fig.9a). The incorporation of a chamfer into the GIK can aid in realigning the faulty GIK (Fig.9b).***

The opening of a chamfer defined by e (refer Figure 9) would play the critical role in determining the threshold for error tolerance that can be built into the GIKs.

.If µ, s respectively represent the mean and standard deviation of the slot width, then for the sake of convenience we can design the chamfer assuming

$$w = \mu + 3s$$

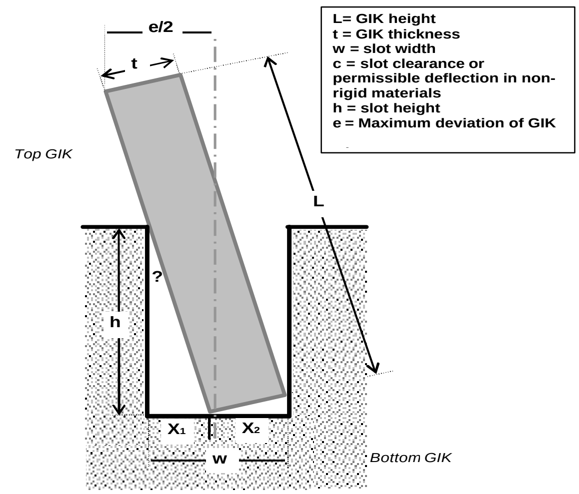


Figure 10 ***Describes the maximum angle ? by which a GIK can swivel and its relationship with GIK geometry***

The value of x_1 can be determined by solving

$$x_1^4 - 2wx_1^3 + \left(w^2 + h^2\right)x_1^2 - 2wh^2 x_1 + h^2\left(w^2 - t^2\right) = 0 \qquad (1)$$

Where :

$$0 < x_1 < w \qquad \& \qquad q = \tan^{-1}\left(x_1 / h\right) \qquad (2)$$

Thus the width of the chamfer opening would be
We can refer to this property of digital material to tolerate the slot clearance, as error tolerance, e.

$$e = 2\times(L\,Sinq + \frac{w}{2} - x_1) \qquad (3)$$

Error reduction: When a structure is built out of GIKs each part you add to the structure is adding geometrical constraints to it and therefore is limiting the free movement of each piece. We measured the amount of free movement as a function of the number of rows in a GIK structure as seen in Fig. 11. We used GIK parts made out of Delrin (Delrin is manufactured by E.I. du Pont de Nemours and Company) cut on a commercial laser cutter. One can see that by adding more constraints along the x direction (1, 2 and 4 rows) one is forcing the x position of all the parts to be closer to 0. If we note $x_{k,n}$ the x position of the nth piece in the structure made out of k rows, then

$$\left|x_{4,10}\right| < \left|x_{2,10}\right| < \left|x_{1,10}\right| \qquad (4)$$

we define

$$e_{k,n-m} = x_{k,n} - x_{k,m} \qquad (5)$$

than we can see that $e_{k,n-m}$ goes down with k, and doesn't really depend very much on n-m.

We can generalize this to y and z axes by symmetry. This property of digital materials can be referred to as error reduction.

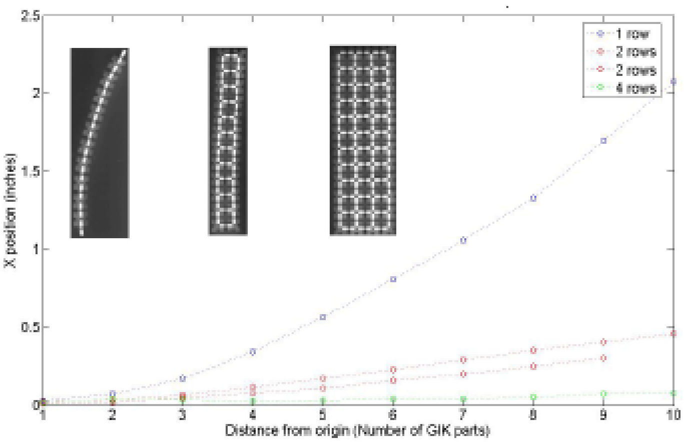


Figure 11 ***Error prevention: the x position of a piece in a GIK structure is constrained by the other GIK parts in the structure. Therefore the larger the structure along the y axis and the smaller the variation of the part's x position as measured here.***

