Single-Build Additive Manufacturing of Autonomous Machines

Trevor Snyder, 3D Systems Corp, Johnathan Mick, Oregon State University, Mark Weislogel, Martin Beyl, Adam Buchholz, Emilio Molina, Daniel Norris, Kyle Viestenz, Jon Vu, Portland State University

Abstract

There are numerous 3D printing methods - each with unique attributes and limitations. There are likewise numerous end-use applications for each method. One such application discussed herein is the ability to manufacture complete and functional additive manufacturing autonomous machines. These machines are made in a single-build with no post-build assembly or added mass. These devices can store and expend internal energy to perform useful functions. While presently only mechanical in design, future materials and machine capabilities will enable the creation of highly complex single-build electromechanical devices.. This paper defines a specific type of single-build autonomous machine termed Addimata and describes key components of such devices. A selection of demonstrated designs are presented and described that utilize commonly available 3D printing processes and materials.

Introduction

The term '3D printing' describes numerous technologies capable of constructing 3D objects through the application of successive layers of material. Many consider Charles Hull the inventor of 3D printing via his creation of stereo-lithography in 1983. He founded 3D Systems in 1986, and in 1987 3D Systems was the first to commercialize a 3D printer, the SLA-1, which used stereolithography technology. Over the past three decades, major advances have been made and several new printing techniques have been developed [1]. Additive manufacturing technology is currently perceived by government and industry as a highly value-added and disruptive technology that will enable many innovations to support or directly supply the next revolution in manufacturing in the US. 3D Systems has invented and currently offers the broadest portfolio of additive manufacturing capabilities in the world [1]. Each of these technologies achieves the basic value proposition of 3D printing, but each also has unique capabilities in terms of quality, cost, and delivery to serve the market in unique ways.

Stereolithography (SLA) exposes photo-polymers to radiation (typically ultraviolet light). The radiation triggers a chemical reaction within the material causing curing of the polymer. SLA systems print with supports and are advantageous due to the speed and possible size of prints – both large and small. SLA parts are strong enough to be machined and can be used as master patterns for injection molding, thermo-forming, blow-molding and various metals casting.

The Selective Laser Sintering (SLS) method fuses powder materials layer by layer until the structure is built. To do this, a layer of material is spread evenly over a bed. Selected sections of this powdered layer are laser-fused by complete or partial melting. SLS can be used for a wide range of powder materials, including types of plastics, metals, ceramics, as well as glass, and can produce structures with high geometric complexity. It is also robust to complex overhangs due to inherent support structure created by the powdered bed.

The Plastic Jet Printing process (PJP) (also known as FDM or FFF) technique consists of the deposition of melted thermoplastics in layers. A bed is placed underneath a heated nozzle which then extrudes molten plastic onto the bed. This technology is ideal for hobbyist and consumer printers such as the 3D Systems CubePro®

The Color Jet Printing process (CJP) uses inkjet technology to deposit a liquid binder across a bed of powder. The powder is released and spread with a roller to form each new layer. The CJP process creates large-build prints in spectacular true-to-life color. Recent advances to CJP in materials and processes are used in the ProJet® 4500 which uses a material that combines full color with the toughness of plastic.

Direct Metal Printing (DMP) refers to the 3D Systems metal printing process. This process spreads fine powders of diverse metal alloys out onto a printbed, and fuses them into precise geometries using an overhead laser beam. This technology is used primarily in medical and aerospace applications, where low volumes of unique and complex models are needed. All 3D Systems' DMP printers create chemically pure, fully dense metal and even ceramic parts, all with EN ISO 2768 (fine) machining tolerances and a repeatability of about 20 μm in all directions. Materials include stainless steel, tool steel, super alloys, non-ferrous alloys, precious metals and alumina.

The MultiJet printing process (MJP) utilizes a high precision 3D inkjet printing process. This ink-jet technology is combined with wax/resin and special UV curable materials to produce highly detailed and accurate physical prototypes. The support material can be easily removed in post processing with heat. Recently introduced lower durometer (softer) parts are possible with newer model MJP printers (i.e, ProJet® 5500X) and offer a substantial increase in elongation and toughness. This allows the user to create rubbery or hard plastic parts for more diverse applications. Also, variations of the MJP process make it possible to produce wax patterns for lost-wax casting of mid-sized and large foundry applications.

