Digital Printing of Digital Materials

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We present a printer that builds functional three-dimensional structures by reversible assembly of a discrete set of components, "digital materials". This approach uses the components rather than a control system to impose the spatial and functional constraints. Printing can be performed as a parallel rather than a linear process. The printing process is reversible for re-use of the pieces or for error correction at any point in the object's life. Error detection, error-reduction and error-tolerance during assembly allows for reliable, high throughput printing. We are presenting development approaches to such a printing device.

The paper "Digital material for digital printing" [1] presents a digital material that can be used to 3-D print functional free-form structures. In the present paper we are describing the technical architecture of a possible printer that can do the assembly. While this assembler will be designed to use vertical GIK, a version of digital material similar to GIK [1], one should be able to modify it to assemble any digital material. Vertical GIK , as presented in figure 1, has the same properties as GIK, is forming the same press fit links as GIK, but can only be assembled vertically. Therefore a vertical GIK structure is formed (as shown in figure 1) by rotating each layer in respect to the last one by 90 degrees in order to brace two lines together.

Because the present machine will assemble a digital material which is error-tolerant and error-reducing, its metrology will be very simple. As shown in figures 1 and 2, in order to assemble a GIK structure the assembler only has to press the parts together vertically. It is therefore a 2.5 axes assembler. It's x and y precision has to be at worse the chamfer dimension ε (as presented in [1]). The chamfer size ε being typically about 1/20 of the size of a vertical GIK brick the printer needs a x-y precision of about 1 micrometer in order to assemble 20 micrometer big vertical GIK.

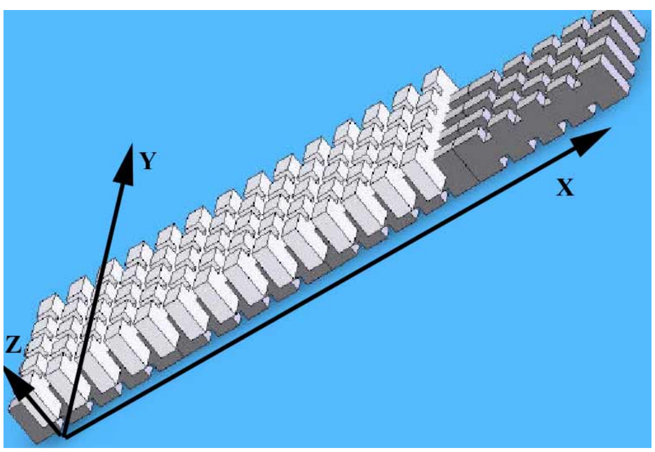

Figure 1 ***vertical GIK bricks forming an incomplete 2 layer vertical GIK structure. One can notice the 90 degree rotation between layers for bracing.***

As shown in figure 2, the assembler will use Blank parts to create overhangs or as place holders. The Blank parts are unable to create links with GIK parts but are the same dimension as a GIK part. Once the structure will be built one can discard the Blanks parts by shaking the resulting structure.

If a GIK part is 20 micrometer big, in order to build a 10 cubic cm structure one would need about 100 billion parts. In order to build such a structure in a reasonable amount of time (1 day) the assembler has to add about 1 million parts a second. This can only be done if the assembler is adding the 1 million parts simultaneously (in parallel).

Assembling Strategy

A GIK structure is composed of layers of GIK. Each GIK layer is composed of GIK lines. The main idea guiding the assembler's architecture is that the assembler is always adding lines of constant length, one entire line at a time. However each line is

