Chapter 2
3-Dimensional Printing and Rapid Device Prototyping

Regardless of economic classification, humanity as a whole finds itself in a perpetual state of change and development that is nurtured by our intrinsic need as a species to consistently innovate in order to develop novel solutions to society's most pressing issues. In this perpetual state of change, elements such as our innate drive for intellectual inquiry and curiosity serve as impetuses for innovation. This intellectual inquiry and curiosity that is innately embedded in our human nature, provides a foundation for technological advancement in today's modern society. One particular technology that has recently grown exponentially is that of rapid prototyping (RP) otherwise known as 3-dimensional (3D) printing. 3D printing technology has seen a myriad of advancement since its initial inception in the early 1980s, and has been radically transformed with the advent of the Internet and innovations in the computer and software technology. With these rapid advancements in this technology coupled with continued research and development, these printing technologies have become more financially feasible and have vastly expanded in their respective interventional applications and capacities. Whereas 3D printers used to cost tens of thousands of dollars only a decade ago, these printing devices can now be purchased for hundreds of dollars (Hostettler, 2015). In addition, the scaling and applications of this technology has rapidly expanded, in which these units can be utilized to print mono-synthetic small-scale models to that of full-sized automobile parts (Hostettler, 2015).

2.1 The Dawn of Disruptive Innovation and Frugal Engineering

In addressing such a profound and dynamic problem such as the global burden of surgical disease in LMICs, the need for what is known as "disruptive innovation" and "frugal engineering" becomes essential. Disruptive innovation(s) refers to

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S.K. Bhatia and K.W. Ramadurai, *3D Printing and Bio-Based Materials in Global Health*, SpringerBriefs in Materials, DOI 10.1007/978-3-319-58277-1_2

technologies that significantly alter or affect the way a particular market functions (Christensen & Raynor 2013). These technologies are not an iteration or reiteration of a previous technology, but rather something completely novel that transcends the market space upon which a previous technology had occupied. Disruptive innovations not only include disruptive technologies, but also the novel functional application of the technology (Christensen & Raynor, 2013). These innovations can be applied in the global health arena and are distinctly geared towards preserving and enhancing the quality of life for others. Disruptive innovations have the functional capacity to drive improvements in the health and well being of communities and entire countries by disrupting the cycle of poverty and improving health outcomes. Disruptive innovations can serve as an impetus for change and global development, fostering an era in which integrative, yet targeted solutions can be derived to address the most pertinent health threats facing societies today. In addition to disruptive innovations, the concept of frugal engineering serves as an equally important component that can drive future applications of advanced technologies in resource-poor settings.

Frugal engineering is essentially a minimalist approach to innovation and is defined as the process of reducing the complexity and cost of a good and its associated production (Maric, Rodhain, & Barlette, 2016). The core concept of frugal engineering involves taking a technology that has been manufactured for use and deployment in advanced infrastructure settings such as high-income countries and essentially breaking it down into its fundamental components to meet the needs of consumers in resource-constrained settings such as those of LMICs (Maric et al., 2016). In deploying the principles of frugal engineering, technologies that may have not been able to be feasibly deployed or implemented in resource-poor settings, can indeed be utilized and further adapted to meet the needs of its respective environment. In addition to physically breaking down technologies, frugal engineering seeks to redefine other aspects related to a technology's development and relative application. In constructing a holistic and integrative approach to frugal engineering, the essence of frugality plus innovation becomes unearthed, creating a defined element known as "frugal innovation" (Bhatti, 2012). Frugal innovation has the potential to not only redefine the physical design, manufacturing process, and distribution of a product, but the also the more theoretical aspects related to a product's business model, value chain, and market inclusivity (Bhatti, 2012; Christensen & Raynor, 2013). In modifying these various elements related to a technology, one can radically alter the application and adaptability complex of various technologies to be suited for markets in resource-constrained settings. This includes primarily reducing the materials cost for these devices so that they can be both affordable and accessible to more people. Coupling the fundamental concepts of disruptive innovation with that of the fundamental elements of frugal engineering can open the door to unparalleled possibilities. This is particularly pertinent for technologies related to global health, as making medical devices available to the

people that need them most is of the utmost importance to creating healthy world and for the sake of this book, pertinent in combating the global burden of surgical disease.

One particular technology that integrates the tenets of disruptive innovation and frugal engineering and could effectively combat the global burden of surgical disease and revolutionize the current global health paradigm is that of rapid device prototyping, otherwise known as 3-dimensional (3D) printing. Traditional fabrication and manufacturing processes are known as subtractive processes, in which objects are fabricated via the successive cutting of material from a solid block of material (Petrick & Simpson, 2013). This traditional process is highly inefficient and creates large amounts of excess material waste making it largely unsustainable. 3D printing creates a 3-dimensional solid object from a digital model via the use of an additive manufacturing process, in which material is successively added in a layering fashion (Petrick & Simpson, 2013). This allows for the fabrication of various parts and components in a highly efficient and sustainable manner that limits materials waste (Petrick & Simpson, 2013). The additive manufacturing process represents a focal disruption to the traditional manufacturing paradigm and ushers in an era of highly-customizable, efficient, and sustainable manufacturing processes. The dawn of disruptive innovations such as 3D printing coupled with the art of frugal engineering has unearthed previously unknown potential for developing countries. In settings such as LMICs where resources are often scare, the need for highly efficient, targeted, and direct manufacturing processes becomes of the utmost importance, not only to promote sustainability, but also to adequately meet the needs of resource-stricken consumers and communities.

