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A Review on Recent Advances in Additive Manufacturing Techniques with Current Challenges and Future Directions

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ABSTRACT

Rapid Prototype is an innovative technology that has evolved within the design and manufacturing industries. In industries the use of RP technology coupled with other techniques has led to improvement in services offered to customers by improvement in areas such as 3D visualization, planning, design production, and polymeric devices. In this article we review the current technologies available in RPT and its application in different fields of medicine and future trends.

Keywords— Rapid prototyping, bio medical engineering, born tissue engineering.

I. INTRODUCTION

Rapid prototyping is the automatic construction of physical objects using solid freeform fabrication. The first technique for rapid prototyping became available in the late 1980s and was used to produce models and prototype parts. Rapid prototyping takes virtual designs from Computer Aided Design (CAD) or animation modelling software, transforms them into thin, virtual, horizontal cross-sections and then creates each cross-section in physical space, one after the next until the model is finished. However, each rapid prototyping platform uses the same principles of slicing, layering and bonding to build parts. Several research institutions and commercial organizations have integrated Computer-aided Design (CAD) and Rapid Prototyping (RP) systems with medical imaging systems to fabricate medical devices or generate 3D hard copy of these objects for use in surgical rehearsal, custom implant design and casting. In manufacturing, models are planned and conceived entirely on the computer screen, then converted to physical reality. In bio-medical applications. Prior to building, this highly complex data needs extensive pre-processing to provide a format that a CAD program can utilize, before transferring to an RP system. Global competition, mass customization, accelerated product obsolescence and continued demands for cost savings are forcing companies to look for new ways to improve their business processes. Rapid prototyping (RP) and rapid tooling (RT) have emerged as key enablers for rapid manufacturing, a new mode of operation promising improvements to the competitive position of companies adopting it. RP is a technology for quickly fabricating physical models, functional prototypes and small batches of parts directly from computer aided design (CAD) data. RT generally concerns the production of moulds and tooling inserts using RP. RP means for compressing the time-to-market of products and, Competitiveness-enhancing technologies, Medical and surgical models, artworks and models for engineering analysis.

1.1 RAPID PROTOTYPING: RP processes may be divided broadly into those involving the addition or the removal of material. According to Kruth [8], material accretion processes may be categorized by the state of the prototype material before part formation, namely liquid, powder or solid sheets. Liquid-based processes may entail the solidification of a resin on contact with a laser, the solidification of an electro setting fluid or the melting and subsequent solidification of the prototype material. Processes using powders (discrete particles) aggregate them either with a laser or by the selective application of binding agents. Those processes that utilize solid sheets may be classified into two types depending on whether the sheets are bonded with light or with an adhesive. Material accretion processes may also be clustered according to the mechanism employed for transferring data from the sliced three-dimensional models into physical structures. Following this method of categorization, the processes fall into one of four groups:

1.1.1. ONE-DIMENSIONAL CHANNEL: The first group of processes transfers data using one-dimensional channels. These data channels may be realized in the form of a laser beam, an extrusion head, a jet of thermoplastic, a nozzle spraying a binder, a welding head, a cutter or a computerized knife.

1.1.2. MULTIPLE ONE-DIMENSIONAL CHANNELS: A process in this category would employ multiple one-dimensional channels working in parallel. Currently, there is only one process implementing this data transfer method with two independently controlled lasers. However, this multichannel approach could be adopted for other processes in the first group to multiply productivity without introducing any changes to the fundamental working principles.

1.1.3. ARRAY OF ONE-DIMENSIONAL CHANNELS: The third group includes processes that utilize arrays of one-dimensional channels to construct three-dimensional structures. These may be arrays of nozzles or jets. Currently, RP systems with the highest build speeds all use this mechanism for data transfer.

1.1.4. TWO-DIMENSIONAL CHANNEL: The fourth group includes processes employing two-dimensional channels, e.g. masks. At present, there are only a few processes using this mechanism although it offers significant productivity advantages over the other three approaches

1.2MATERIAL ACCRETION PROCESSES

1.2.1LIQUID POLYMER: Of the three processes in this category, which all involve the solidification of a resin by applying electromagnetic radiation, and construct the part using points to build up the layers while the other four solidify entire layers or surfaces at once:

1.1.2.1. Stereo lithography (SL): This process relies on a photosensitive liquid resin which forms a solid polymer when exposed to ultraviolet (UV) light. SL systems consist of a build platform (substrate) which is mounted in a Vat of resigand a UV helium– cadmium or argon ion laser. The first layer of the part is imaged on the resin surface by the laser using information obtained from the three-dimensional solid CAD model. Once the contour of the layer has been scanned and the interior hatched, the platform is lowered and a new layer of resin is applied. The next layer may then be scanned. Once the part is completed, it is removed from the vat and the excess resin drained. The ‘green’ part is then placed in a UV oven to be post-cured. To broaden the application area of SL, research and technology development efforts have been directed towards process optimization.