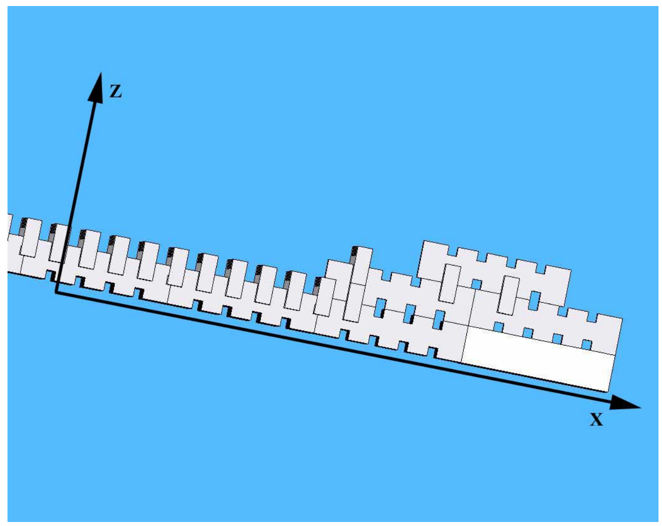

Figure 2 ***vertical GIK (gray) and Blank (white) parts forming an overhang structure. One can notice that Blank and vertical GIK are the same size and that Blank and vertical GIK don't form any links.***

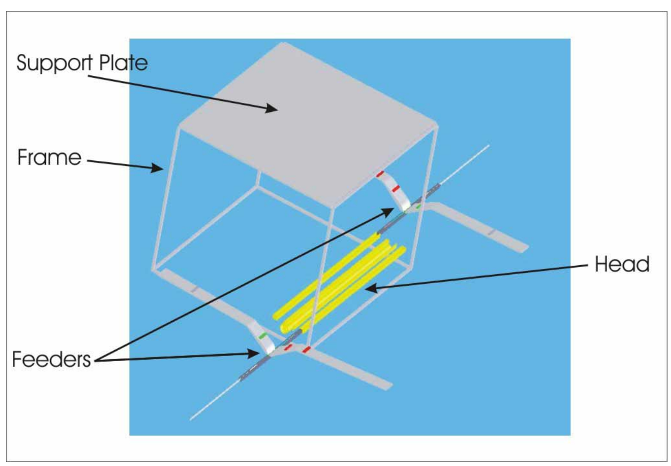

Figure 3 ***Schematic overview of a digital assembler. The digital assembler consists of a support plate which provides support for the first layer of vertical GIK and holds the object to be assembled, one or more assembly heads (yellow), and 2 feeders for each head, all of which are held together on a frame.***

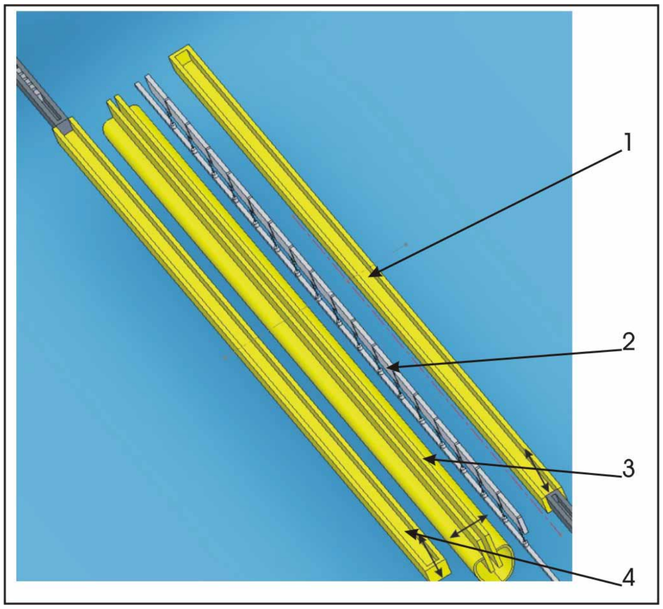

Figure 4 ***The assembler head is composed of 4 blades. 1 : building blade, 2 : error detection blade, 3: line removing blade 4: line rebuilding blade. In construction mode the blades 3 and 4 only work if an error was detected. In disassembly mode, only blade 3 functions.***

