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Review Article

Rapid Prototyping – Principle, Technologies and Applications: An Overview

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Abstract: The idea to develop processes capable to produce physical components quickly and without requiring tooling, led to the development of the "free form fabrication" (FFF) or "rapid prototyping" (RP) technologies in the early 1980s. Rapid prototyping (RP) also known as additive manufacturing or three-dimensional (3D) printing is a group of evolving technologies that create 3D objects additively in a layer-by-layer manner from a predefined 3D computer model. The RP technologies have brought several advantages to the manufacturing industry in such a way that these technologies are evolving toward the production of end-use parts. This paper presents a review of rapid prototyping and manufacturing (RP&M) technologies from their origins.

Keywords: 3D, Image, Implant, Printing, Prototyping, Rapid.

INTRODUCTION

Since the late 1980s, rapid prototyping (RP) technologies have changed the essence of product development, tooling, and manufacturing [1]. The initial economic motivation for the development of RP was to support product development by providing the possibility to create physical models for the validation of new designs rapidly and at low cost. Thus, design changes could be shifted to earlier stages of product development processes, enabling design security and eliminating the need for more expensive amendments at later stages [2, 3]. RP technologies find application in manufacturing of custom-made parts – including prototypes and small series parts [4]. Additive manufacturing is not only by far more flexible than conventional formative molding or casting processes, but may as well be considered economically favourable as long as the high financial and time expenditure necessary for the production of molds and tools for formative manufacturing exceeds the usually higher production costs per part in RP [5]. In comparison to the subtractive manufacturing technologies such as computerized numerical control (CNC) machining, additive manufacturing benefits from a lower waste of construction material and enables the incorporation of more complex internal sub-structures and undercuts [4].

Basic Principle

Rapid prototyping is the automatic construction of physical objects using additive manufacturing technology. Rapid Prototyping process belongs to the generative (or additive) production processes unlike subtractive or forming processes such as lathing, milling, grinding or coining etc. in which form is shaped by material removal or plastic deformation. In all commercial RP processes, the part is fabricated by deposition of layers contoured in a (x-y) plane two dimensionally [6]. The third dimension (z) results from single layers being stacked up on top of each other, but not as a continuous z-coordinate. Therefore, the prototypes are very exact on the x-y plane but have stair-stepping effect in z-direction. If model is deposited with very fine layers, i.e., smaller z-stepping, model looks like original. RP can be classified into two fundamental process steps:

- Generation of mathematical layer information
- Generation of physical layer model [7].

The application of rapid prototyping technology is emerging rapidly in medical applications. However, the rapid prototyping process in medical applications has some specific features in comparison with typical technical usage. For example, pre-processing preparation with 3D scanning by volumetric computer tomography is significantly different than the one in machine industry, where the engineers use usually CAD parametric software or the reverse engineering with surface scanners. Furthermore, surface of medical bodies modelled by RP, also shows significant difference in surface roughness and the degree of curvature is so variable. Also, every medical body is unique, and in every case, it is necessary to process a new 3D scanning. In addition, there are many internal features like various and complex cavities, gaps and channels. So, all major aspects of rapid prototyping should be considered: nature of application, features of methods, input models of data, material variations for processing of prototype models. Then, it is important to identify, analyze and optimize the rapid prototyping process in accordance with applications [7, 8].

The various steps in production of a RP model include [9]

- Anatomical data and image acquisition
- Acquisition of DIACOM files
- Conversion of DIACOM into .STL files
- Evaluation of the design
- Surgical planning and superimposition if desired
- Additive Manufacturing and creation of model
- Validation of the model

Anatomical data and image acquisition [5]

The clinical input for rapid prototyping is represented by all the information contained in imaging data. Most commonly, MRI and computerized tomography (CT) imaging are used for this purpose. Other sources include laser surface digitizing, ultrasound and mammography. It is preferable that the CT scan is of high slice calibre and that slice thickness is of 1- 2mm. The output of the imaging acquisition process and input of the rapid prototyping following appropriate processing is a DIACOM image (Digital Imaging and Communications in Medicine), which is the outcome of virtually all medical professions utilising images including endoscopy, mammography, ophthalmology, orthopaedics, pathology and even veterinary imaging.

(a) Magnetic Resonance Imaging [10,11]

MR imaging is an imaging technique based on detecting different tissue characteristics by varying the number and sequence of pulsed radio frequency fields, taking advantage of the magnetic relaxation properties of different tissues. MR imaging has the crucial advantage of not emitting X-ray radiations. Instead, the MR scanner provides a strong magnetic field, which causes protons to align parallel or anti-parallel to it. MR measures the density of a specific nucleus, normally hydrogen, which is magnetic and largely present in the human body, except for bone structures. The speed at which protons lose their magnetic energy varies in different tissues allowing detailed representation of the region of interest. This measurement system is volumetric.

