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A TRIZ-BASED ANALYSIS OF THE FUNDAMENTAL LIMITS OF FUSED FILAMENT FABRICATION

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Abstract

Each category of additive manufacturing (AM) has specific fundamental limitations bounded by the physics and material properties involved. For example, the speed of fused filament fabrication (FFF) processes is bounded by how quickly thermoplastics can be melted, deposited, and resolidified while retaining material properties and dimensional accuracy. Incremental improvements approaching these theoretical limits will continue to occur, but more radical changes are necessary to completely overcome the current constraints. This paper considers some of the fundamental limits bounding FFF processes and investigates possible avenues for future research to overcome these limits. The framework for this analysis is the "Theory of Inventive Problem Solving" (TRIZ), a formalized problem solving and ideation tool that generalizes design-specific problems into contradicting engineering parameters, then suggests universal design principles based on analogy to solutions in other systems and patents. TRIZ has been used in many fields successfully, including the design of parts to be more manufacturable through AM, but literature on its application to additive manufacturing processes themselves is limited. Two case studies are shared demonstrating how TRIZ-based analysis can lead to radical improvements in FFF and other AM technologies.

Keywords

TRIZ, Theory of Inventive Problem Solving, Design for Additive Manufacturing

Introduction

The evolution of additive manufacturing (AM) has consistently been a path of combining and repurposing technologies in novel ways. Stereolithography (SLA) combined the idea of lithography, (where an image is transferred between media via a liquid) with photosensitive polymers, ultraviolet lasers, and computer-controlled motion [1]. Similarly, fused filament fabrication (FFF) took the basic idea of material extrusion, like a hot glue gun, and added computer control of motion, temperature, and extrusion rate sufficient to create free-standing structures [2]. Later developments also found innovative solutions by combining techniques and materials in new ways. Multi Jet Fusion (MJF), for example, combines aspects of binder jetting

(BJ), material jetting (MJ), and selective laser sintering (SLS) to form a new process that has distinct advantages in areas like speed and material properties [3].

Innovation in any field is comprised by steady incremental improvement, punctuated by more substantial shifts like those described above. Within each AM technology, processes are improving steadily every year as parameters are adjusted, new materials are developed, and hardware is improved. However, this incremental, continuous improvement is bound by fundamental limits in physics, chemistry, and other areas. Properties like the heat transfer rate of polymers, the wavelength compatibility of photopolymers, and the effect of heating and cooling rates on metal grain structure place limits on the speeds, resolution, and material strengths possible through AM, which incremental improvements can approach, but never surpass. Only through the development of "out-of-the-box" innovations can these fundamental limits be overcome.

Fused filament fabrication is characterized by several of these fundamental limits. At a high level, applications using this technology are typically bounded by three aspects:

1. Processing speed – how quickly the part can be produced.
2. Accuracy/resolution – the dimensional accuracy, smallest feature size, surface finish, etc.
3. Material properties – strength, toughness, ductility, hardness, inter-layer bonding, etc.

There are many lower-level rate limits that affect these three aspects. Research by Go, et al. found that processing speed, for example, is limited by the amount of force that can be exerted by the extruder to reliably feed the filament, the heat transfer in the liquefier (hot end) and nozzle, and the dynamic behavior of the motion system. These rates can be improved to an extent but will eventually approach the theoretical limits for the hardware and materials.

This concept of incremental improvement, limited by fundamental limits or contradictions, interrupted by significant leaps as the limits and contradictions are overcome or avoided, is well described by the Theory of Inventive Problem Solving ("TRIZ," from the original Russian). TRIZ states that all designed systems evolve towards ideality (greatest benefit and least cost), and that this evolution is characterized by both slow continuous improvement and sudden bursts of radical change. This is also shown by the concept of an innovation "S-curve," popularized by Foster [4] and Christensen [5]. As a system develops, it improves quickly for a while, but eventually reaches a point of stagnation, where no further improvement is possible. At this point, innovation continues by a shift to a new underdeveloped system, which grows to outperform the previous iteration (Figure 1). The new system can either be a completely new technology or the existing technology with a radical innovation that overcomes previously insurmountable limits.

The changes in technology in the music and film industries are often shared as an example of this concept [5]. Delivery systems for media have undergone drastic changes over the last few decades. Some jumps between S-curves were due to new technological breakthroughs, like the changes from CDs to DVDs to Blu-ray. Other jumps occurred when entire platforms were abandoned in favor of different solutions, like the changes from cassette tapes to CDs and from CDs to mp3 files.