With the glaring disparities in medical supply attainment, limited infrastructure, and fiscal constraints prominent in LMICs, the utilization of 3-dimensional printing technologies has the potential to harness the productivity of an entire small-scale domestic manufacturing facility in a single, highly adaptable apparatus that can be deployed in a plethora of settings and environments (Hostettler, 2015). These unique devices have limitless potential, specifically when it comes to the field of global health and medicine. The ability to fabricate low-cost, custom, and high-utility medical devices utilizing 3D printers in developing countries has sparked great interest in various fields of medicine and applied engineering including biomaterials research, prosthetics and orthopedics, medical and laboratory instrument design, as well as areas such as humanitarian and disaster relief (Ibrahim et al., 2015). In developing a solution to combating the global burden of surgical disease, deployment of 3D printing devices in LMICs could be feasibly implemented to fabricate a variety of medical tools such as surgical instruments. By delivering critical surgical instruments directly onsite and in an on demand fashion, one can drastically enhance the interventional capacities of healthcare facilities in LMICs and improve a fundamental component in enhancing surgical access and delivery. It is through this enhanced surgical access and delivery that human life can be saved both in the short and long terms.

2.2 3-Dimensional Printing: An Introduction to Rapid Device Prototyping and Extant Fabrication Processes

3-dimensional printing is formally defined as the synthetic fabrication and manufacture of 3-dimensional products from a computer-driven digital model via an additive fabrication process (Gross, Erkal, Lockwood, Chen, & Spence, 2014). This process allows for the creation of physical objects and prototypes from a virtual digital model in a variety of materials such as plastic, steel, aluminum, and cobalt (Taneva, Kusnoto, & Evans, 2015). 3D printing apparatuses come in a variety of sizes and variations based upon application specialty, in which some printers can print large-scale components such as automobile parts and even entire homes, and others can fit on a desk and fabricate small, high-definition parts and models (Hostetler, 2015). A common thread that connects all 3D printing apparatuses is the standardized printing and rendering process from digital modeling to physical object fabrication. The process, as depicted in Fig. 2.1, first begins with the creation of a 3D computer aided design (CAD) model, which is designed or obtained via scanning of a physical object and drafted in various computer software programs such as Solidworks or AutoCAD (Gross et al., 2014; Taneva et al., 2015). Once the CAD model is created in the software, the CAD model is then automatically converted into a stereolithographic file or .STL file (Taneva et al., 2015). This file stores the information for each surface of the 3D model in the form of triangulated sections, where the coordinates of the vertices are defined in a text file (Gross et al., 2014). The .STL file spatially defines the object surface in order to create a virtual design grid via coordinate geometric configuration of the object as shown in Fig. 2.2 (Taneva et al., 2015). The 3D printer interprets the digital geometric coordinate configuration derived from the .STL file by converting the file into a G-code file via slicing software (Taneva et al., 2015). The G-code divides the 3D .STL file into a series of 2-dimensional horizontal cross sections generally between 25 and 100 μm, based upon fabrication technique (Gross et al., 2014). This digital



Fig. 2.1 Depiction of the 3-dimensional printing process from 3D CAD Model to 3D object fabrication (Taneva et al., 2015)

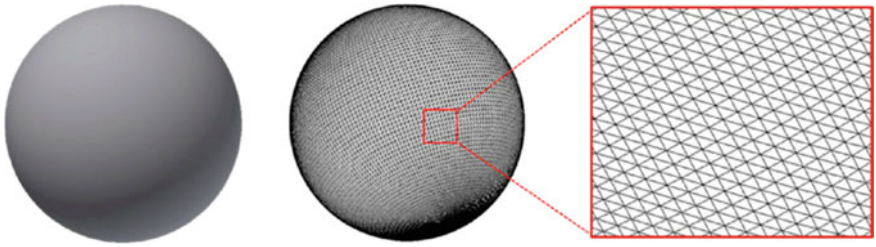


Fig. 2.2 Representation of the coordinate geometric configuration of information in an .STL file; the object as depicted on the *left* was created in a CAD program and saved as an .STL file. The graphical information displayed in the .STL file is shown on the *right* for the same object, with the surface of the object being represented in a coordinate triangulated pattern (Gross et al., 2014)

slicing of the object allows the 3D printer to print the object beginning at the base and the continue to fabricate consecutive layers in a additive fashion, essentially constructing the model from a series of 2D layers derived from the original CAD file (Gross et al., 2014).

While there are indeed a variety of different printing apparatuses and technologies that have come to fruition, it is important to note that not only does the scope of application matter when utilizing these technologies, but the manner in which they fabricate 3-dimensional objects. Rapid prototyping provides an ideal manufacturing method for 3-dimensional structures with complex, intricate, or distinct geometric configurations, which often times require custom fabrication processes typically not afforded with traditional manufacturing methods (Liska et al., 2007). While there are indeed an array of 3D fabrication processes, there are five primary types of rapid prototyping processes, also known as "extant" processes, that hold the most utility in fabricating medical devices (AlAli, Griffin, & Butler, 2015; Jones et al., 2011). Each of these fabrication processes employ a distinct mechanical fabrication process and utilize specific printing filaments. These five processes as shown in Table 2.1 are: stereolithography (SLA), selective laser slintering (SLS), fused deposition modeling (FDM), digital light processing (DLP), and inkjet printing (AlAli et al., 2015). Table 2.1 also describes the various attributes of each type of printing process including the mechanism, advantages, disadvantages, materials utilized, and the micron layer density of each process.