(b) Computerized Tomography [12, 13]

Hard tissues and bony structures, which are assessed less well by MRI, can be captured by means of CT. This is a radiographic technique that uses a narrow fan X-ray beam to scan a slice of tissue from multiple directions. The absorption of different tissues is calculated and displayed according to gray-scale values. The resolution of CT data can be increased by decreasing the slice thickness, producing more slices along the same scanned region. However, the resulting longer scanning time has to be weighed by the clinician against the consequence of increased radiation dose. The technology known as spiral CT allows for shorter scanning time and small slice intervals with respect to previous scanners. In this case, the patient is translated continuously through the gantry while the X-ray tube and detector system are continuously rotating; the focus of the X-ray tube essentially describing a spiral, producing isometric 3D images (i.e. the same resolution in all directions).

(c) Other methods [14]

Laser surface digitizing is a technique that permits acquisition only of external data. This technology is based on a laser probe emitting a diode-based laser beam which forms profiles on the surface of the anatomy being imaged. Each profile is collected as a poly line entity and the combination of profiles yields a 3D volume. Apart from the speed of acquisition, this method has the advantage of not emitting any radiation. 3D ultrasound has also been used as input for rapid prototyping applications, as in the case of foetal modelling.

Acquisition of DIACOM files and conversion to .STL file format [9]

After the data is exported in DIACOM file format, it needs to be converted into a file format which can be processed for computing and manufacturing process. In most cases the desired file format for Rapid manufacturing is STL or stereolithographic file format. The conversion requires specialised softwares like MIMICS, 3D Doctors, AMIRA. These softwares process the data by segmentation using threshold technique which takes into the account the tissue density. This ensures that at the end of the segmentation process, there are pixels with value equal to or higher than the threshold value. A good model production requires a good segmentation with good resolution and small pixels. Software available for conversion:

- MIMICS by Materialise
- Analyse by the Clinique Mayo
- Amira
- 3D Doctor
- BioBuild by Anatomics
- SliceOmatic by TomoVision

Evaluation of design and surgical planning [9, 15]

This step requires combined effort of surgeon, bio engineer and in some cases radiologist. It is important that unnecessary data is discarded and the data that is useful is retained. This decreases the time required for creating the model and also the material required and hence cost of production. Sometimes this data can be sent directly to machine for the production of model especially when the purpose of model is to teach students. The real use however is in surgical planning in which it is critical that the surgeon and designer brain storm to create the final prototype.

There may be a need to incorporate other objects such as fixation devices, prosthesis and implants. The step may involve a surgical simulation carried out by the surgeon and creation of templates or jigs. This may require in addition to the existing converting softwares, computer aided designing softwares like Pro- Engineer, Auto CAD or Turbo CAD.

Additive manufacturing and production of the model [16]

There are various technologies available to create the RP model including stereolithography, selective laser sintering, and laminated object manufacturing (LOM), fused deposition modelling (FDM), Solid Ground Curing (SGC) and Ink Jet printing techniques. The choice of the technology depends on the need for accuracy, finish, and surface appearance, number of desired colours, strength and property of the materials. It also takes a bit of innovation and planning to orient the part during production so as to ensure that minimum machine running time is taken. The model can also be made on different scale to original size like 1: 0.5, this ensures a faster turnaround time for production and sometimes especially for teaching purpose this may be convenient and sufficient.

Validation of the model [9]

Once the model is ready, it needs to evaluated and validated by the team and in particular surgeon so as to ensure that it is correct and serves the purpose.

Advantages of Rapid Prototyping [17]

- Almost any shape or geometric feature can be produced
- Reduction in time and cost
- Errors and flaws can be detected at an early stage
- RP/RM can be used in different industries and fields of life (medicine, art and architecture, marketing)
- Discussions with the customer can start at an early stage
- Assemblies can be made directly in one go
- Material waste is reduced
- No tooling is necessary
- The designers and the machinery can be in separate places

Disadvantages of Rapid Prototyping [17]

- The price of machinery and materials
- The surface is usually rougher than machined surfaces
- Some materials are brittle
- The strength of RP parts are weaker in z-direction than in other

Rapid Prototyping Technologies [6]

- Stereolithography (SLA)
- Fused Deposition Modeling (FDM)
- Selective Laser Sintering (SLS)
- Laminated Object Manufacturing (LOM)
- 3D Printing
- Solid Ground Curing (SGC)