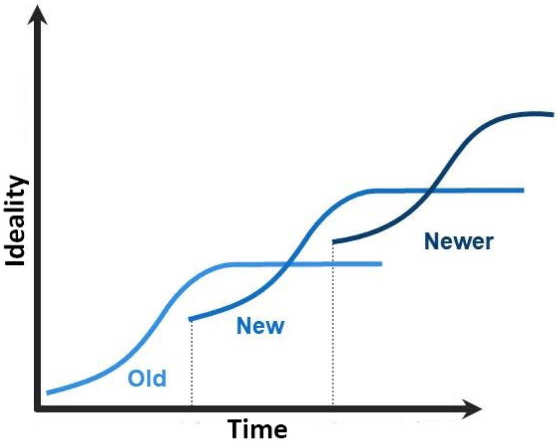


Figure 1. Innovation follows a repeated S-curve.

Fused filament fabrication may be approaching the top of an S-curve. Following the expiration of key patents in and around 2009 [6], there was a massive influx of new development and innovation, resulting in the creation of a thriving population of inexpensive and reasonably capable consumer 3D printers. However, over the last few years, though incremental improvements and prices reductions continue, there has been a slowing of substantial deviation from a few popular templates. It may be time to investigate the possibility of radical improvement to FFF technology that goes beyond optimizing parameters, fundamentally shifting the technology to a new S-curve.

TRIZ offers a powerful method for innovating new solutions to difficult engineering problems. This design theory is an inductively based set of principles, laws, and guidelines based on the study of hundreds of thousands of existing products, patents, and inventions [7]. Through a four-step process described in the following sections, TRIZ searches for solutions that do not compromise or optimize between competing aspects of a design like speed and accuracy, but rather overcome the contradiction entirely. This paper explains the basic process followed in the TRIZ methodology. It then investigates some of the fundamental properties limiting improvement of the FFF additive manufacturing process. Finally, the study applies the tools of TRIZ to recommend areas of innovation that may be able to overcome these limitations in FFF.

Overview of TRIZ

TRIZ was first developed by Genrick Altshuller in the Soviet Union starting in 1946 [7]. Through the analysis of literally millions of patents worldwide, TRIZ identifies common themes, principles, and methods that are used in innovation. Some of the main ideas found by TRIZ include:

- The same problems and solutions appear repeatedly across different industries and sciences (someone has seen your problem before and solved it).
- The most effective solution eliminates compromises between contradictory aspects of a design (it finds a way to satisfy both fully).
- The strategies for eliminating these contradictions are common across different industries and sciences (there are a small number of general principles that occur over and over in innovation).
- The most effective solutions also make better use of resources already available instead of adding new resources to the system (make what is already there work better before adding more complexity).
- Technology evolution trends follow predictable paths (you can predict the general directions a technology will evolve based on what has occurred in other fields).

TRIZ includes many tools, but the overall methodology for innovation is shown in Figure 2. For any given engineering problem, a solution may be sought by translating the problem into a generic contradiction between competing elements, observing what principles are generally used in solving this type of contradiction, and then using the same principles to innovate specific solutions to the problem.