The first process depicted is that of SLA or stereolithography printing (Fig. 2.3), which was the first commercialized rapid prototyping fabrication method (Gross et al., 2014). Stereolithography works by focusing an ultraviolet laser onto a vat of photopolymer resin, in which the UV laser is used to draw pre-programmed designs on to the surface of the photopolymer vat (Gross et al., 2014). Since photopolymers are indeed photosensitive under ultraviolet light, the resin is solidified and forms a single layer of the desired 3D object (Gross et al., 2014). This process is repeated for each layer of the design until the 3D object fabrication is complete. The main advantage of this process is that it can fabricate high-resolution prototypes with adjustable micron layer density, in which manufactured prototypes are produced

Table 2.1 Five primary types of 3-dimensional printing processes: SLA, SLS, FDM, DLP, and Inkjet (AlAli et al., 2015)

Type	Mechanism	Advantages	Disadvantages	Material	Other
SLA	UV light is used to create the object by curing and solidifying a liquid resin	• High-resolution prototypes • Good finishing at the surface	• Support structure is needed • Require postcuring	Resin; a curable laser photopolymer or other plastic-like products	Layer thickness: 0.05–0.2 mm
SLS	Laser fuses the layers of a powder material	• Ability to produce complex/functional parts • Does not require support structure • High productivity	• Surface finish is rough	Plastic, nylon, polystyrene, metals; steel, titanium, and composites	Layer thickness: 0.06–0.18 mm
FDM	Extruding small beads of the melted plastic material, which hardens afterward	• No postcuring • Easy material changeover • Low-cost machines compared with others	• Slow processing, especially on large parts • Low detailing accuracy • Low surface finish integrity	Filament of thermoplastic polymer; ABS, PLA	Layer thickness: 0.15–0.25 mm (adjustable)
DLP	DLP projector projects the light in a repetitive process	• Good resolution • Fast processing time	• Support structure is needed	Liquid resin	Accuracy: 139 μm
INKJET	Spraying liquid or the photopolymer depending on the type of the jetting; binder or material	• A variety of material choice • High precision • Colored parts	• Require postcuring	Plastic, metal, and ceramics	Layer thickness: material: 0.013 mm (min) binder: 0.09 mm (min)

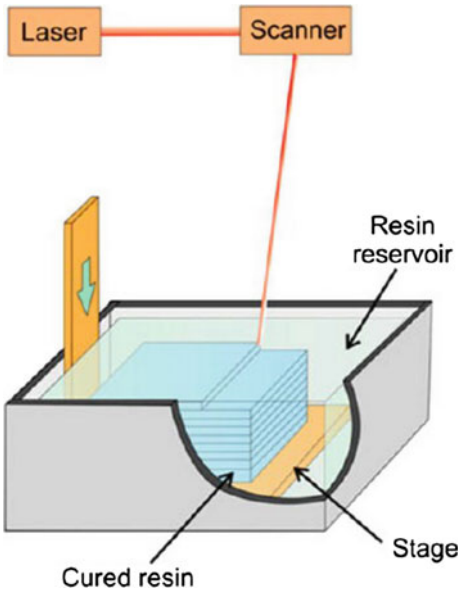


Fig. 2.3 Stereolithography (SLA) 3-dimensional printing process (Gross et al., 2014)

with a high-resolution and smooth finish (Gross et al., 2014). The main disadvantages of SLA printers are that they only utilize specific resin materials not conducive to bio-based materials, require extensive post processing in the form of rinsing the resin in isopropyl alcohol, and are generally more expensive to purchase and operate resulting in higher per-unit object costs (Gross et al., 2014).

The next process is SLS or selective laser slintering (Fig. 2.4), which is a powder-based 3D model fabrication process. SLS utilizes a high power carbon dioxide laser to sinter polymer powders in order to generate a 3D model, instead of utilizing liquid binding materials to attach powder particles together (Gross et al., 2014). In the SLS

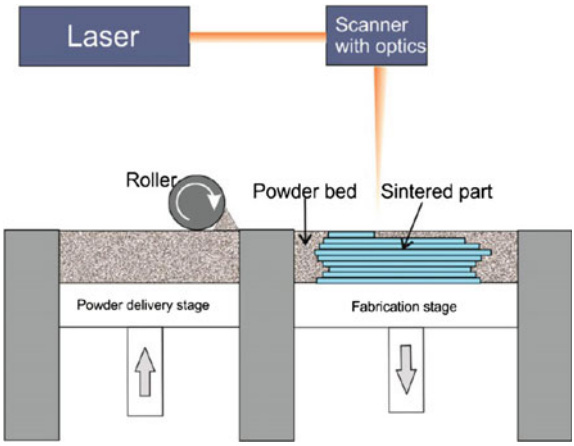


Fig. 2.4 Selective Laser Slintering (SLS) 3-dimensional printing process (Gross et al., 2014)