***Stereolithography (SLA)* [6, 7, 14]**

The term sterelithography was coined by Charles W. Hull in 1986. Stereolithography is the most widely used rapid prototyping technology. SLA was introduced in the market in 1988 by 3D Systems Inc. SLA uses a low-power, highly focused UV laser to produce a three dimensional object in a vat of liquid photosensitive polymer. Due to the absorption and scattering of beam, the reaction only takes place near the surface and voxels of solid polymeric resin are formed. A SL machine consists of a build platform (substrate), which is mounted in a vat of resin and a UV Helium-Cadmium or Argon ion laser. The laser scans the first layer and platform is then lowered equal to one slice thickness and left for short time (dip-delay) so that liquid polymer settles to a flat and even surface and inhibit bubble formation. The new slice is then scanned.

In new SL systems, a blade spreads resin on the part as the blade traverses the vat. This ensures smoother surface and reduced recoating time. It also reduces trapped volumes which are sometimes formed due to excessive polymerization at the ends of the slices and an island of liquid resin having thickness more than slice thickness is formed. Once the complete part is deposited, it is removed from the vat and then excess resin is drained. It may take long time due to high viscosity of liquid resin. The green part is then post-cured in an UV oven after removing support structures. Overhangs or cantilever walls need support structures as a green layer has relatively low stability and strength. The main functions of these structures are to support projecting parts and also to pull other parts down which due to shrinkage tends to curl up. These support structures are generated during data processing and due to these data grows heavily specially with STL files, as cuboid shaped support element need information about at least twelve triangles. A solid support is very difficult to remove later and may damage the model. Therefore a new support structure called fine point was developed by 3D Systems and is company’s trademark.

Selective Laser Sintering [17]

In Selective Laser Sintering (SLS) process, fine polymeric powder like polystyrene, polycarbonate or polyamide etc. (20 to 100 micrometer diameter) is spread on the substrate using a roller. Before starting CO_2 laser scanning for sintering of a slice, the temperature of the entire bed is raised just below its melting point by infrared heating in order to minimize thermal distortion (curling) and facilitates fusion to the previous layer. The laser is modulated in such a way that only those grains, which are in direct contact with the beam, are affected. Once laser scanning cures a slice, bed is lowered and powder feed chamber is raised so that a covering of powder can be spread evenly over the build area by counter rotating roller. In this process support structures are not required as the unsintered powder remains at the places of support structure. It is cleaned away and can be recycled once the model is complete.

Fused Deposition Modelling **[17, 19]**

In Fused Deposition Modelling (FDM) process a movable (x-y movement) nozzle on to a substrate deposits thread of molten polymeric material. The build material is heated slightly above (approximately 0.5° C) its melting temperature so that it solidifies within a very short time (approximately 0.1 s) after extrusion and cold-welds to the previous layer. More recent FDM systems include two nozzles, one for part material and other for support material. The support material is relatively of poor quality and can be broken easily once the complete part is deposited and is removed from substrate. In more recent FDM technology, water-soluble support structure material is used. Support structure can be deposited with lesser density as compared to part density by providing air gaps between two consecutive roads.

Laminated Object Manufacturing [20, 21]

In Laminated Object Manufacturing (LOM), slices are cut in required contour from roll of material by using a 25-50 watt CO_2 laser beam (Fig.20). A new slice is bonded to previously deposited slice by using a hot roller, which activates a heat sensitive adhesive. Apart from the slice unwanted material is also hatched in rectangles to facilitate its later removal but remains in place during the build to act as supports. Once one slice is completed platform can be lowered and roll of material can be advanced by winding this excess onto a second roller until a fresh area of the sheet lies over the part. After completion of the part they are sealed with a urethane lacquer, silicone fluid or epoxy resin to prevent later distortion of the paper prototype through water absorption. In this process, materials that are relatively cheaper like paper, plastic roll etc. can be used. Parts of fibre-reinforced glass ceramics can be produced. Large models can be produced and the building speed is 5-10 times as compared to other RP processes. The limitation of the process included fabrication of hollow models with undercuts and re-entrant features. Large amount of scrap is formed. There remains danger of fire hazards and drops of the molten materials formed during the cutting also need to be removed.