3D printing is distinct when compared to subtractive processes- such as sheet metal forming and machining- that require material to be mechanically deformed and/or removed during fabrication. Processes like plastic injection molding and die-casting are common production methods for forming parts, and force molten plastic or metal into molds. In these traditional processes, the mold is of a fixed shape and size. Therefore, these processes are ideal for the high volume manufacture of identical parts at low cost, but are extremely non-ideal for custom manufacture of unique, low-volume items and/or applications that require customization. These methods involve a significant investment in time and money to create the tooling for mass production and even small changes to a design can be prohibitive. Current high volume manufacturing processes have explicit design rules and only certain types of parts with unambiguous and limited complexity can be created. In contrast, 3D printing requires no pre-forming or tooling costs and is able to directly manufacture unique parts at low volume with high geometric complexity. Additive manufacturing techniques bring benefits such as ease of prototyping, significantly increased geometric complexity, and extreme design versatility.

Certain 3D printing processes and devices are not limited to the construction of a single part during a build, but are also capable of printing an entire assembly. For example, the newest machine being engineered by 3D Systems carries the parts on numerous carts which run on a system of tracks. Figure (1) shows the top view of such a printer.

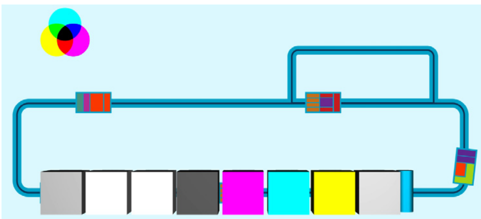

Figure 1. *Top view of printer showing cart/racetrack approach.*

This printer currently utilizes the Multijet printing process (MJP) and has banks of high precision 3D inkjet printing stations. These modular print engines can be connected together to create huge 3D printing machines and/or small factories. More materials and processes can be added through the use of this modular design concept. This type of design opens up a new and broad capability in 3D printing and will allow for increased capability and functionality of parts to be produced now and increasingly in the future. This new architecture is of particular interest with regard to the present paper.

Single-Build, Digital Additive Manufacturing of Self-Operating Machines

The adoption of 3D printing grew mostly out of a need for rapid prototypes for design and engineering. However, over time an evolutionary process has taken place where the specific needs of users and customers have crossed paths with the capabilities of the machine to create value added businesses. An example of a new field of development is in single-build digital additive manufacturing of self-operating machines. This is as fun a topic for hobbyists as it is an inspiring topic for researchers, product developers, and innovators. It is a highly synergetic field with the newest inkjet based technologies capable of utilizing multiple materials and multiple printing stations. The term used to describe these machines is DigiAddimata (Addimata for short) - machines created digitally, layer-by-layer or pixel-by-pixel. The terms DigiAddimata (plural) and Addimaton (singular) derive from the term Automata (plural) and Automaton (singular), which is a self-operating machine. Therefore, Addimata is a combination of roots from 'Additive' and 'Automaton.' The qualities of many additive manufacturing technologies are ideal for the creation of an Addimaton. The 3D Systems MultiJet Printing process in particular provides a good mix of material properties, large build area, easy to remove support material, and striking fidelity. This process was used for the work presented herein. Other print technologies can be employed, but may suffer from materials limitations and/or modular constraints. These single-build electromechanical designs require precise definitions, referred to as "The Rules of Addimata," and these rules describe and define an Addimaton. To satisfy the 'Rules of Addimata,' the Addimaton 1) must be made in a single session on one machine, 2) must be manufactured entirely by a digital additive process, 3) must be able to internally accept, store and output energy (potential energy, kinetic energy, chemical energy, electrical energy, thermal energy, etc.) 4) energy added to the device can not add significant mass to the device – electrons for battery charging can be used, 5) there can be no assembly, lubrication, or other additions of mass to the device, 6) removable components, such as projectiles or winding devices, must be printed in operating position, 7) the device must serve a noble and useful purpose to society.

Images of a sample Addimaton are shown in Fig (2) printed using the 3D Systems MJP print process.