manufacturing process, an initial layer of powder is distributed onto a platform by a roller and is then heated to a temperature just below the powder's melting point. Following the cross-sectional profiles designated in the .STL file, a laser beam is selectively scanned over the powder to raise the powder's melting point to fuse powder particles together (Gross et al., 2014). After the first layer is completed, a second layer of powder is added, leveled, and sintered in the desired localities as indicated by the CAD model, and these steps are repeated to create a 3D model (Gross et al., 2014). The powders that are not sintered by the laser serve as structural support scaffolding for the model during the process and are removed after fabrication of the 3D object (Gross et al., 2014). One advantage of SLS is that a wide range of materials can be used, from polymers such as polycarbonate (PC), polyvinyl chloride (PVC), acrylonitrile butadiene styrene (ABS), nylon, and polyester to that of metal powders (Gross et al., 2014). In addition, a binding liquid material is not required, but SLS printed models are prone to shrinkage or deformation due to thermal heating from the laser and subsequent cooling and SLS printers are often expensive to purchase and operate (Gross et al., 2014).

The next process is that of FDM or fused deposition modeling (Fig. 2.5), one of the most commonly used manufacturing technologies for rapid prototyping. FDM fabricates a 3D model via the extrusion of thermoplastic materials such as polylactic acid (PLA) or acrylonitrile butadiene styrene (ABS), depositing semi-molten thermoplastic material onto a modular build platform layer-by-layer (McCullough & Yadavalli, 2013). The thermoplastic filament that composes the 3D models is

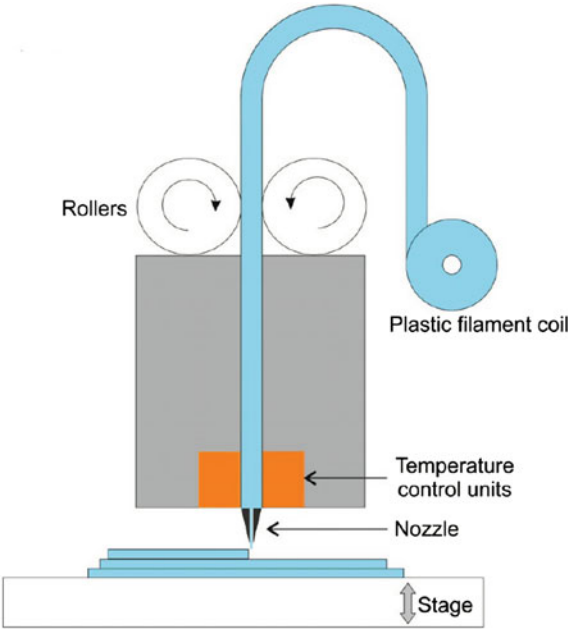


Fig. 2.5 Fused Deposition Modeling (FDM) 3-dimensional printing process (Gross et al., 2014)

moved by two internal mechanical rollers downwards towards to the heated nozzle tip of the extruder of the print head (McCullough & Yadavalli, 2013). The modular platform is generally heated to approximately 50–70 °C and the extrusion head is heated to approximately 190–215 °C based upon the thermoplastic material utilized (McCullough, & Yadavalli, 2013). As the print head traces the design of each defined cross-sectional layer horizontally, the semi-molten materials are extruded out of the nozzle and solidified upon the build platform in an additive fashion (Gross et al., 2014). These steps are repeated to fabricate a 3D structure layer-by-layer, with the outline of the part is usually printed first, with the internal structures on the 2D-plane printed layer-by-layer with various internal structural patterns (3D Matter, 2016; Gross et al., 2014). The advantages of utilizing FDM are that it is highly adaptable for the usage of various thermoplastic materials including bio-based thermoplastics and can be utilized a multitude of environments. In addition, the printing device itself has the lowest cost setup of all four processes and is extremely user friendly with regards to mechanical output and software setup (Rankin et al., 2014). The high extrusion temperature makes the printed objects sterile upon fabrication as well as extremely durable and malleable. The primary disadvantages of FDM are that the process is slower and has a lower micron resolution compared to other rapid prototyping processes (Gross et al., 2014).

The next rapid prototyping process is DLP or digital light processing (Fig. 2.6), in which a 3D model is fabricated via projection onto a liquid photopolymer basin (AlAli et al., 2015; Liska et al., 2007). DLP utilizes a light projector that displays a

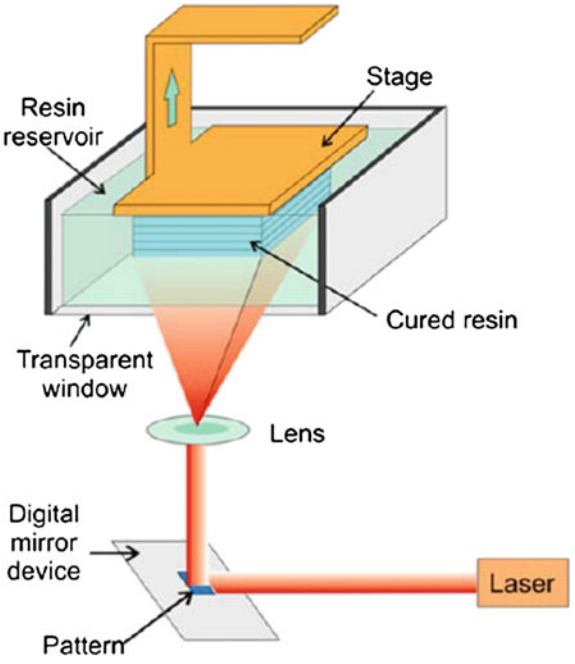


Fig. 2.6 Digital Light Processing (DLP) 3-dimensional printing process (Gross et al., 2014)

