FULLY RECYCLABLE MULTI-MATERIAL PRINTING

Jonathan D. Hiller, Hod Lipson
Mechanical and Aerospace Engineering
Cornell University
Ithaca NY, 14853, USA

Reviewed, accepted September 15, 2009

Abstract

Recycling is often a costly and inefficient process, particularly for objects composed of multiple integrated materials. Here, we demonstrate a freeform fabrication system that prints with fully reusable physical voxels and minimal recycling effort. This new paradigm of digital (discrete) matter enables any number of materials to be printed together in any configuration. The individual voxels may then be reclaimed at will by dissolving the bonds holding the structure together. Coupled with a compatible voxel sorting process, we demonstrate multiple generations of freeform fabricated objects using the same physical material. This opens the door to a flexible desktop fabrication process in which 3D multi-material objects are fully recyclable and re-usable with minimal infrastructure.

Introduction

With the advent of multi-material additive manufacturing (AM) processes and the recent push for sustainability among developed nations, the need for recycling of additively fabricated 3D parts has become a critical need for future research (Bourell et al., 2009). The AM industry is growing steadily (Wohlers, 2008), but as AM parts see widespread adoption the potential impact has not been thoroughly considered (Yanchun et al., 1999). Here, we focus specifically on recycling end-use additively manufactured objects, not the full lifecycle analysis of additive manufactured parts (as in Jansen and Krause, 1995, Drizo and Pegna, 2006 and Hopkinson et al., 2006).

The vast majority of parts created with additive manufacturing processes today are not recycled. This is primarily for two reasons. First, in many AM processes the material in use undergoes irreversible changes such as polymerization or infiltration with binder which makes further re-use of the material intractably inefficient. Second, AM parts made of material which could theoretically be recycled, such as those using thermoplastic or metals, are not recycled due to lack of volume, incentives and infrastructure. To recycle these parts would require an infrastructure involving an energy-intensive melting stage, along with specialized equipment to return the material to its original form, such as extruded thermoplastic for fused deposition modeling (FDM) or powder of an appropriate size distribution for laser sintering. Although technically feasible, this is not common in practice, mainly due to the low volume of AM parts and the lack of economic incentive.

The challenges of recycling multi-material objects extend far beyond the realm of additive manufacturing. Vast amounts of electronics waste are laboriously and hazardously decomposed by hand in developing countries (Hilty, 2005). More generally, many manufactured parts consisting primarily of recyclable material cannot be recycled because separating the materials is often prohibitively expensive (Sodhi and Knight, 1998). A manufacturing process which addresses these challenges could have significant impact on how waste is handled. Additionally, remote situations such as space exploration would benefit from completely recyclable materials (Malone and Lipson, 2006, Robert et al., 2002).

The results presented here should not be confused with the process of recycling material involved in an AM process but unused in the final part. For instance, it is common practice to reuse the leftover resin in a stereolithography build, and it is also possible to recycle the unused bed of powder in power-based processes (Pham and Gault, 1998). The challenges in re-using and recycling these unused materials are wholly different than those needed to recycle the material used to make the actual end-use part as we address here.

Background

Digital materials are a new paradigm in which 3D matter is composed of elemental physical building blocks (voxels), as illustrated in Figure 1 (Hiller and Lipson, 2009a). In the same way as a digital signal is represented as a series of logical ones and zeros, a 3D object is represented completely by the presence or absence of a voxel at each location within its 3D lattice. The advantages of the digital realm observed in other technologies such as computing and communications have direct parallels in the world of 3D matter. An object is perfectly repeatable over an infinite number of generations and error correction can be employed to create "perfect" objects, but at the expense of increased processing effort and a finite resolution.