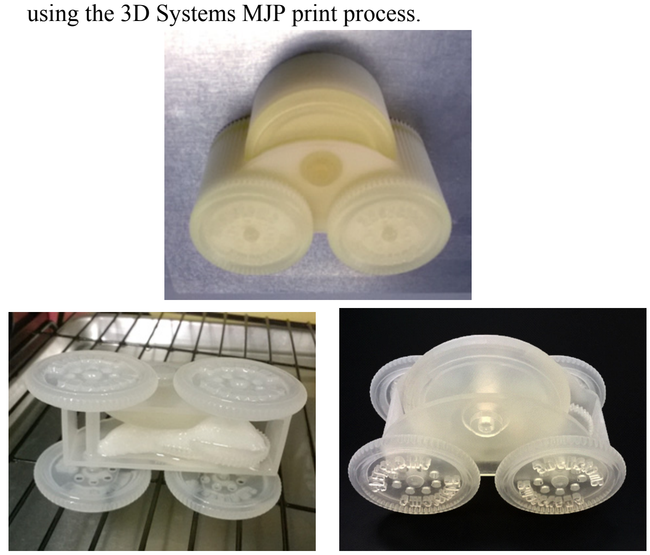

Figure 2. *A small "push-toy" car created by a single print on a 3D Systems ProJet® 3500 a) out of the printer, b) melting the support material away, c) final functional car produced in a single build with no assembly.*

'Addimata Theory' is the study of electro-mechanical machines that are manufactured with an additive manufacturing device and that obey the Rules of Addimata. For example, each member of an assembly must be carefully positioned such that there is no overlap to prevent the system from locking together kinematically. But even the simplest tolerance rules are not well known or widely published – not to mention rules for many other materials and fabrication methods foreseen for such complex components as motor design, conductor design, transistors and battery design, etc…

If an Addimaton is repaired using non-additive methods (i.e., glue, tape, soldering iron, etc.) it does not obey the rules of Addimata and the device is referred to as a 'Zombie.' The authors foresee future discussions and competitions where judges will scrutinize the purity of an Addimaton. If multiple devices are printed individually and connected together it is referred to it as a 'Frankenstein.' Specific sub-classes of Addimata are defined by their method of energy storage (mechanical, hydraulic, pneumatic, electrical, etc.) and will require slight modifications to the Rules of Addimata for each class – such as the addition of liquids and/or gasses to the device.

Machine Design Rules and Elements

There are a number of key 3D printer attributes that vary for different 3D printing processes and are foundational mechanical design elements for the construction of an Addimata. These include, but are not limited to, smallest feature resolution, slip fit capability, entrapped cavity creation, and digital material mixing.

These foundational elements can be used in the creation of beam members, shafts and frames, rotating elements, gear designs, spring designs, ball bearings, wheel designs, etc. Certain 3D printers are able to create grayscale, color, and/or surface texture which can be used for purely aesthetic purposes.

Smallest Feature Resolution

One of the most common and useful design criteria which must be understood and leveraged in the design of an Addimata is the resolution of the smallest features possible for a given technology and orientation. The simplest and most common method is to print geometric features of variable dimension and characterize those that the printer is able to reproduce. Such measurements can be made for holes and slots, as well as for protruding features such as shafts and beams. Figure (3) shows one such possible diagnostic part.

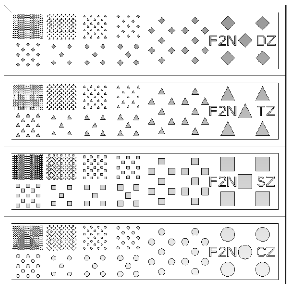

***Figure 3.** Diagnostic pattern to quantify feature resolution.*

This type of pattern can be positive (external protrusions) or negative (holes). Patterns such as this can also be printed with variable heights as the support material can often completely plug such holes in a manner that is impractical if not impossible to remove. Figure (4) shows such a pattern for a 3rd party process compare to 3D Systems MultiJet Printing process.