computer-generated image of the 3D model onto liquid photopolymer resin, in which the photopolymer hardens when exposed to the projection's light (AlAli et al., 2015). As the build plate of the printer proceeds downward in a y-axial trajectory, the liquid photopolymer is further exposed, thus further constructing the projected 3D model image, and is repeated until the model is fully fabricated and solidified (Gross et al., 2014; Liska et al., 2007). In examining the benefits of utilizing DLP printing, the primary advantage is that this process garners high-micron resolution models in a quick and efficient manner (AlAli et al., 2015). The primary disadvantages of this technology are that it is expensive overall, not only for the printing apparatus, but also specifically for the photopolymer resin, which typically costs hundreds of dollars. In addition, the support structure and 3D scaffolding that is fabricated to stabilize each model during the fabrication is integrated into the 3D model itself. This means that the support structure must be meticulously removed by hand in order to access the true model that has been fabricated. In doing this, there is indeed the potential to damage the model if the support scaffolding is not removed in an articulate manner.

The final process is 3D inkjet printing (Fig. 2.7), which is a powder-based method where layers of solid particles, approximately 200 μm in height with particle sizes between 50 and 100 μm, are bound together by a printed liquid material to generate a 3D model as shown in Fig. 2.7 (Napadensky, 2010). First, a layer of powder is distributed evenly on the top of a support stage by a roller, after which an inkjet printer head prints droplets of liquid binding material onto the powder layer at desired areas of solidification (Gross et al., 2014; Napadensky, 2010). After the first layer is completed, the platform drops and a second powder layer is distributed and selectively combined with printed binding material (Napadensky, 2010).

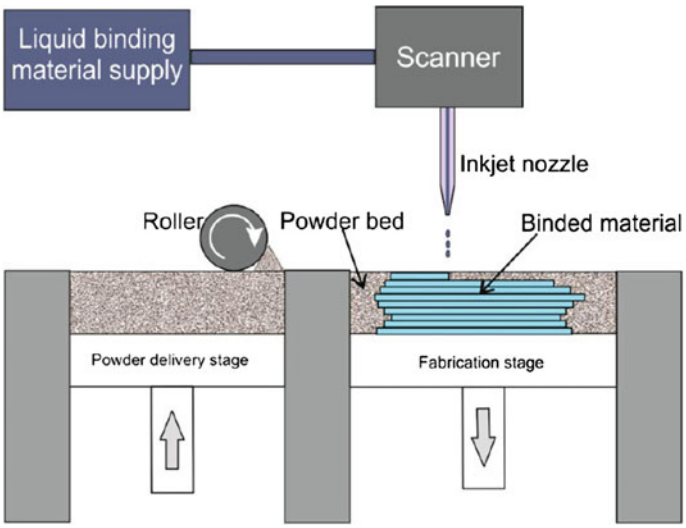


Fig. 2.7 Inkjet 3-dimensional printing process (Gross et al., 2014)

These steps are repeated continuously until a functional 3D model is fabricated, with the model being heat-treated afterwards, in order to enhance the binding of the powders in the object. The unbound powder serves as structural support scaffolding during the process and is removed after fabrication of the 3D prototype (Napadensky, 2010). The main advantage of the process is that it is relatively low-cost to purchase and operate and can utilize a variety of materials. The primary disadvantage of this process is that the unbound particles can result in significant porosity of finished materials and surface roughness, two critical elements that are importance when fabricating medical devices (Napadensky, 2010).

One of the most important elements upon deciphering the ideal additive manufacturing processes is the scope of application and the in-field deployment feasibility. These two elements are of critical importance, as these printing apparatuses would be deployed in healthcare facilities in LMICs, which often only have access to the basic support entities including infrastructure and fiscal capital (Ishengoma & Mtaho, 2014). This means that upon deployment of one these printing devices, the device would have to be cost and energy efficient, user-friendly, transportable, reliable, and deliver a consistent fabricated product that is functional and able to be directly deployed in the field. This is especially important for the fabrication of surgical instruments, as the printing device would have to print a consistent run of instruments that are free of any catastrophic mechanical or structural deficits (Ishengoma & Mtaho, 2014). Another important element is that the printing apparatus must have easily replaceable parts and support, in case of mechanical failure in the unit. If the unit has components that cannot be easily sourced or fabricated, it will be extremely difficult to source parts to be delivered to these often resource-poor settings (Tatham, Loy, & Peretti, 2015). Based upon these criteria, the process of fused deposition modeling proves to be the most ideal process for deployment in LMICs. The reason for FDM being the most ideal additive manufacturing process is that it is highly adaptable for utilization of bio-based thermoplastic materials, cost-efficient, and highly efficient. While this section has focused on the types of printing processes, thought must be given to the type of printing apparatus that will house this process and will actually be deployed in the field.