3D Printing [22,23]

Three Dimensional Printing (3DP) was developed at the MIT and licensed to several corporations. The process is similar to the SLS process, but instead of using a laser to sinter the material, an ink-jet printing head deposits a liquid adhesive that binds the material. Layers of powder are applied to a substrate and are selectively joined using a binder sprayed through a nozzle. In order to avoid excessive disturbance of powder when it is hit by the binder, it is necessary to first stabilize it by misting it with water droplets. Materials used vary from plastics, ceramics to metals. 3D printing is quite fast, typically 2 –4 layers/minute. With the lower cost of the equipment and an increase in printer speed, this technology is being used for customized and on demand manufacturing. It is being used to design and then print a wax pattern of a restoration. Operating like an inkjet printer, the machine builds wax patterns of frameworks and full crowns. The wax pattern subsequently is cast or pressed in the same manner as manually waxed restorations would be.

*Solid Ground Curing (SGC) [*5, 8*]*

In this laser polymerizes successive layers of resin through a stencil. It is a combination of stereolithography, fused deposition and CNC milling. SGC cures an entire layer a time. First, photosensitive resin is sprayed on the building platform. Next, the machine develops a photomask (like a stencil) of the layer to be built. This photomask is printed on a glass plate above the build platform using an electrostatic process similar to that found in photocopiers. The mask is then exposed to UV light, which only passes through the transparent portions of the mask to selectively harden the shape of the current layer. After the layer is cured, the machine vacuums up the excess liquid resin and sprays wax in its place to support the model during the build. The top surface is milled flat, and then the process repeats to build the next layer. When the part is complete, it must be dewaxed by immersing it in a solvent bath.

Rapid Prototyping Applications [9]

- Orthopaedic and Spinal Surgery
- Maxillofacial and Dental Surgeries
- Oncology and Reconstruction surgeries
- Customised joint replacement Prosthesis
- Patient Specific Instrumentation
- Implant design Testing and Validation
- Teaching Tool

Functions of Rapid Prototyping in Clinical World

- *Pre-surgical Planning:* A 3D model not only can be useful in surgical practice (i.e. a better fitting, purposefully designed implant), but it can also help

a surgical team in visually analysing the location, size and shape of the problem. In the event of a long operation, the model can also be used to plan and customise the surgery. This can be especially valuable when the surgery is performed on anatomical abnormalities [14].
- *Mechanical Replicas:* A 3D model can be tailored to specific material properties, including non-homogenous variations within a region. Specifically, mechanically correct bone replicas are useful in evaluating the behaviour of the bone under different testing conditions [24].
- *Teaching Aids:* Offering both visualisation of anatomical details and the possibility of practicing directly on a specimen without involving a patient, 3D models can be a valuable tool for training nurses and doctors [15].
- *Customised Implants:* Instead of using a standard implant and adapting it to the implantation site during the surgical procedure, rapid prototyping enables the fabrication of patient-specific implants, ensuring better fitting and reduced operation time [9].
- *Microelectromechanical Systems (MEMS):* These are micro-sized objects that are fabricated by the same technique as integrated circuits. MEMS can have different applications, including diagnostics (used in catheters, ultrasound intravascular diagnostics, angioplasty, ECG), pumping systems, drug delivery systems, monitoring, artificial organs, minimally invasive surgery [15].
- *Forensics:* Reconstruction of crime scene and wound are also benefiting from rapid prototyping. In particular, in the case of a surviving victim where a wound is of difficult access, e.g. the skull, a model can be used for detailed analysis [25].
- *Bioengineering:* Bioengineers are growing living artificial tissues to repair the damage from burns and chronic wounds, using laser based rapid prototyping technologies to render the biomimetic material designs in solid form [14].

Dental Applications of Rapid Prototyping [20, 26]
- Production of auricular and nasal prosthesis
- Obturators
- Duplication of existing maxillary/mandibular prosthesis especially crucial when an accurate fit to natural teeth or an osseointegrated implant is needed
- Manufacturing of surgical stents for patients with large tumours scheduled for excision
- Manufacturing of lead shields to protect healthy tissue during radiotherapy treatment
- Fabrications of burn stents, where burned area can be scanned rather than subjecting delicate, sensitive burn tissue to impression making procedures
- Fabrication of invisible orthodontic prosthesis / aligners for straightening teeth
- Fabrication of surgical templates in implant surgeries
- Fabrication of inlays, onlays and crowns

CONCLUSION
Rapid prototyping is an emerging technology of designing, creating and applying the use of working models or prototypes to test on product‟s features, which include the design, the performance, and the output. With the development and research of the diversity for RP systems and correspondingly built materials, it is possible to generate different kinds of dental prostheses for different applications. Despite the recent advancements and successes of rapid prototyping, there are various limitations which still exist. Some points can be further explored in the future, such as Rapid Prototyping with Vacuum Casting Methodologies.

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