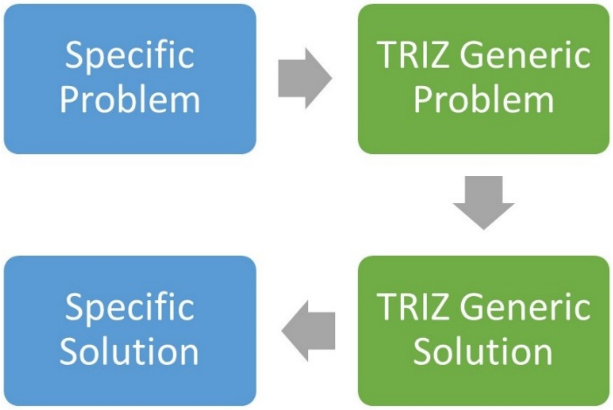
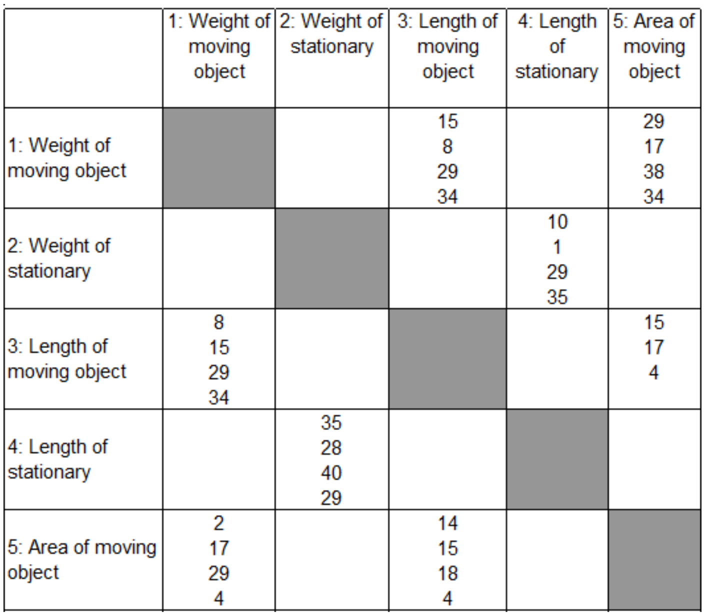


Figure 2. The basic TRIZ problem solving process.

As an example, one problem encountered in FFF processes is that the polymer must have low viscosity during extrusion so it can flow easily, but then have high viscosity immediately afterward, so it stays where it is deposited without spreading or oozing. Typical problem solving would try to find a compromise – the extruder temperature that offers the best tradeoff between extrusion force and stability of the printed layer. However, by looking at other problems that dealt with improving a force or temperature while preserving stability, we might come across ideas like “preliminary action” (pre-arranging objects so they are used exactly where and when needed) and “segmentation” (splitting a system into isolated parts). This might lead us to the specific solution of aiming a cooling fan at the polymer right as it comes out of the nozzle and meets the print surface – which of course is the solution commonly used in this situation to allow higher extrusion temperatures while maintaining stability of the printed material.

The data on how situations like this were solved over and over in various fields have been collected into a set of 39 “engineering parameters” (like force, temperature, stability, etc.) and 40 “inventive principles” (like preliminary action, segmentation, etc.). For any pair of contradicting parameters, there may be one or more principles that are frequently used to innovate solutions. For example, for the contradiction between force and stability described above, TRIZ recommends the principle of preliminary action, as well as the principles of “parameter changes” and “skipping.” All these parameter contradictions and their corresponding principles can be mapped out on a 39 x 39 matrix (Figure 3) or can be accessed via website apps [8].



	1: Weight of moving object	2: Weight of stationary	3: Length of moving object	4: Length of stationary	5: Area of moving object
1: Weight of moving object	▨		15 8 29 34		29 17 38 34
2: Weight of stationary		▨		10 1 29 35	
3: Length of moving object	8 15 29 34		▨		15 17 4
4: Length of stationary		35 28 40 29		▨	
5: Area of moving object	2 17 29 4		14 15 18 4		▨

Figure 3. A portion of the 39 x 39 Contradiction Matrix. Note that each cell refers to relevant inventive principles by number (1-40).

The contradictions matrix and other similar TRIZ tools are particularly well suited for innovating in the flat areas at the beginning and end of an S curve [9]. In a brand-new technology, there are many technical hurdles to overcome in areas where the designers lack experience. In a mature, stable technology, the effectiveness of the systems begins to run into the hard limits imposed by the physical realities of the processes involved. In both instances, TRIZ tools can help designers find “out-of-the-box” solutions that spur rapid innovation and growth into new areas.

Limits of FFF Processes

Fused filament fabrication, also called fused deposition modeling (FDM), is the most popular and widespread form of 3D printing, especially at the consumer/hobbyist level. FFF is a method of additive manufacturing where a thermoplastic filament is fed into a heating chamber, heated to melting temperature, and then extruded in tracks onto a surface layer-by-layer to form the desired part. Figure 4 shows a Prusa i3 MK3S, a popular desktop 3D printer. FFF machines typically are composed of the following subsystems:

- A printhead assembly consisting of a filament feeder, a heating chamber (“liquifier” or “hot end”), and a nozzle.
- An extrusion motor that drives the filament feeder (can be attached to the printhead or fixed elsewhere on the printer).
- A print bed, on which the extruded material is deposited.
- A gantry system with motors to drive the XYZ position of the printhead relative to the print bed.
- Fans, heating elements and sensors to control the temperatures of the heating chamber, extruded material, and print bed.
- Electronics and a power source to coordinate the motors, heating elements, fans, and sensors.