There are a variety of 3D printer makes and models such as MakerBot, DaVinci, and Micro3D, but given the unique circumstances that are faced upon deploying an advanced technology in often resource-stricken settings such as LMICs, the need for a basic, user-friendly, and highly adaptable modular printing platform become essential (Tatham et al., 2015). While it could indeed be feasible to ship other types of printing devices, as previously noted this is difficult given the supply chain inefficiencies and deficits as well as the fundamental problem of allocating replacement parts and support in case of printer mechanical failure (Tatham et al., 2015). This fallacy could indeed be catastrophic for deployment of an advanced technology such as 3D printers as most likely, if the device were to breakdown, most likely would not be fixed due to the complexity of the device parts and design, thus rendering the entire intervention a failure. Upon acknowledgement of these problems, one particular printing apparatus stands out above all else, this being the RepRap 3D FDM printer. Utilization of the RepRap modular rapid prototyping

printing apparatus can potentially serve as a cost-effective, highly efficient fabricator of surgical instruments in LMICs, a concept that will be examined further in this chapter.

2.3 Fused Deposition Modeling and the RepRap Rapid Prototyping Device

RepRap is a novel and innovative open-source self-replicating rapid prototyping 3D printer that utilizes a FDM rapid prototyping process to fabricate 3D objects as depicted in Fig. 2.8 (Romero et al., 2014). RepRap was developed and is still in development by an open community on RepRap.org, which was founded in 2004 by Adrian Bowyer at the University of Bath (Romero et al., 2014). The RepRap online community functions in highly unique manner, in which it develops and modifies RepRap 3D printing hardware via open-source publishing (Jones et al., 2011). This means that the RepRap design modifications, components, blueprints, and applications are available for anyone to access on the Internet, without the need to provide royalty payments for device design or components (Jones et al., 2011). The ultimate goal of this is to promote an open platform for inquiry as well as rapid device input, enhancement, and improvement (Romero et al., 2014). This open-source availability has fostered an unprecedented paradigm shift in 3D printing availability and accessibility. Individuals ranging from hobbyists to professional engineers and academics have all shared ideas to further improve the

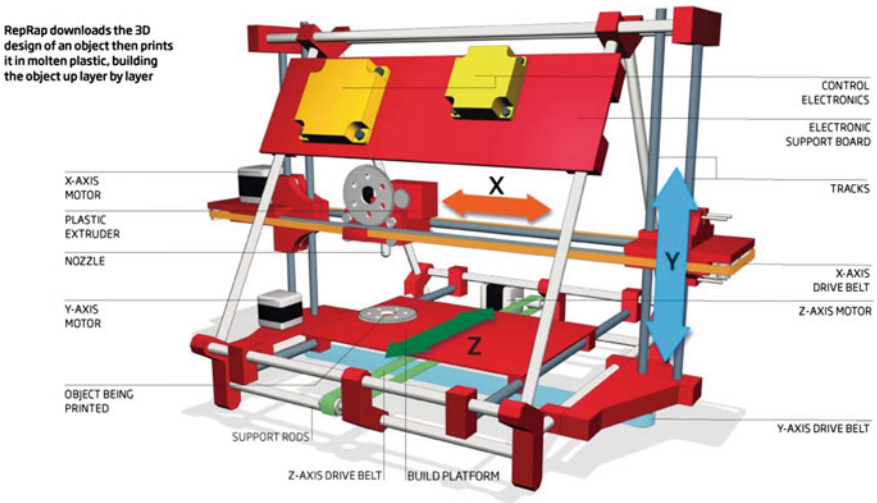


Fig. 2.8 Overview schematic of the RepRap FDM 3D printer design and self-replicated components shown in *red* (Simonite, 2010)

RepRap platform. This has led to rapid improvements in the design and application of RepRap devices in only a few years and has embraced the true essence of frugal innovation and engineering to create devices that could indeed be feasibly utilized in resource-poor settings.

Since RepRap devices are open-source, one could imagine that there could indeed be hundreds of variants, each of which have its own distinct components and design. While this is indeed possible, all RepRap 3D printers have three primary characteristics that are the foundational elements for these devices. The first is that they are machines that utilize FDM additive manufacturing to fabricate objects utilizing thermoplastic polymers such as acrylonitrile butadiene styrene (ABS) (3D Matter, 2016; Romero et al., 2014). The second is that there are four models that have been developed thus far, including: Darwin, Mendel, Huxley and Wallace (Romero et al., 2014). With these four models comes a variety of different variants including: Prusa Mendel, MendelMax, RepRapPro Huxley, and the RepRapPro Mendel (Romero et al., 2014). The final characteristic of RepRaps is that the accuracy of each model is widely determined by the diameter of the filament extrusion nozzle, which is generally between 0.4 and 0.5 mm (Jones et al., 2011; Romero et al., 2014).