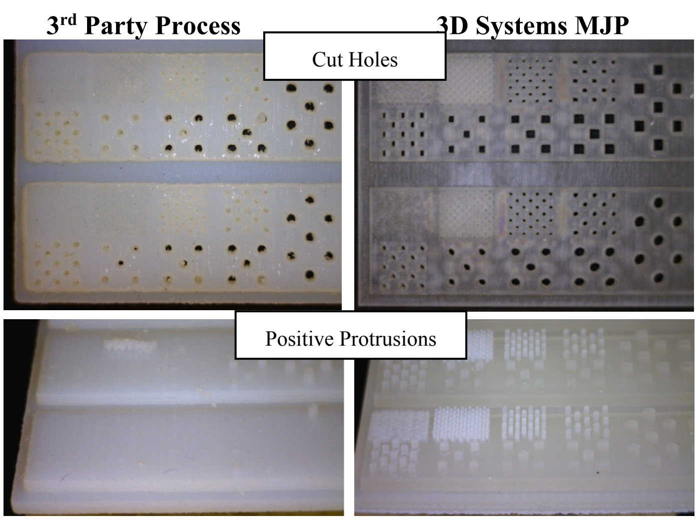

***Figure 4.** 3rd party process and MultiJet Printing cut holes and positive protrusion fine feature capability. 2.5mm thick diagnostic part with square and round holes at 0.9mm, 0.8mm, 0.7mm, 0.6mm, 0.5mm, 0.4mm, 0.3mm, 0.2mm 0.1mm.*

For hole features the 3rd party process resolves features down to ~0.6mm. 3D Systems MJP technology resolves to ~0.3mm. For positive protrusions, the 3rd party process is unable to reproduce any feature below ~0.9mm. The 3D Systems' MJP technology is able to resolve positive protrusions as small as ~0.2mm. While these features are not strong enough for many practical purposes, this diagnostic does provide a one-for-one measurement of feature resolution capability for both technologies. These capabilities are often also a function of feature depth. Figure (5) shows a diagnostic used to characterize the impact of depth and Figure (6) provides the cut hole resolution for both processes.

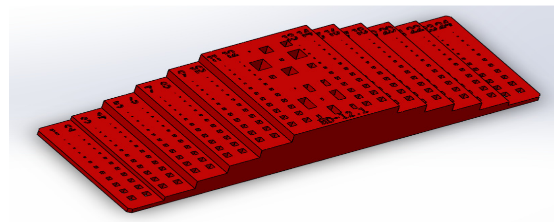

***Figure 5.** Hole test diag with variable heights*

3rd Party		Wall thickness (mm)						
		1.0	2.0	4.0	6.0	8.0	10.0	20.0
Diameter (mm)	0.1	N	N	N	N	N	N	N
	0.2	N	N	N	N	N	N	N
	0.3	N	N	N	N	N	N	N
	0.4	Y	N	N	N	N	N	N
	0.5	Y	N	N	N	N	N	N
	0.6	Y	N	N	N	N	N	N
	0.7	Y	Y	N	N	N	N	N
	0.8	Y	Y	N	N	N	N	N
	0.9	Y	Y	N	N	N	N	N
	1.0	Y	Y	N	N	N	N	N
	2.0	Y	Y	N	N	N	N	N

3DS MJP		Wall thickness (mm)						
		1.0	2.0	4.0	6.0	8.0	10.0	20.0
Diameter (mm)	0.1	N	N	N	N	N	N	N
	0.2	Y	Y	Y	Y	Y	Y	Y
	0.3	Y	Y	Y	Y	Y	Y	Y
	0.4	Y	Y	Y	Y	Y	Y	Y
	0.5	Y	Y	Y	Y	Y	Y	Y
	0.6	Y	Y	Y	Y	Y	Y	Y
	0.7	Y	Y	Y	Y	Y	Y	Y
	0.8	Y	Y	Y	Y	Y	Y	Y
	0.9	Y	Y	Y	Y	Y	Y	Y
	1.0	Y	Y	Y	Y	Y	Y	Y
	2.0	Y	Y	Y	Y	Y	Y	Y

***Figure 6.** 3rd party process and MultiJet Printing cut holes fine feature capability.*

Entrapped Cavities

Another unique requirement for many 3D printed mechanical machines is the ability to print large entrapped cavities. Each additive manufacturing technology utilizes a specific method to support overhangs. For example, SLS and CJP utilize the powdered build materials themselves which naturally surround the part. SLA is built in a liquid bath and these machines must create very small structures to support overhangs, which are typically easily removed. For example, Figure (7a-c) shows a simple pump that was printed on MJP and a 3rd party process.