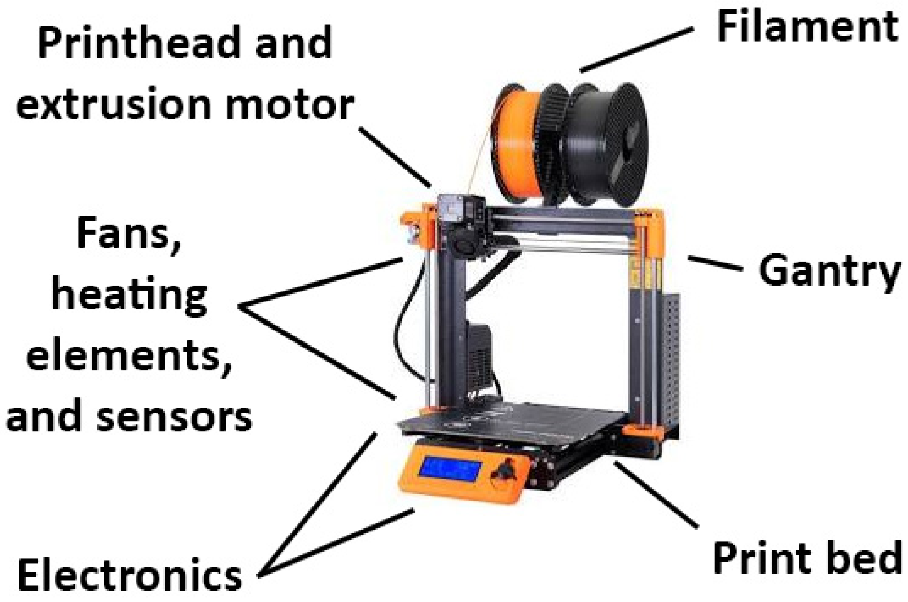


Figure 4. Subsystems of an FFF machine.

Table 1. Limiting Factors for Processing Speed in FFF Processes [10].

Filament feeder	Extruder force capability	• Extruder motor torque • Friction between drive wheel and filament • Shear strength of filament • Stiffness of filament • Resistance pressure from heating chamber and nozzle • Structural integrity of printhead components
Heating chamber and nozzle	Melting rate of polymer in heating chamber	• Material properties of polymer filament • Heat transfer from heating elements to heating chamber to polymer • Geometry of heating chamber and nozzle
Nozzle, fans, and print bed	Cooling rate of polymer after deposition	• Material properties of polymer filament • Convection heat transfer from extruded polymer to air aided by fans • Conduction heat transfer from extruded polymer to print bed and previously printed material
Gantry	Dynamic motion of gantry	• Capabilities of stepper motors • Stiffness and mass of gantry components, print bed, and printhead • Control of motors by electronics
Print bed, nozzle, and filament	Adhesion of extruded polymer to print bed and previous layers	• Material properties of polymer • Surface properties of print bed • Heating and cooling capabilities of system • Accuracy of distance between nozzle and print bed/previous layer • Pressure of extruded material against print bed/previous layer • Temperature of extruded material • Temperature of print bed/previous layer
Electronics	Data speed of commands to motors	• Memory available • Computing power available • Buffer/cache sizes allotted • Protocol (USB, Wifi, etc.)

The technologies driving FFF have developed through the hard work and innovation of countless engineers, designers, and makers over several decades. New improvements continue to appear every year. However, at some point, theoretical limits to various properties and phenomena involved in FFF printing will begin to bound the extent of its capabilities. Table 1 shows a list of factors inherent to current FFF processes that limit processing speed capabilities. Table 2 shows factors that limit the dimensional accuracy, resolution, and surface finish capabilities, and Table 3 shows factors limiting the physical properties of the final printed part. Detailed description of each limiting factor will not be included in this paper, but a few examples will be explored in more depth as a case study of the TRIZ method.

Table 2. Limiting Factors for Accuracy and Resolution in FFF Processes [11-14].