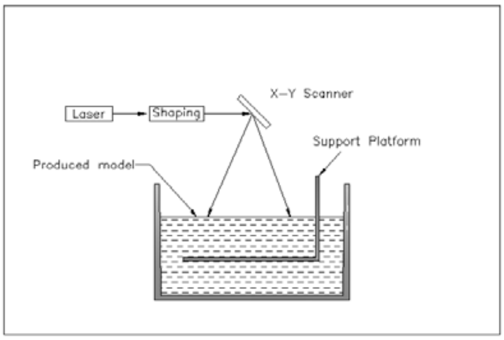

Figure 1: Stereo Lithography

1.1.2.2. Liquid thermal polymerization (LTP): This process is similar to SL except that the resin is thermosetting and an infrared laser is used to create voxels (three dimensional pixels). This means that the size of the voxels may be affected through heat dissipation, which can also cause unwanted distortion and shrinkage in the part. The system is still being researched.

1.1.2.3. Solid ground curing (SGC): This system again utilizes Photo polymerizing resins and UV light [5]. Data from the CAD model are used to produce electro-statically mask on a glass that is developed using a toner. Then the mask is placed above the resin surface and the entire layer is illuminated with a powerful UV lamp. Once the layer has been cured, the excess resin is wiped away and any spaces are filled with wax. The wax is cooled with a chill plat, and the wax chips removed. A new layer of resin is applied and the process is repeated. Similar to stereo lithography (SL) in that both use ultraviolet light to selectively harden photosensitive polymers. Unlike SLA, SGC cures an entire layer at a time. It is also known as the solider process. First, photosensitive resin is sprayed on the build platform. Next, the machine develops a photo mask (like a stencil) of the layer to be built. This photo mask 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 de-waxed by immersing it in a solvent bath.

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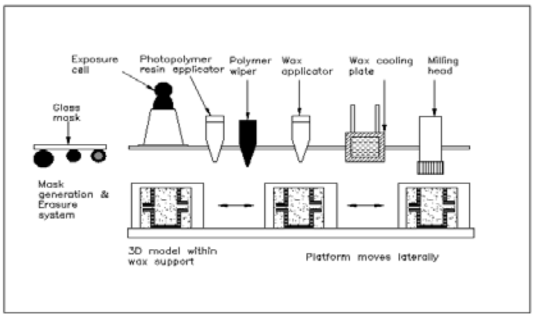

Figure 2: Solid Ground Curing (SGC)

1.2.2MOLTEN MATERIAL

There are four processes that involve the melting and subsequent solidification of the part material.

1.2.2.1 Ballistic particle manufacture (BPM). The process builds parts by ejecting a stream of molten material from a nozzle. The stream separates into droplets that hit the substrate and immediately cold-weld to form the part.

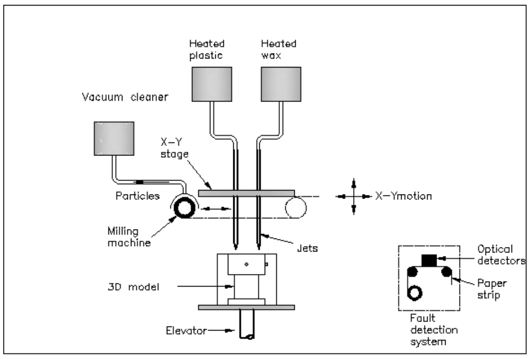

Figure 3: Ballistic Particle Manufacture (BPM)

1.2.2.2 Fused deposition modeling (FDM): FDM systems consist of two movable heads (one for building the part and one for the supports) which deposit threads of molten material onto a substrate. The material is heated just above its melting point so that it solidifies immediately after extrusion and cold-welds to the previous layers. In Fused Deposition Modeling (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 ^{0}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 as shown in figure. Various important factors need to be considered and they are steady nozzle and material extrusion rates, addition of support structures for overhanging features and speed of the nozzle head, which affects the slice thickness. 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. FDM creates 3-D models out of heated thermoplastic material, extruded through a nozzle positioned over a computer controlled x-y table. The table is moved to accept the material until a single thin slice is formed. The next slice is built on top of it until the object is completed. FDM utilizes a variety of build materials, such as polycarbonate, polypropylene and various polyesters which are more robust than the SLA models. FDM models can also be made in wax, enabling custom-made implants to be investment cast for individual patients.