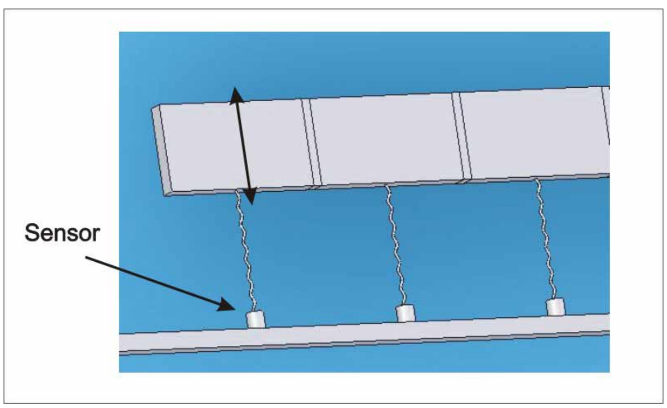

Figure 5 ***The error detection blade is composed of a touch pad which is able to move up and down and a sensor which is sensing how much pressure is applied against each touch pad. An error is detected if there is a too high pressure difference between 2 adjacent pads.***

composed of GIK only in the positions where it is supposed to add a GIK to the structure and of Blank parts otherwise. This way the structure to be built is encoded in the temporal sequence of parts that the assembler is adding.

The Digital Assembler (figure 3),a synchronized state machine, is composed of different subunits. The different subunits are: assembler head, parts feeder, the machine frame and the controller. In this proposed version of the assembler, the head consist of four “blades” that move in a linear direction as a unit, assembling GIK line by line (see figure 4).

The feeder provides the GIK parts to the head in an ordered manner, one line at a time.

The machine frame is the rigid cage all the machine functions are assembled upon. The control unit is controlling the actuators and synchronizing the different parts of the machine.

As mentioned earlier, the head consists of 4 blades and each blade has a different function: they do printing, error detection and

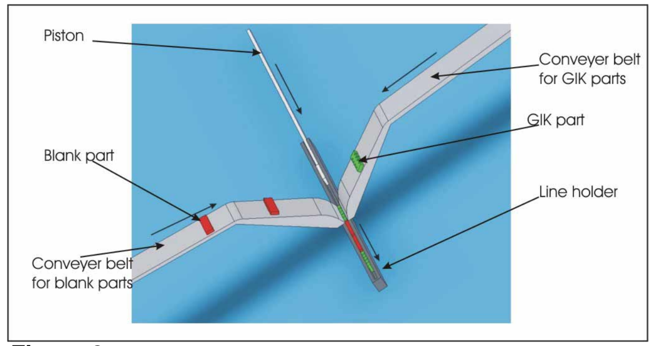

Figure 6 ***Scheme of a feeder formed by 2 conveyor belts, one for vertical GIK one for Blanks. If more than 2 parts are needed more conveyor belts can be added. The parts are deposited in a line holder (dark gray) and a piston pushed the parts in the head when the line is built.***

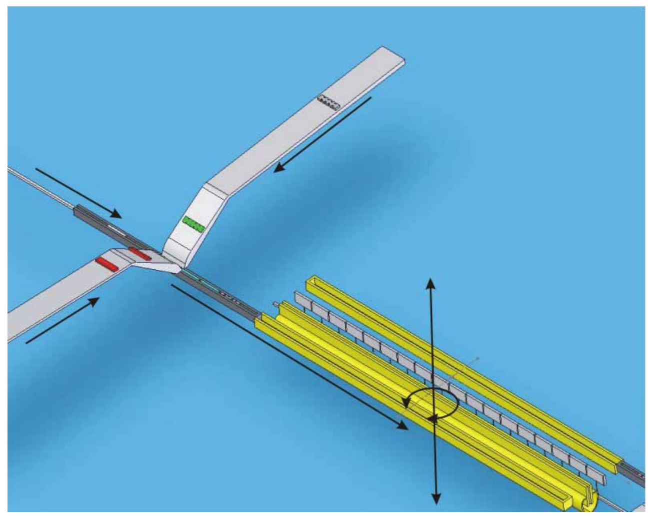

Figure 7 ***The feeder is pushing in the building blade of the head the line to be added. A second feeder (not represented) is feeding the second building blade.***

error correction (Figure 4).

The first blade in the assembler's head adds GIK. The second blade recognizes errors. The third blade removes those errors, and the fourth blade fills in GIK where the third blade had removed GIK due to errors. This method reduces the number of errors by one order of magnitude relative to not having error detection at all. Eventually, several of these head units could work in parallel.