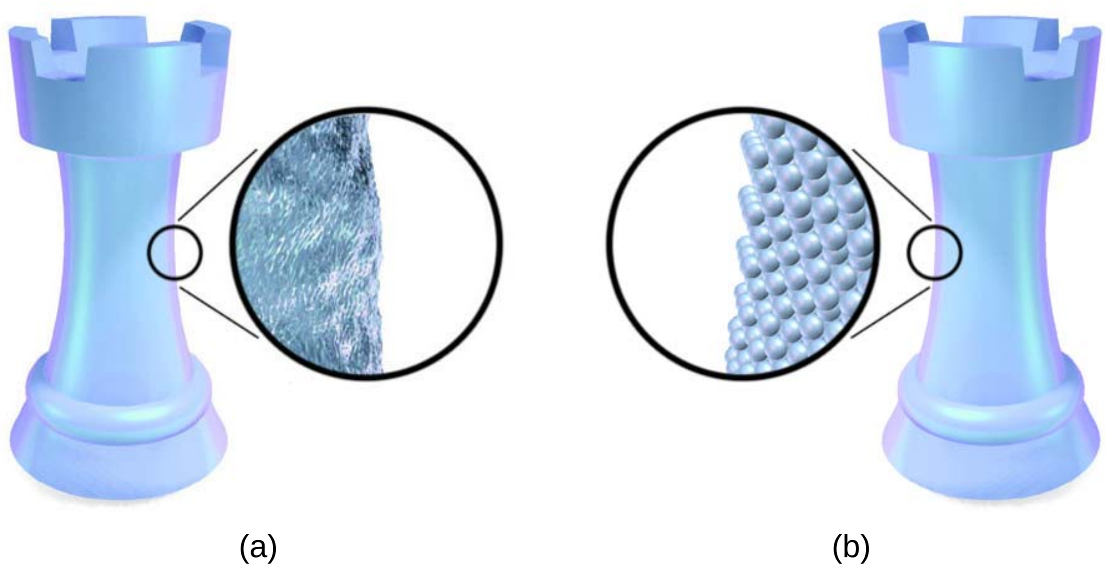


Figure 1: Traditional analog materials (a) are continuous in nature and every dimension has an associated finite error. Digital (discrete) materials are composed of fundamental, aligned building units (voxels) and the structure is defined perfectly by the presence or absence of a voxel at each location within the lattice.

When this abstract idea of digital materials becomes concrete as part of a physical voxel-based manufacturing process, a number of additional advantages are also realized. (Hiller and Lipson, 2009a) If the pre-fabricated physical voxels self align relative to their neighbors upon assembly, (such as is the case with LEGOs™ or the spherical voxels presented here) then the accuracy of the digital object is purely a function of the precision of the voxels, and not the fabricator that assembled them. This assumes the fabricator is accurate enough to place each voxel within its region of self alignment. Additionally, since the voxels are fabricated separately in highly optimized conditions, they may be composed of any sort of material, and even contain specific functionality. For instance, metal, polymer, semiconductor, ceramic, and organic voxels can be created in bulk using processes suitable for each, but in the end, each is poured into the digital fabricator and assembled identically, regardless of material or function as long as it is solid.

This opens the door to a desktop process that can print integrated, multi-material 3D objects with high precision. Much like TTL (transistor-transistor logic) standardized the physical parameters (voltage and duration) of digital signals between semiconductor devices, there must be a standard or set of standards defining the interface between voxels in a digital material in order to facilitate widespread adoption. As with other digital technologies, a finite resolution must be chosen based on the needs of the part. To appear smooth to the eye, voxels must be less than approximately 0.5mm. However, larger voxels or smaller may be more suitable, depending on the application, so a spectrum of well-defined sizes may become necessary, such as is the case for screws and other fasteners.

Another challenge facing the widespread adoption of digital materials involves the fabrication of the voxels. Technology exists to accurately manufacture voxels at virtually any size scale, such as casting, photolithography, etching, stamping, etc. However, none of these processes are currently cost effective in making millions of voxels. In order for digital materials to be economical, economies of scale must be leveraged to make billions or trillions of voxels in parallel manufacturing processes. Complexity will always have a price, but with appropriate scale and infrastructure, digital materials could conceivably become nearly as cheap as the bulk material itself.