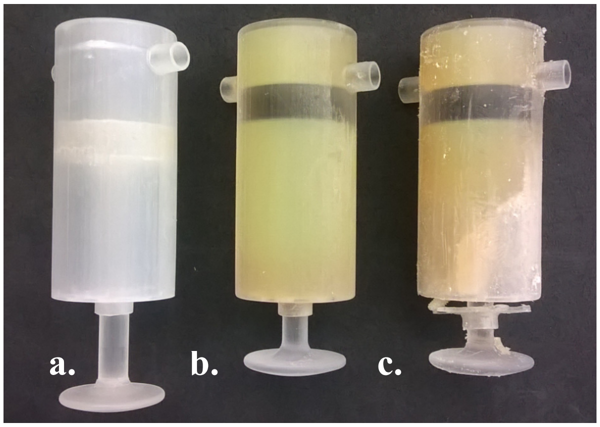

Figure 7a-c. *Simple pump printed on a) 3D Systems MJP technologyand b,c) 3rd party process*

The 3rd party process utilizes a UV curable support material that creates a solid structural mass and 3D Systems MJP utilizes a melting support wax/resin. This difference in support method can severely limit the design flexibility of single-build machines. For example, in Figure (7a) the wax support used by the 3D Systems MJP process is naturally and easily removed from the pump. Basically any entrapped cavity can be created as long as the cavity has a single small hole for the melted wax to be removed. The fluid simply drains out. In Figure (7b) the pump was printed with the 3rd party process and shows how the solid support becomes stuck within the pump cavity. Also, as shown in figure (7c) even after using high pressure water and a caustic soda soak, the 3rd party process support could not be easily removed. It is also worth noting the components of the pump in Figure (7c) were actually broken during the post process steps. Such 3rd party process failures can be avoided if strict precautions are taken, but the methods are fundamentally deficient to eliminate all such concerns.

Slip Fits

There are many uses for slip fits in engineering machine design. For example, functional turning shafts for wheels and gears can be composed as a simple slip fit between a hole and a shaft. However, even for such simple functions, 3D printing introduces new complexities for predictable and proper function. For example, 3D printers typically have raw machine resolutions that limit the minimum size of the slip fit. Also, 3D printers typically use multiple raw pixels together in a grouping known as a voxel. Therefore, the resolution and/or voxel size can be the limiting factor of the fit and rounding occurs for certain geometries. For most orientations, a slip fit is composed of a circular overhang requiring support material for its construction. The support material must be removed for proper function. Slip fits can be quantified with a simple diagnostic part like that shown in Figure (8), which can be printed in multiple directions.

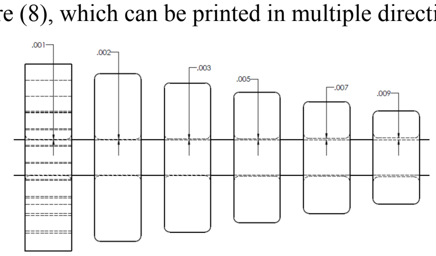

Figure 8. *Simple slip fit diagnostic with a single size shaft with five different rings, each with a variable slip fit gap.*

Additionally, the actual material and printing process can further limit the size and functionality of the slip fit. For the MJP process, the support material can be used as a lubricating surface to assist in proper function. For some gear designs performance is highly dependent on post process cleaning due to the thrust of the gears against the shafts. The gap for a functional turning slip fit using this diagnostic is shown in Figure (9) for both a 3rd party process and 3D Systems MJP technology.