The second blade is represented in figure 5. The blade is formed of the same number of position sensors as there are GIK pieces in a line. Each position sensor has a “touch pad” and sensor which is feeling how much pressure is applied against the “touch pad”. If this blade is pushed against a GIK line with errors, it will feel a difference in pressure between 2 adjacent sensors, and will therefore detect an error. The blades 1, 3 and 4 can be seen in figure 4. The blades 1 and 4 are building by pressing down a new line. The 3rd blade in Fig. 4 is removing GIK parts if an error occurred. The 3rd blade is removing one row at a time by clamping it and pulling it out.

The order in which the feeder supplies the GIK to the assembler determines which structure the digital printer is building. An important issue is to find at least one sequence of parts which, when assembled, will build the structure the user wants. To this purpose software must be developed.

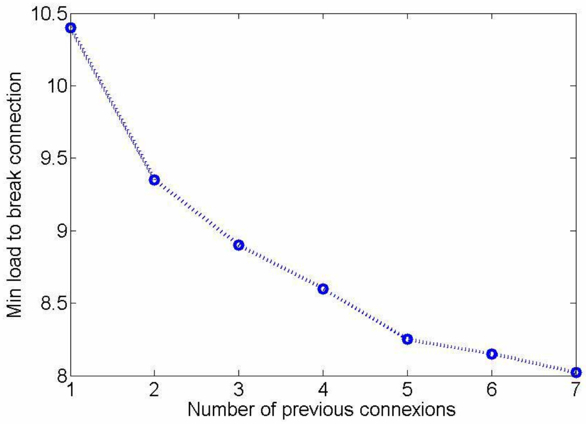

Figure 8 ***Minimum load to break a connection as a function of the number of previous connections the 2 parts previously made. The more you connect two parts together and the easier it is to disconnect them. However the lower limit seams to be within 30% of the initial value which is acceptable.***

There are different ways to implement a GIK parts feeder. In order for the machine to work at high speed, any feeder has to be able to feed one entire line to the head in the same amount of time the head takes to add one line. Figure 6 shows one possible implementation of the feeder. In this implementation, the feeder has a continuous supply of GIK and Blank parts arriving on 2 separate conveyor belts (Blank in red, GIK in green). The feeder moves the line holder (dark gray) while it is either actuating the GIK line or the Blank line. This way a legal line made out of GIK and Blank parts is formed. Once the line is ready the piston (white) is pushing the entire line into the assembler's head while making sure all the parts are in contact. If the parts are packed together appropriately they will face the slot to which they will connect.

So far, we have build by hand stable GIK structure at different scales as shown in [1]. For practical reasons, the first assembler to be built will assemble GIK at the centimeter scale. However we want to force ourselves to use only technology that can be easily adapted to future machines that will assemble micrometer big GIK parts.

Given that GIK connections are reversible, GIK structures can be changed and partially or totally recycled. In this case the assembler can use only the disassembly blade and disassemble line by line the GIK structure. The discarded parts can therefore be recycled.

However as parts are connected and disconnected, one can assume that the links get weaker and weaker. The link strength versus number of connections was measured experimentally. GIK parts were cut out of 0.1 inch +/- 5 mils white birch plywood on a commercial laser cutter. The parts were connected by hand and installed in an Instron 4411 commercial material testing machine. The parts were connected and disconnected at constant speed of 1mm per minute and the load necessary to maintain constant speed was recorded. We considered that the maximum load recorded during the disconnection part of the cycle is an indication of the link strength. As shown in Fig 7, the link strength decreases with the number of previous connections. However the lower limit seams to be within about 30% of the initial value which is satisfactory.

We presented a simple, rapid, reversible, and highly versatile printer for assembling three-dimensional digital structures. The printer achieves these qualities by employing parts that are digital in nature, and that can be made out of various materials among which are functional materials. Digital printing of digital materials, as presented in this paper, is a cheap and simple solution for 3-D printing of functional materials for free-form fabrication.

Acknowledgments

The work presented in this paper was supported by MIT's Center for Bits and Atoms (CCR-0122419).

References

[1] George A. Popescu, Tushar Mahale, Neil Gershenfeld , Digital Material for Digital Printing, Digital Printing IST Conference 2006, Denver , Colorado, USA..

[2]Neil Gershenfeld, Patrik Kunzler, George A. Popescu, Digital assembler for digital materials, Pending Provisional Patent , Assignee MIT