Results and Discussion

Here we present the use of a multi-material digital fabricator using 1.5mm spherical voxels to demonstrate the reclamation and re-use of the physical voxels used to manufacture simple objects. Spherical voxels were chosen due to their ready availability in a wide range of materials and their large region of self-alignment upon deposition. This means that the voxels used in this process do not physically interlock, necessitating the use of a binder to hold the voxels together. It is important to note that the binder does not change the underlying principle of the digital material, namely the self-alignment of the voxels, it simply holds them in places during and after assembly.

Voxjet Research Platform

The Voxjet printer used here is shown in Figure 2. This USB-controlled platform is capable of simultaneously printing with three different materials and binding them together as they are placed. Additionally, a laser distance sensor enables closed loop feedback to perform error correction on the printed part. The print head scans continuously in a similar manner to an inkjet printer, and can deposit spheres of any given material in a continuous line at approximately 10Hz. When taking into account the time between rows, motion system, feedback, etc., the printer builds at a net rate of approximately 2-4 voxels per second, depending on the geometry. Thus, a 1000 element structure takes on the order of 5 minutes to build.

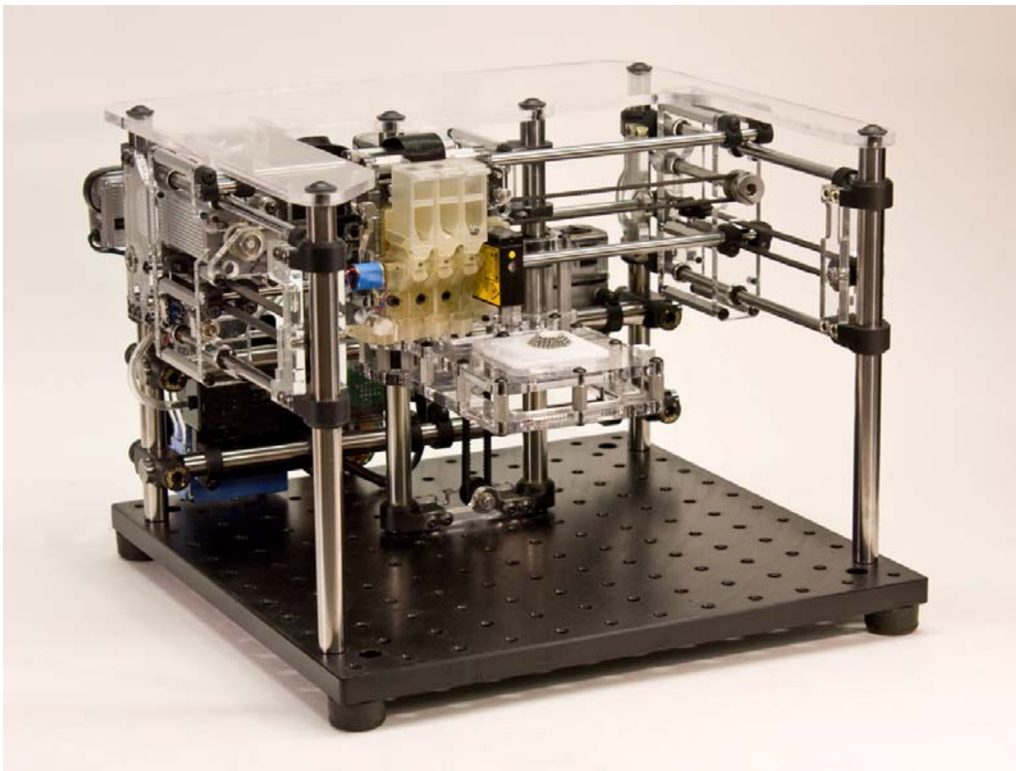


Figure 2: The VoxJet research platform was used to quickly and autonomously build multi-material structures made of hundreds of 1.5mm spherical voxels. The system also deposits binder to hold the structure together and includes error correction via closed loop deposition feedback.