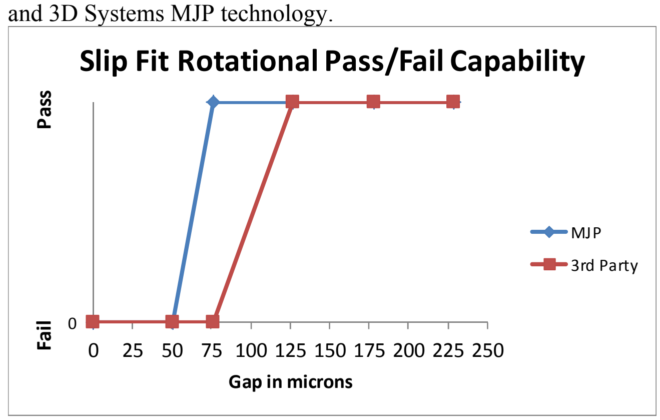

Figure 9. *Rotational slip fit for single size shaft with five different rings*

The 3D Systems MJP technology is able to create a slip fit turning shaft with as little as 76 µm (0.003") while the 3rd party process was successful at 127 µm (0.005"). Besides simple turning, this gap can impact the ability of other parts to function, as with gear meshing. It is also worth noting, that for both technologies, different diameter shafts, different length rings, and different gap sizes all require different rotational torques for proper rotation. Therefore, there is actually a 3D surface map which defines the slip fit ability for a 3D printing process. For example, small shafts may break before turning compared to a large shaft with the same turning torque requirement.

Mechanical Design Elements

With this type of basic machine understanding (and a lot of iterative testing to refine, understand, and fix errors) a basic Addimata can be created. Beams, shafts, frames, gears, springs, seals, and wheels are the fundamental building blocks for a mechanical Addimata. Such structures are items which most all current 3D printers are designed to print. Design of such elements can be completed in a similar fashion as those of traditional manufacturing processes and materials. For example, simplified algebraic solutions to governing stress equations, empirically derived relations, and finite element analysis can be utilized. This has been shown to be valid for beams and frames, gears and springs [3]. It is well known that certain 3D printing technologies can have significant material anisotropy and that often needs to be considered in the final design. However, this is not an important factor for the 3D Systems MJP technology utilized in this paper.

The use of a 3D printer with multimaterial capability (like the ProJet® 5500X) introduces many new options in terms of machine design and grayscale colorization. This printer is able to create numerous different materials by digitally mixing a UV curable soft material with a hard material in different proportions. These materials span the range of hardness between ~30 Shore A to ~75 Shore D. The softer the materials have higher toughness and higher elongation before break, but are less stiff. Currently, the soft material can be either neutral or black in color, while the hard material can be either white or clear. Most of the grayscale gamut change occurs when the material is fairly stiff and so some grayscale can be added to a design without a significant reduction in stiffness. A lightness delta of ~32 L* can be achieved with a hardness of 80 to 60 Shore D which, though not optimal, is sufficient for many aesthetic features in Addimata frames, skins, logos, etc. Figure (10) shows the hardness for 14 material levels.

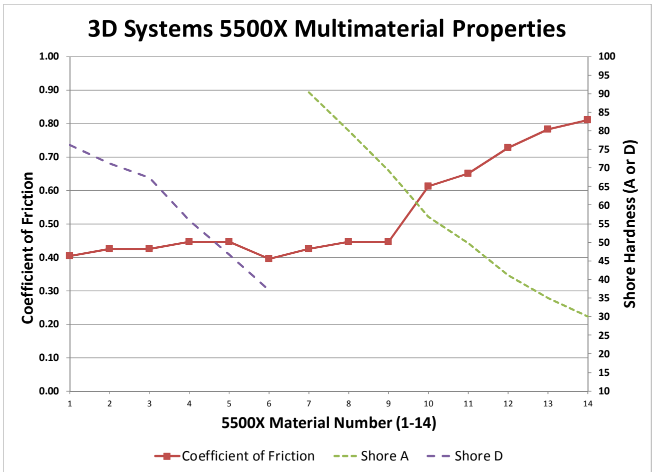

Figure 10. *Hardness and Coefficient of Friction for 5500X materials*

Coefficient of friction (COF) is important for many design features, yet is impossible to calculate empirically. Therefore, measurements were taken for COF between a wheeled surface and steel and are also plotted in Figure (10). From these measurements it can be seen that most of the traction of a wheel occurs above about a level 10 material (~55 Shore A). This level would have the best traction, while maintaining optimal resistance against wear and tearing.