RepRaps are an extremely unique printing apparatuses, as they are designed to have the capability to print out a significant amount of their own parts, a critical element when it comes to being deployed in resource-poor settings. The remaining parts that the device cannot print are generally parts and components that are cheap and available worldwide (Jones et al., 2011). This makes this modular printing apparatus extremely flexible when it comes to device repairs, improvements, and overall printing capacity. Another important element of the RepRap is that the device functions based upon the tenets of what is known as "frugal engineering," which is the process of reducing the complexity and cost of a technology and its production (Maric et al., 2016). This essentially refers to the removal of nonessential features from a technology in order to make it feasible to utilize and function in resource-poor settings (Maric et al., 2016). With the reduction of nonessential components, the RepRap apparatus is extremely cost-effective generally costing less than $150.00 and has the ability to be modified in order to meet the various manufacturing needs of the device user (Jones et al., 2011). The availability of open-sourced blueprints and designs allows for users of the product to address mechanical and fabrication issues instantly, thus allowing for proper unit operation.

The RepRap printer utilizes the FDM rapid prototyping process to construct 3D objects and utilizes a modular build platform that moves in conjunction with the extrusion head. The decision to utilize the FDM extant process for RepRap rapid prototyping devices was made based upon multiple factors. Any fabrication process that needed and operated utilizing a laser was rejected, as a rapid prototyping device could not fabricate its own laser, and because lasers are a costly component and likely difficult to source in a variety of environments and localities (Jones et al., 2011). In removing this functional laser component, this effectively removed selective laser sintering (SLS), stereolithography (SLA), and digital light projection (DLP) from being utilized in RepRap printing devices (Jones et al., 2011). In

addition, any process that required inkjet print heads was rejected, as it is rather unlikely that a RepRap device would feasibly be able to fabricate an inkjet print head by itself (Jones et al., 2011). With these four printing processes eliminated, only one process remained, this being fused deposition modeling (FDM). Fused deposition modeling provides the ability to fabricate objects with an array of various filament materials. This provides a significant advantage in the future, as the RepRap would be able to fabricate a larger proportion of its own components than could be created out of just one material (Romero et al., 2014).

The RepRap rapid prototyping device is a stepping-motor-driven Cartesian 3D printer, in which the basic components of RepRap machines can be classified according their respective function and attributes (Jones et al., 2011). The first group is that of the RepRap self-replicable plastic components, which are the components that can be manufactured by the RepRap printer. These components generally represent almost half of the total of the parts of the printer and are generally fabricated with ABS or PLA thermoplastic filament and primarily include the structural, extruder, and carriage print components shown in Fig. 2.9 (Romero et al., 2014).

The second group is that of the non-replicable components, which includes structural components such as the threaded and smooth rod frame assembly, washers, nuts, bearings, and belts. These components are generally made of metal, steel or aluminum, and the belts are rubber (RepRap Bill of Materials). The third group is that of the electronic components, which are vital for printer operation and include the microcomputer and electronic board, stepping motors, temperature and end stop sensors, resistances, and cables (Romero et al., 2014). The fourth group is that of the software, which includes the RepRap firmware and an external computer/laptop for 3D object splicing. The remainder of the parts that the RepRap



Fig. 2.9 RepRap self-replicated plastic components (Romero et al., 2014)

cannot fabricate by itself, other than the electronics and the motors, can be locally sourced from local hardware shops that occupy many urban centers in LMICs.

The RepRap operates an extruder nozzle that runs on the horizontal X and Y-axes and is driven by stepping motors that operate via toothed timing belts, which move at a feed rate of approximately 3000 mm/minute (Jones et al., 2011). The extrusion head moves on the x and y-axes adding a 0.15-micron thick layer for each layer of the object, while the build platform moves on the z-axis in a simultaneous fashion to allow for proper object fabrication on all planes as shown in Fig. 2.9 (Romero et al., 2014). Printing an object with a RepRap device follows the same schematic as any other FDM 3D printer. A 3D model file is uploaded and modified via the appropriate software and then sent to the printer, which requires a series of mechanical processes that the printer conducts in order to start fabrication. First, a 2 kg coil reel otherwise known, as a filament spool, containing the 1.75 mm thermoplastic filament is loaded in the machine (Jin, Li, He, & Fu, 2015). After this, the machine begins to simultaneously heat both the filament extrusion head as well as the build platform. This step is critical as each thermoplastic material has varying heating protocols and must be heated at a precise range otherwise the material will be compromised. The extrusion head is generally heated to approximately 190 °C for ABS thermoplastic and 215 °C for PLA thermoplastic (Chia & Wu, 2015). The build platform is temperature is also adapted based upon the filament material utilized, but is generally between 50 and 70 °C (Rengier et al., 2010). Once both these components are properly heated, the extrusion head is directed to the (0, 0) coordinate plane on the build platform and is lifted approximately 0.2 mm above the build platform (Rengier et al., 2010). The thermoplastic filament from the 1.75 mm filament spool is then fed through a driving motor in the extruder head and fed onto the 10 × 10 inch build platform as shown in Fig. 2.11 (Jin et al., 2015). A platform scaffold is generally fabricated as the model is created in order to provide support and attachment of the 3D object to the build platform (Fig. 2.10).