In order to address the challenge of scalability, all the alignment and placing of the spheres is handled mechanically by modular deposition modules. (Figure 3) To load digital material in the module, spheres of the desired material are simply poured into the reservoir at the top of the voxel deposition module. In the first stage of the printing process, the randomly aligned spheres are ordered into a singe, one-dimensional buffer for printing. Here, the buffer is approximately twenty spheres, which is sufficient to smooth out any random variances in the rate of refilling the buffer under continuous voxel deposition. The buffer is loaded by a continuously rotating paddle wheel at the bottom of the reservoir. Each paddle captures an individual spheres and drops it into the gravity-fed buffer tube. Special care was taken in designing the geometry such that the paddle wheel does not jam with spheres and that spheres are never forced downwards into the buffer. This allows the paddle wheel to rotate continuously, even when the buffer is full, such as in between row depositions. This eliminates the need for feedback in this alignment process. The deposition modules were designed modularly such that any number may be stacked side-by side, and a single micro gearmotor attached to one extreme provides the rotation for the alignment wheel of all attached modules.

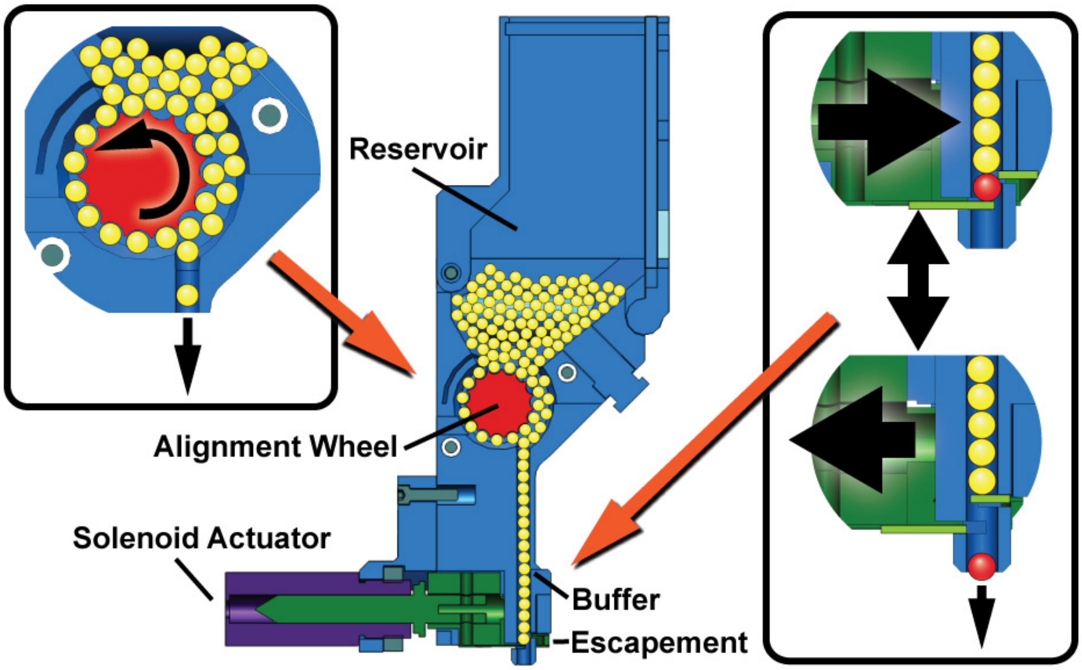


Figure 3: A cutaway diagram of the material deposition modules. Loose spheres are poured into the reservoir, which are aligned into a one-dimensional buffer by the continuously rotating alignment wheel. A solenoid actuated escapement mechanism deposits precisely one sphere with each cycle, and can reliable deposit up to ten spheres per second.

The actual deposition of individual voxels is controlled by a variation of an escapement mechanism (Figure 3) actuated by a solenoid. With each cycle of the solenoid, the buffer is advanced under the force of gravity by exactly one voxel. This works because when the solenoid activates, one tab enters the buffer stream right above the bottom sphere, holding the rest of spheres from advancing while (with the same motion) the tab holding the bottom sphere from falling is removed. When the solenoid is deactivated, it returns to the original position, allowing the buffer to advance by one. Thus, exactly one voxel falls out the bottom of the tube, at a very predictable delay from the actuation of the solenoid.