Electronics	Control of motion system	• Resolution of Gcode movement commands • Ability of software to correct for dynamic behavior of motion system and extruder (linear advance, etc.) • Timing accuracy of commands to motors
Stepper motors	Accuracy of motor movement	• Accuracy of motor steps to distance conversion • Response time after receiving signal • Dynamic behavior of motors (acceleration, jerk, etc.)
Gantry	Dynamic motion of gantry	• Stiffness and mass of gantry components, print bed, and printhead
Filament feeder	Extrusion rate	• Consistency of extruder motor torque • Consistency of flow within heating chamber • Consistency of flow through nozzle
Nozzle	Accuracy of material deposition	• Geometry and surface finish of nozzle • Temperature of molten polymer • Accuracy of distance from nozzle to surface • Extrusion rate
Print bed, fans, material and environment	Warping or sagging after deposition of material	• Localized stresses and shrinkage due to heating and cooling of extruded material and adhesion to print bed or previous layer • Density, viscosity, and surface tension of material

Table 3. Limiting Factors for Material Properties in FFF Processes [15, 16].

Polymer filament	Raw material physical properties	• Strength, hardness, stiffness, ductility, density, etc. of material in filament form
Heating chamber and environment	Thermal effects of heating and cooling	• Changes to material properties due to degradation, localized stresses, or annealing as the material is heated and cooled
Extruded polymer, print bed, previous layers	Inter-track and interlayer adhesion	• Mechanical bond between different tracks of material in the same layer • Mechanical bond between tracks on different layers • Mechanical and/or chemical bond between material and print bed surface • Surface area, surface roughness, porosity, and defects of surfaces in contact
Slicing software	Internal geometry of part	• Infill, perimeters, layer height, and other parameters

The remainder of this paper explores a sample methodology for applying TRIZ to additive manufacturing's bounding limits. It then illustrates how using this method can spur innovation focused on some of the major issues currently facing FFF technology.

Method

Several studies in recent years have applied a TRIZ framework to the area of Design for Additive Manufacturing (DfAM) to aid in harnessing the strengths of AM to create better parts and products [17, 18]. One such study [19] considered the 39 parameters of TRIZ and determined that most common problems in DfAM could be tracked to just eight of the parameters: weight of a stationary object, length of a stationary object, shape, strength, loss of time, accuracy, ease of manufacture, and stability of an object. This simplification allowed for a quicker and more understandable means of exploring the contradiction matrix without getting hung up on options that rarely applied. It would be beneficial to apply a similar simplification process to the parameters involved in FFF processes.

The limiting factors of FFF can be considered at multiple levels. At the highest level, we can identify common trade-offs between the three categories of speed, accuracy, and material properties (such as strength). Some of the primary contradictions between these goals are shown in Table 4.

Table 4. Common Contradictions in FFF

First parameter	**Competing parameter**
SPEED VS ACCURACY	
Speed	Manufacturing Accuracy
Speed	Weight of Moving Object
Speed	Pressure
Speed	Force
Speed	Stability of Object
SPEED VS MATERIAL PROPERTIES	
Speed	Strength
Speed	Temperature
Speed	Ext. Harm Affecting Object
Speed	Pressure
Speed	Stability
ACCURACY VS MATERIAL PROPERTIES	
Manufacturing Accuracy	Strength
Temperature	Strength
Shape	Strength
Shape	Stability

Table 5. Simplified contradiction matrix for FFF processes

	1 weight of moving object	9 speed	10 force	11 pressure	12 shape	13 stability of object	14 strength	17 temperature	29 mfg accuracy	30 external harm affects object
1 weight of moving object		2,8, 15,38	8,10, 18,37	10,36, 37,40	10,14, 35,40	1,35, 19,39	28,27, 18,40	6,29, 4,38	28,35, 26,18	22,21, 18,27
9 speed	2,28, 13,38		13,28, 15,19	6,18, 38,40	35,15, 18,34	28,33, 1,18	8,3, 26,14	28,30, 36,2	10,28, 32,25	1,28, 35,23
10 force	8,1, 37,18	13,28, 15,12		18,21, 11	10,35, 40,34	35,10, 21	35,10, 14,27	35,10, 21	28,29, 37,36	1,35, 40,18
11 pressure	10,36, 37,40	6,35, 36	36,35, 21		35,4, 15,10	35,33, 2,40	9,18, 3,40	35,39, 19,2	3,35	22,2, 37
12 shape	8,10, 29,40	35,15, 34,18	35,10, 37,40	34,15, 10,14		33,1, 18,4	30,14, 10,40	22,14, 19,32	32,30, 40	22,1, 2,35
13 stability of object	21,35, 2,39	33,15, 28,18	10,35, 21,16	2,35, 40	22,1, 18,4		17,9, 15	35,1, 32	18	35,24, 30,18
14 strength	1,8, 40,15	8,13, 26,14	10,18, 3,14	10,3, 18,40	10,30, 35,40	13,17, 35		30,10, 40	3,27	18,35, 37,1
17 temperature	36,22, 6,38	2,28, 36,30	35,10, 3,21	35,39, 19,2	14,22, 19,32	1,35, 32	10,30, 22,40		24	22,33, 35,2
29 mfg accuracy	28,32, 13,18	10,28, 32	28,19, 34,36	3,35	32,30, 40	30,18	3,27	19,26		26,28, 10,36
30 external harm affects object	22,21, 27,39	21,22, 35,28	13,35, 39,18	22,2, 37	22,1, 3,35	35,24, 30,18	18,35, 37,1	22,33, 35,2	26,28, 10,18	