The RepRap printer consumes approximately 60 W when operating, and is designed to work off a single 12-volt power supply, which can be obtained by using the power supply from an old PC or even a car battery (Jones et al., 2011). Each year, the RepRap modular apparatus receives new updates to its fabrication methods and manufacturing processes. The most current open source model available is the Mendel series shown in Fig. 2.10, which incorporates a modular heated 10 × 10 inch build bed/platform, threaded aluminum rod frame assembly, and compact filament extruder (RepRapPro, 2017). Given this printer's innate flexibility and adaptability, these printers provide the ideal platform for fabricating medical devices such as surgical instruments in LMICs and could serve as vital elements in stimulating domestic manufacturing initiatives to address medical device shortages in countries around the world. While these devices are indeed highly adaptable for an array of field interventions it is important to note some limitations associated with the technology. RepRap printers in most cases, require an external computer to be physically connected to the printer, usually via a Universal Series Bus (USB) cable. As previously discussed, the external computer is responsible for calibrating the printer, running the 3D splicing software,

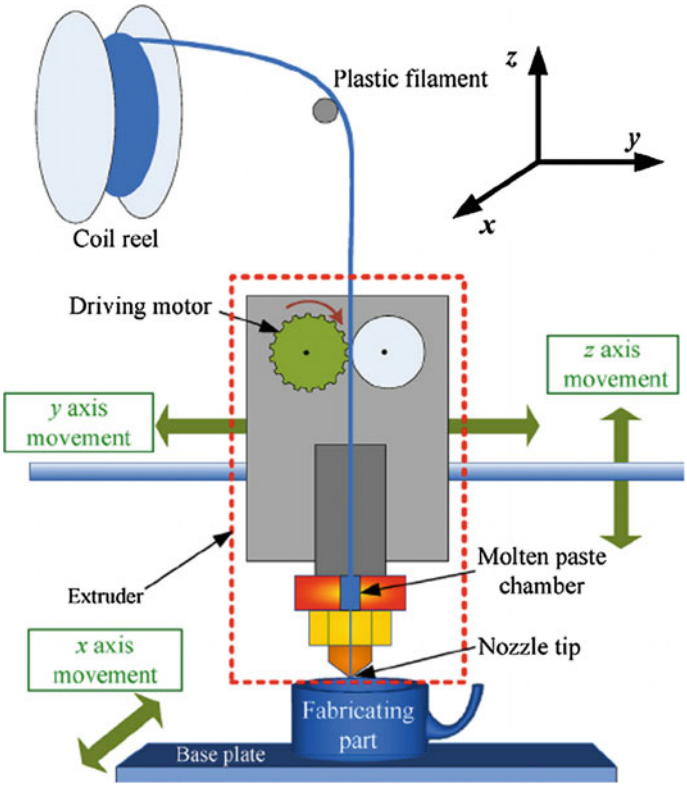


Fig. 2.10 Internal and axial mechanics of RepRap FDM rapid prototyping (Jin et al., 2015)

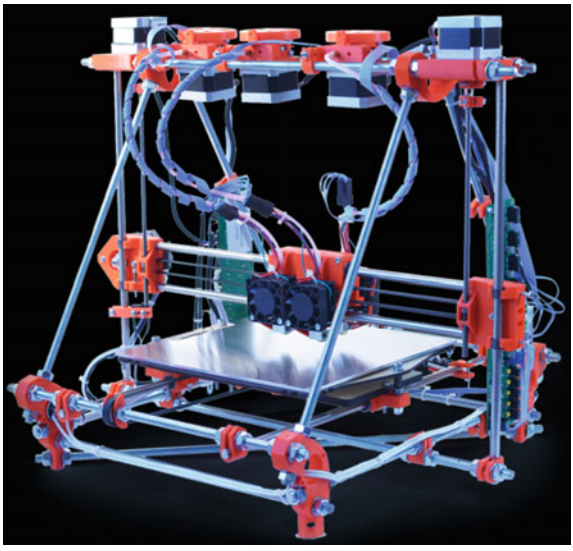


Fig. 2.11 A RepRap Mendel FDM 3D Printer with threaded aluminum rod frame assembly and modular build platform (RepRapPro, 2017)

processing the files into .STL format, and transmitting directions to the printer via G-code (Tatham et al., 2015). In addition, the computer must remain connected to the printer while the 3D model is printing. Recently, RepRap builders have devised way to eliminate this physical dependence on an external computer. Many RepRap machines can be retrofitted with controllers that include memory card readers such as micro-SD cards, in which .STL files can be saved as G-code instructions on these SD cards. This means that these printers can function independently without the need for an external computer and can be deployed in any environment that provides a suitable power source.

In utilizing these printers to fabricate medical devices such as surgical tools and instruments, the question of what type of material would be utilized is great importance. As previously stated FDM printers utilize a variety of thermoplastic materials to fabricate 3D objects, in which the most commonly used filament is ABS plastic. Previous studies have utilized FDM printers to fabricate instruments, but when utilized in medical devices, there are significant limitations. These limitations include nanoparticle aerosol emissions and mechanical application in addition to sustainability and toxicity complexes of the materials utilized. In cases such as these the use of bio-based materials instead of synthetic materials such as ABS provides a unique opportunity to harness natural materials that are biocompatible with human tissues, yet provide the same mechanical dexterity as conventional synthetic plastic polymers. The most feasible bio-based material that can be utilized in substitute of ABS plastic is that of polylactic acid or PLA.

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http://www.springer.com/978-3-319-58276-4

3D Printing and Bio-Based Materials in Global Health
An Interventional Approach to the Global Burden of Surgical Disease in Low-and Middle-Income Countries
Bhatia, S.K.; Ramadurai, K.
2017, XV, 115 p. 84 illus., 75 illus. in color., Softcover
ISBN: 978-3-319-58276-4