The deposition head also glues and verifies the placement of spheres (Figure 4). The application of the binder is accomplished using the standard method of a pressurized reservoir of binder controlled by a solenoid valve. For these experiments we used a polyvinyl acetate binder in aqueous solution. Advantages of this system include a relatively quick drying time, mechanical robustness, and the ability to reverse the bonding upon submersion in water. Regular white multi-purpose glue was further watered down at a ratio of 1:1 (glue to water) to yield a solution with low enough viscosity to jet. This was jetted at approximately 10psi (using a regulated diaphragm pump) through a nozzle 0.020" in diameter and solenoid actuation duration of about 17 ms.

Closed-loop feedback of the voxel deposition process is accomplished using a Baumer OADM-12 laser distance sensor, which enables error correction on the physical structure. With a theoretical measurement precision of two microns, it is trivial to determine whether a 1.5mm sphere is present or not at any giving location within a layer. The laser sensor works robustly for all materials tested, including those with diffuse surfaces and highly reflective surfaces. Even clear acrylic spheres are sensed correctly, making this a robust, material independent solution for feedback. However, the sensor does not differentiate between materials, so errors involving misplacement of material could pass undetected without the addition of optical feedback.

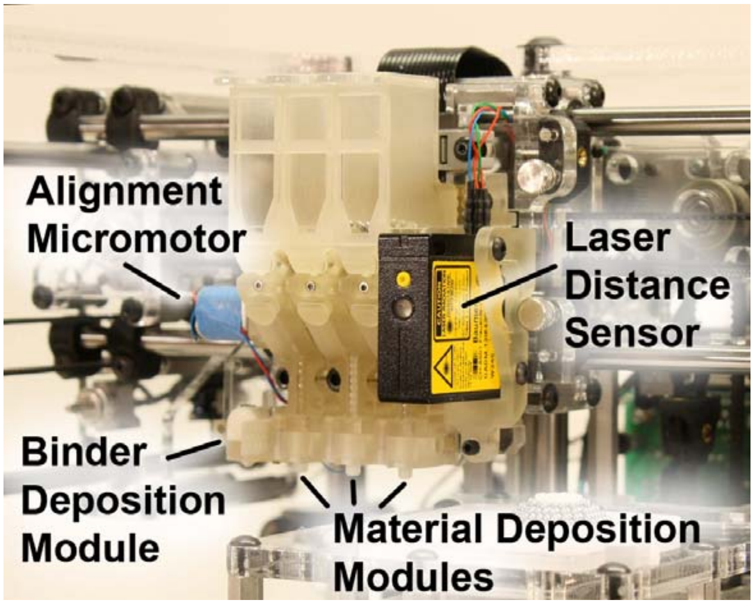


Figure 4: The deposition head consists of a binder depositing system, three separate material deposition modules, and a laser distance sensor. As the print head scans from right to left, binder is deposited appropriately, followed by spheres of any available material. The laser sensor verifies the placement of each sphere.