However, at a more fundamental level, contradictions also occur within each of these categories. For example, to increase speed, we may want to reduce the weight of moving objects like the printhead assembly. This would, however, limit the extruder motor torque, heating capabilities of the liquefier, and other aspects that also influence print speed. These more complicated relationships correlate to most, if not all, of the original 39 parameters, and we recommend considering the full contradiction matrix for these instances.

Table 5 shows the simplified contradiction matrix that includes the competing aspects discovered in Table 4. This matrix can be used for an initial analysis of the three top categories (speed, accuracy, and material properties). As noted earlier, a full analysis of the complete contradiction matrix is also recommended when considering contradictions on a more fundamental level.

Once the contradiction matrix has been used to identify the principles associated with solving the contradiction in question, these principles can be used as seeds for ideation, using any number of common concept generation techniques. To aid in this, many TRIZ resources include example solutions in their descriptions of the innovation principles. For example, one repository [8] shares the following for their description of principle #1:

Segmentation

- Divide an object into independent parts
    - Example: Replace mainframe computer by personal computers
- Make an object easy to disassemble
    - Example: Quick disconnect joints in plumbing
- Increase the degree of fragmentation or segmentation
    - Example: Replace solid shades with Venetian blinds

Through design-by-analogy, mind mapping, 6-3-5 brainwriting, or other methods, new innovative concepts can be developed that use the principle to solve the issue at hand.

Case Studies

As a case study of this methodology, we will consider a common tradeoff in FFF additive manufacturing: speed vs accuracy. It is commonly accepted that there is a relationship between these two areas – for a given machine, it is possible to increase process speed (often by moving the gantry faster, using a larger nozzle, or increasing layer height), but the speed comes at a cost of accuracy/resolution (due to vibration and inertia of the gantry and the path cross section resulting from the nozzle size and layer height). We will examine this situation at two levels: at a general level as a contradiction between "speed" and "manufacturing accuracy", and at the nozzle level as a contradiction between "volume of moving object" (the amount of polymer we want to extrude) and "area of moving object" (the cross-sectional area of the nozzle opening though which the polymer is extruded). Many other interpretations of the inherent contradiction could also be posed, which would give other principles as possible solutions. For both cases, we will suggest several paths for innovation resulting from this analysis.

Case Study 1: Improve "speed" (9) while preserving "manufacturing accuracy" (29)

This contradiction yields four innovation principles as common solutions:

- *Principle 10 – Preliminary Action*
    - Perform, before it is needed, the required change of an object
    - Pre-arrange objects so they come into action at the most convenient place
- *Principle 28 – Mechanics Substitution*
    - Replace a mechanical means with a sensory means

  - Use electric, magnetic and electromagnetic fields to interact with the object
  - Change from static to movable fields, from unstructured fields to structured
  - Use fields in conjunction with field-activated (e.g. ferromagnetic) particles
- *Principle 32 – Color Changes*
  - Change the color of an object or its external environment
  - Change the transparency of an object or its external environment
- *Principle 25 – Self Service*
  - Make an object serve itself by performing auxiliary helpful functions
  - Use waste resources, energy, or substances

These four principles can lead a designer to many possible innovations. One example improvement could be generated from the idea of "mechanics substitution" (Principle 28). Most current machines are "feed-forward" designs that track the movement of the printhead by signaling the gantry motors to turn certain amounts. Other than electronic end-stop switches that communicate the correct starting positions for each motor, there is often no feedback to the controller to ensure the printhead is in the correct location. As a result, increasing the speed of the gantry increases the chances of the printhead position becoming misaligned, leading to layer shifts and other problems. If instead of this electromechanical system, we used a sensor-based feedback system that tracked position in real time and adjusted motors automatically to compensate for errors, we could design a machine that could move the printhead much faster and still maintain an acceptable level of positional accuracy.