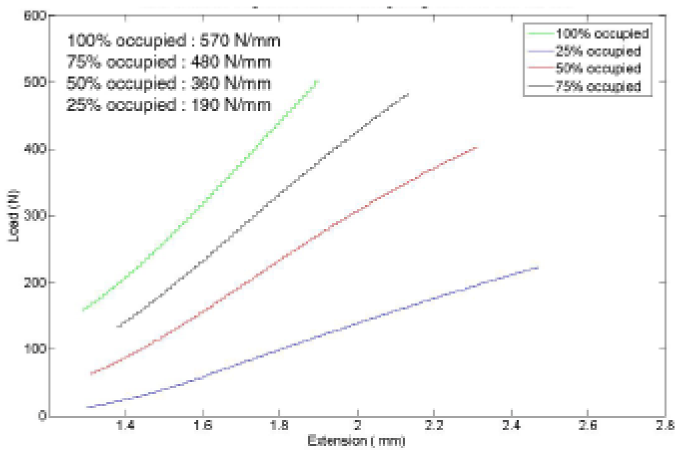


Figure 12 ***Material Tuning : one can vary the percentage of sites occupied in a GIK structure and therefore tune the mechanical behavior of the structure. Shown here: the variation of the compression modulus (the slope of load/extension graphs) for 4 different occupancies.***

Error detection: As seen in Figure 1, an ideal square GIK tile can be decomposed in 21 identical cubes of size s. An ideal square GIK brick is of size 5s. We are using a manufacturing process to make GIK parts of size 5s, supposedly all the same. Processing limitations inherent to a manufacturing technique will produce random errors in the size of the GIK brick. Let the size of a manufactured brick be defined by a random variable S. We call such a manufacturing process *unbiased* if and only if the random variable S describing the size of each object has a Gaussian distribution of expectation (i.e. average) $E(S)=5s$ and the size S of two different parts are uncorrelated. Let's call s^2 the variance of S, $Var(S)= s^2$. s^2 can also be seen as the manufacturing process precision. If one builds a mono-dimensional GIK structure with n of these GIK square bricks, then the size of the resulting structure will be a random variable R. R is the sum of the size of each brick and is therefore has an expected value, $E(R)=5ns$ and of variance $Var(R)=ns^2$. $\sqrt{n\,s}$ is then the standard deviation of R.

Let's assume $\sqrt{n\,s}$ is smaller than 5s. If S_{Final}, the measured size of the resulting structure, verifies

$$\left|S_{Final}-5ns\right|>2\sqrt{ns} \qquad (6)$$

there is 95% probability that there was at least one error in the structure. One can measure this parameter as the structure is being built and proceed to error correction as soon as an error rises. One can also notice that the deviation of the structure, $\sqrt{n\,s}$, is proportional to the square root of n..

The voxel based approach to building digital structures, permits us to build without achieving 100% density. This is done by selectively rejecting individual voxel sites during the building process. We built a multi layered GIK structures made out of Delrin, in which we varied the occupancy of every other layer. Structures were built with 25%, 50%, 75% and 100% of the sites occupied. We then measured the compression resistance in N/mm of the resultant structure. As seen in Fig.12, a structure can be designed with an occupancy strategy to meet a precise compression resistance. Similarly, digital materials like GIK can be engineered, to obtain the desired mechanical behavior in compression, tension and shear. Generalizing, GIK structures made of soft and hard materials during assembly could yield digital composites with unique properties.

Digital materials, like GIK, are an example of a new range of error-reducing, error-tolerating and error-detecting functional materials. GIK bricks are not limited to those described in this paper, and can be made out a gamut of materials like metals, semiconductors, insulators, ceramics, magnetic, piezoelectric optically active materials and with varying geometries. Future research in this area could open up possibilities in assembling multi-material GIKs to form active and passive electronics components (e.g. a metal GIK part and a Si GIK part can probably be put together to form a Schottky diode). Similarly, assembling together micron resolution GIKs of suitable material properties could result in photonic crystals or sonic crystals.

We propose printing of digital material as the next technology for 3-D printing of free-from structures of functional materials.

Acknowledgements

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