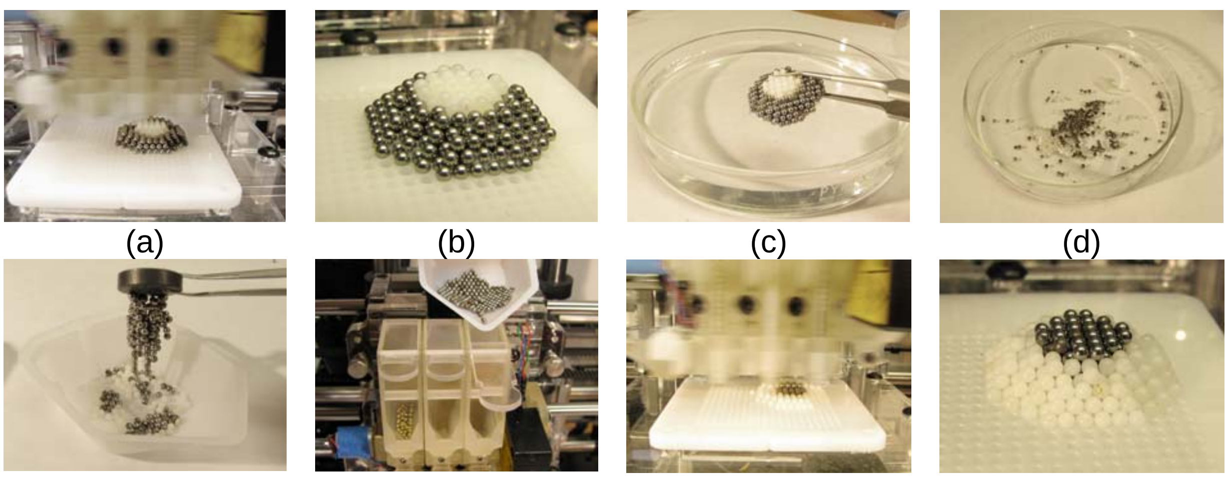
Recycling multi-material digital materials

With this robust, repeatable digital material printing framework in place, we demonstrated fully recyclable digital materials. First, two dissimilar materials were chosen to print with, in this case steel and delrin. It may be noted that this combination of materials could not be printed together using any other process. A two-material dome shape was designed for printing, containing approximately 400 voxels. (Figure 5a & b)

In the first phase, the center region of the geometry was selected to be delrin, while the periphery region was steel voxels. The structure was printed in approximately three minutes, and allowed to dry for 4 hours at room temperature, to allow the interior of the structure to dry. After this, the finished structure was removed from the base-plate. Next the voxels were reclaimed by dissolving the binder. (Figure 5c & d) The entire structure was placed in water and allowed to soak for several minutes. With the help of mechanical agitation, the spheres were separated from each other in solution, then dried. This process was repeated with clean water a second time to ensure minimal glue residue left on the voxels.

In the case of steel and delrin spheres, separating them from a common pile is trivial with the help of a low-intensity magnet (Figure 5e). High intensity magnets were avoided so that the steel spheres did not become significantly magnetized, which could interfere in the subsequent alignment and deposition process. The remaining spheres in the reservoir for each material were emptied to ensure that the recycled spheres were in fact the ones being printed, then each constituent material was poured right back into the material reservoir (Figure 5f).

The inverse shape was then printed, with steel spheres now in the center region of the geometry and delrin spheres on the peripheral region. This object was then physically printed in a similar amount of time, using the same voxels as the first object (Figure 5g & h). This demonstrates completed recycling of both materials, discounting the trace amounts of binder which was lost in the process.



(a) (b) (c) (d) (e) (f) (g) (h)

Figure 5: The process of recycling printed material: The initial object is printed consisting of both steel and delrin voxels (a and b). The finished object is removed from the base plate (c) and dropped into water to dissolve the bonds holding the voxels together (d). After mechanical agitation and drying, the spheres are sorted using a magnet to retrieve the steel spheres (e). The reclaimed raw materials are directly poured back into the deposition modules (f) and another object is printed (g) with the materials reversed (h).

Conclusions

Here, we have demonstrated for the first time the complete recycling of the materials used in a multi-material, additive manufacturing process. The process presented here scales effortlessly to arbitrarily large numbers of voxels in an object, arbitrarily small voxels, and an arbitrarily high number of materials, arranged in any spatial combination, including dense interleaving.

This paradigm is enabled by the concept of digital material, or matter composed of discrete, self-aligned fundamental building units. The spheres used here lack geometric interlocking, so binder was used to hold the structure together, which then dominates the properties of the material, especially in tension. Although this binder is not reclaimed here (It certainly could, with some additional effort), the volume of binder is very small compared to the volume of the material in the voxels. By moving to interlocking voxels in the future (Hiller and Lipson, 2009b), the need for binder is eliminated, and the physical properties of the structure are purely a function of the component voxels.