In terms of aesthetics, 3D Systems MJP technology has a unique capability whereby the white support material can be entrapped within the build material. If a translucent material is used such as VisiJet® M3 Crystal or Navy, this feature can also be used to create grayscale colorization through the application of variable thickness or halftoning as shown in Figure (11).

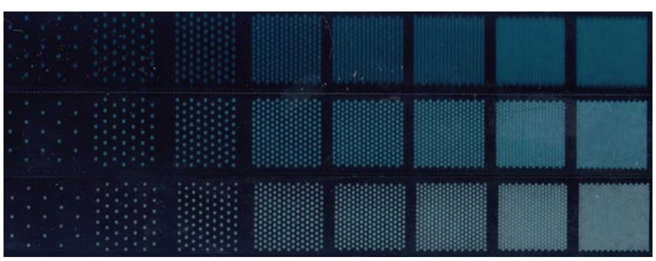

Figure 11. *MJP Grayscale Colorization using entrapped support and thickness*

Additive Manufacturing Autonomous Machine (Addimata) Design Examples

Flywheel Car

Figure (12) shows the final design of an Addimata flywheel car. The basic principal of the flywheel car is that it relies on potential energy stored in a rotating flywheel: $E = I\omega^2$, where E is kinetic energy stored, I is the moment of inertia, and ω is the angular rotation. The moment of inertia is based on mass, m, the inertial constant, k, and the radius, r, such that $I = mkr^2$. The gear train value was based on the analysis of other designs and empirical testing, e = (product of driving teeth)/(product of driven teeth). For this vehicle, the gear train value changes from 16 when being charged to 0.625 when releasing the energy. This design allowed for quick energy storage and slow release energy. The flywheel mass was 41.2 g and radius of 30.75 mm. This design was a balance of total energy while keeping the print height as low as possible for the fastest printing. Large radial fillets were added to reduce the stress concentration between the vehicle support cross beams. The essential traction of the tires is significantly enhanced by printing the exterior rim of the tires with a softer grooved material.

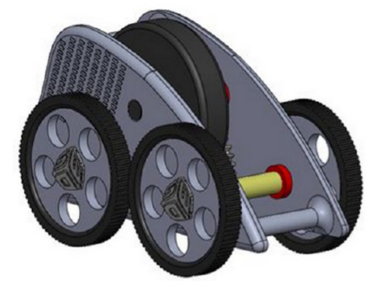

Figure 12. *Flywheel Car (push-toy) [3]*

Wind-up Car

Figure (13) shows the final design of an Addimata wind-up car. A single spring energy system is a simple and compact way of storing energy. A ratchet and pawl mechanism was used to transmit the torque of the unwinding spring to the gear train. This method allows the user to wind the spring without overcoming the friction of the gear train and provides audible clicks as the system is being charged. Spur gears were used to step up the velocity of the rotational motion as the spring unwinds.

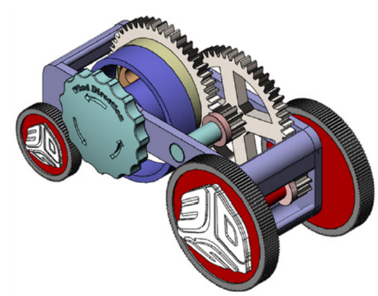

Figure 13. *Wind-up (Spring) Car [3]*

This design also allows for easy visual verification of the clearances and tolerances during the fabrication process. A gear ratio of 100:1 was chosen via empirical testing. Higher gear ratios require prohibitively large spring forces and much lower ratios and the car would not travel a significant distance. A gear module of 1.2 mm/tooth, and a fairly large backlash clearance of 0.5 mm were chosen. In total, an overall size of 130 mm in length and 75 mm in print height was used providing ease of use, a short printing time, and robust performance.