Case Study 2: Improve "volume of moving object" (7), preserve "area of moving object" (5)

This contradiction also yields four innovation principles as common solutions:

- *Principle 1 – Segmentation*
  - Divide an object into independent parts
  - Make an object easy to disassemble
  - Increase the degree of fragmentation or segmentation
- *Principle 7 – Nested Doll*
  - Place one object inside another; place each object, in turn, inside the other
  - Make one part pass through a cavity in the other
- *Principle 4 – Asymmetry*
  - Change the shape of an object from symmetrical to asymmetrical
  - If an object is asymmetrical, increase its degree of asymmetry
- *Principle 17 – Another Dimension*
  - Move an object in two- or three-dimensional space
  - Use a multi-story arrangement of objects instead of a single-story arrangement
  - Tilt or re-orient the object, lay it on its side
  - Use 'another side' of a given area

This contradiction applies to a more specific problem than the framing of the first case study. Focusing specifically on the problem of moving more material through the nozzle while preserving the small nozzle size helps us home in on precise and workable solutions to the problem. It does have the tradeoff of not considering other valid avenues that could influence this problem, such as temperature, pressure, geometry, etc., so it would be important to explore these other aspects through TRIZ as well. A few possible solutions to the problem as posed include:

- Segmentation – Split up the model and use multiple printheads simultaneously. Printing a part with more than one printhead is an obvious improvement that has been explored [20-22], but still requires a lot of development [23]. Currently, it is very difficult to handle the motion planning of even two simultaneous printheads covering the same print area. But if path planning methods could coordinate five or even ten printheads at once, the print time of parts would be drastically reduced.
- Nested Doll – The nested doll idea could include the concept of material passing through a small opening, then unfolding or expanding. Current FFF printing makes use of a relatively incompressible liquid polymer that solidifies into a fully dense solid of about the same volume. If instead, we transform the material into a foam as it exits the nozzle (either by injecting gas bubbles or through a simultaneous chemical reaction), the resulting volumetric print rate could be greatly improved with the same limited nozzle cross-sectional area.
- Asymmetry – Some features on a part may require greater precision, while others may be acceptable with lower resolution. Many slicing programs allow the user to choose different layer heights at different points in the print. A printer with an adjustable nozzle size could likewise offer fine detail when needed, then expand to extrude at a higher rate on simpler features. A second concept would be to use an oblong or elliptical nozzle instead of a circle. Like a calligraphy pen, this nozzle would allow finer paths when travelling in one orientation, and wider paths when travelling in the perpendicular direction. The nozzle could be rotated as necessary to offer the most efficient profile for the geometry.
- Another Dimension – The thought of operating in two dimensions instead of one, or three dimensions instead of two seems a natural fit for a 3D printing process. DLP resin printing, for example, takes advantage of this by curing an entire 2D layer at once instead of moving point-to-point like conventional SLA technology. One possible innovation for FFF printing would be to use multiple printheads (like the discussion on segmentation) but to operate them at different heights. After one printhead has completed part of a layer, a second printhead could begin printing the subsequent layer on top while the original layer continues to be deposited.

Conclusion

Fused filament fabrication processes in additive manufacturing are becoming more mature, and they may begin approaching physical bounds that limit further improvement in capabilities. Because of this, FFF is ripe for more radical innovation that would shift the technology to a different S curve and allow for future growth. The framework of TRIZ is an excellent methodology for identifying these bounds and contradictions, looking to unrelated fields for inspiration and guidance, and innovating solutions based on universal principles.

The case studies included above show that the TRIZ method, often used to improve product designs, is also an effective innovation technique for improving manufacturing processes and systems, including additive manufacturing processes. The problems and limits posed by current FFF technology are well known and understood. TRIZ offers a systematic means to explore and ideate new solutions that don’t compromise between competing parameters but instead meet them both fully.

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