Here we demonstrate the recycling of two dissimilar materials which can easily be sorted using a magnet once the structure is decomposed. The challenges in sorting the voxels for re-use becomes more difficult when three or more materials are used, especially when those material have similar material properties. However, we do not expect this to be a significant obstacle to moving forward. Passive sorting based on density will be particularly effective, using vibrations, graded bins, etc., although the process becomes more difficult if two materials with very similar density are used. Efficient active sorting systems also exist which are capable of sorting objects based on optical properties, and one could certainly devise sorting systems based on other material properties such as electrical conductivity, permittivity, dielectric strength, thermal effects, permeability, acoustic properties, etc.

Over the course of the last several decades, many technologies have transitioned from analog to digital and never looked back, enabling greater functionality and increased adoption in all cases. Digital materials hold the promise of a precise, multi-material desktop additive manufacturing process with complete recyclability and re-usability of the component voxels. Challenges include the need for standardized interfaces between voxels and the infrastructure to produce many voxels at a reasonable cost with interesting functionality. However, when these challenges are addressed, recycling can take place at an unprecedented level. For example, an unneeded camera could be decomposed and turned into a glucose sensor in a desktop process. Waste will be minimized, and a global economy of interoperable voxels could fundamentally change the world of manufacturing.

This work was supported in part by a National Science Foundation Graduate Research Fellowship and DARPA Programmable Matter Program, grant W911NF-08-1-0140.

References

BOURELL, D. L., LEU, M. C. & ROSEN, D. W. (Eds.) (2009) *Roadmap for Additive Manufacturing: Identifying the Future of Freeform Processing,* Austin, TX, The University of Texas at Austin Laboratory for Freeform Fabrication.

DRIZO, A. & PEGNA, J. (2006) Environmental impacts of rapid prototyping: an overview of research to date. *Rapid Prototyping Journal,* 12**,** 64-71.

HILLER, J. & LIPSON, H. (2009a) Design and Analysis of Digital Materials for Physical 3D Voxel Printing. *Rapid Prototyping Journal,* 15**,** 137-149.

HILLER, J. & LIPSON, H. (2009b) Tunable Digital Material Properties for 3D Voxel Printers *Rapid Prototyping Journal*.

HILTY, L. M. (2005) Electronic waste--an emerging risk? *Environmental Impact Assessment Review,* 25**,** 431-435.

HOPKINSON, N., GAO, Y. & MCAFEE, D. (2006) Design for environment analyses applied to rapid manufacturing. *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering,* 220**,** 1363-1372.

JANSEN, H. & KRAUSE, F.-L. (Eds.) (1995) *Life-Cycle Modelling for Innovative Products and Processes,* Berlin, Chapman & Hall.

MALONE, E. & LIPSON, H. (2006) Freeform Fabrication of Complete Devices: Compact Manufacturing for Human and Robotic Exploration. *AIAA Space 2006.* San Jose, CA.

PHAM, D. T. & GAULT, R. S. (1998) A comparison of rapid prototyping technologies. *International Journal of Machine Tools and Manufacture,* 38**,** 1257-1287.

ROBERT, K. T., HAFLEY, R. A. & DICUS, D. L. (2002) Solid Freeform Fabrication: An Enabling Technology for Future Space Missions. *2002 International Conference on Metal Powder Deposition for Rapid Manufacturing.* San Antonio, TX.

SODHI, M. & KNIGHT, W. A. (1998) Product Design for Disassembly and Bulk Recycling. *CIRP Annals - Manufacturing Technology,* 47**,** 115-118.

WOHLERS, T. (2008) *Wohlers Report 2008,* Ft. Collins, CO, Wohlers Associates.

YANCHUN, L., ZHIMING, J., LEU, M. C. & CAUDILL, R. (1999) Environmental performance analysis of solid freedom fabrication processes. *Electronics and the Environment, 1999. ISEE -1999. Proceedings of the 1999 IEEE International Symposium on.*