Pressure Vessel Rocket Launcher

Figure (14) shows the final design of an Addimata pressure vessel rocket launcher. This design utilizes a pump, two check valves, a pressure vessel, a release valve and a rocket. Air is pumped into the pressure vessel with the use of an external pump connected to a check valve. The check valve is composed of a simple ball element with a tapered seal on one end and an open structure on the other. The release valve is composed of an angled surface that mates tightly with a sealing surface that is at the same angle. The compressed air is released by pushing down on the release valve which directs airflow toward the exit nozzle where the rocket rests. In alternative designs the pump can be printed as well. In these designs, the pump seal can be composed of a simple slip fit. Also, a ring with an open slot can be printed within a groove in the pump wall. The ring is compressed when the pump is first engaged and this compression creates the seal similar to an automotive ring design. In an alternative design, the piston can be printed with flexible material using a printer such as the ProJet® 5500X and can be printed within the pressure vessel. To create the required pressure seal, the flexible material on the pump surface is printed within a groove that is cut out from the pump wall. The geometry allows the flexible material to act as a spring loaded O-ring. This prevents wear of the material while maintaining the seal. It was determined that the pressure vessel can operate between 5-40 psig with an evaluated factor of safety of 2 via Finite Element Analysis (FEA). Following pressurization, the pressure relief valve is depressed and the high pressure gas expands behind the rocket which is printed of a soft polymer and can be propelled across a room ~5m

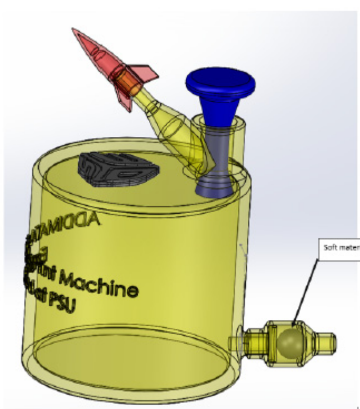

Figure 14. *Pressure Vessel Rocket Launcher [3]*

Table-top Helical Spring Rocket Launcher

Figure (15) shows the final design of the tabletop rocket launcher. A rectangular housing was designed with cutouts to see the operation of the four helical springs for aesthetic purposes and to release support material. The housing has four posts that span the height and are centered on each helical spring. These provide stability for springs and structural support for the housing. The springs were designed using classical spring equations as discussed previously. Latches were added to the sides of the housing to lock the launch platform in the charged position. When the bottom, angled portions of the latches are squeezed, the latches open and release the platform. An FEA was performed on the launch platform and the latches to highlight key areas where structural support was needed and was used to decide how to stiffen the platform. A shelled platform was used with large cross rib and solid launch tabs and this achieved a 14% reduction in weight compared to the solid platform while maintaining structural integrity. Numerous other additive manufacturing machines were produced State University as part of

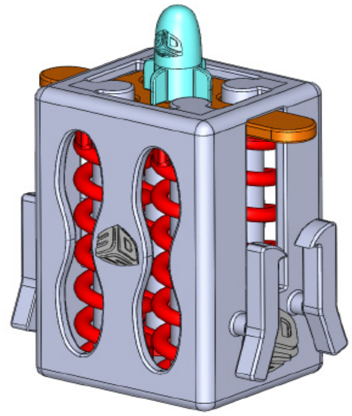

Figure 15. *Table top rocket launcher [3]*

Conclusion

3D printers are currently able to print not only highly complex components and parts, but also highly complex and fully functional assemblies. In such designs, the capability and complexity of the design is highly dependent on the 3D printing technology. One of the most capable technologies for such devices is the 3D Systems MultJet printing process (MJP) which utilizes a high precision 3D inkjet printing process. This ink-jet technology is combined with wax/resin and/or UV curable materials to produce highly detailed and accurate physical prototypes. High resolution is attainable using a support material that can be easily removed in post processing. Recently introduced lower durometer (softer) parts are possible with newer model MJP printers (i.e, ProJet® 5500X) and offer a substantial increase in elongation and toughness. These attributes allow the user to create soft (rubbery) or hard plastic parts for a wide range of applications. While these complex assemblies are possible, additive manufacturing of autonomous machines is currently in its infancy. Hopefully, the information in this paper and its numerous examples will foster connections in the community with others who can help develop design rules and engineering data as well as join the fun in designing and printing additive manufacturing autonomous machines.

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Author Biography

Dr. Trevor Snyder is a Principal Mechanical Engineer and Scientist working for 3D Systems in Wilsonville Oregon. Mark Weislogel is a professor at Portland State University. Jonathan Mick is a student at Oregon State University, The other authors are students in mechanical engineering who completed much of this work as part of their senior design capstone project.