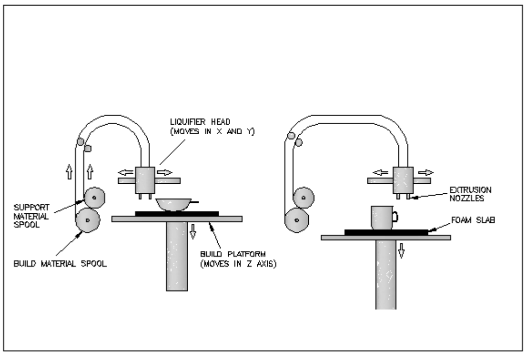

Figure 4: Fused Deposition Modeling (FDM)

1.2.2.3Laminated object manufacturing (LOM): In this technique, developed by Helisys of Torrance, CA, layers of adhesive-coated sheet material are bonded together to form a prototype. The original material consists of paper laminated with heat-activated glue and rolled up on spools. A feeder/collector mechanism advances the sheet over the build platform, where a base has been constructed from paper and double-sided foam tape. Next, a heated roller applies pressure to bond the paper to the base. A focused laser cuts the outline of the first layer into the paper and then cross-hatches the excess area (the negative space in the prototype). Crosshatching breaks up the extra material, making it easier to remove during post-processing. During the build, the excess material provides excellent support for overhangs and thin walled sections. After the first layer is cut, the platform lowers out of the way and fresh material is advanced. The platform rises slightly below the previous height, the roller bonds the second layer to the first, and the laser cuts the second layer. This process is repeated as needed to build the part, which will have a wood-like texture. Although these models are robust, it is difficult to remove unwanted regions of paper from areas of complex geometry.

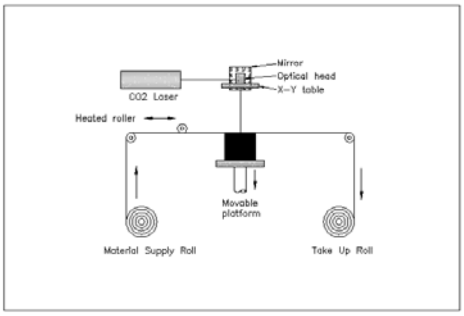

Figure 5. Laminated Object Manufacturing (LOM)

1.2.2.4Shape deposition manufacturing (SDM): Still experimental, this layer-by-layer process involves spraying molten metal in a near-net shape on to a substrate and then removing unwanted material via numerically controlled (NC) operations. Support material is added in the same way either before or after the prototype material, depending on whether the layer contains undercut features. The added material bolsters subsequent layers. If the layer is complex, support material may need to be added both before and after the prototype material. Each layer is then shot-penned to remove residual stresses. The prototype is transferred from station to station using a robotized pallet system. To date, stainless steel parts supported with copper have been produced. The copper may then be removed by immersion in nitric acid. These prototypes have the same structure as cast or welded parts and the accuracy of NC milled components

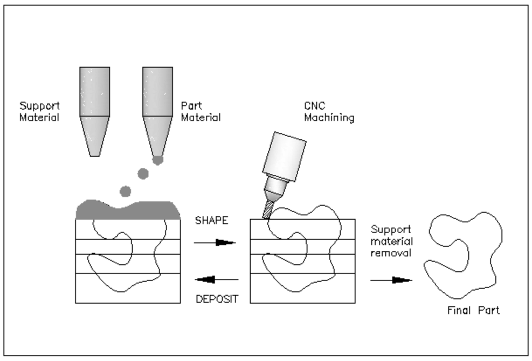

Figure 6. Shape deposition manufacturing (SDM)

1.2.3PROCESSES INVOLVING DISCRETE PARTICLES

These processes build the part by joining powder grains together using either a laser or a separate binding material. The main processes in this category are described briefly below.

1.2.3.1Selective laser sintering (SLS): SLS uses a fine powder which is heated with a CO_2 laser so that the surface tension of the particles is overcome and they fuse together. Before the powder is sintered, the entire bed is heated to just below the melting point of the material in order to minimize thermal distortion and facilitate fusion to the previous layer. The laser is modulated such that only those grains that are in direct contact with the beam are affected. A layer is drawn on the powder bed using the laser to sinter the material. The bed is then lowered and the powder-feed cartridge raised so that a covering of powder can be spread evenly over the build area by a counter-rotating roller. The sintered material forms the part while the un sintered powder remains in place to support the structure and may be cleaned away and recycled once the build is complete. There is another process, laser sintering technology (LST) that employs the same physical principles. Figure shows an LST system equipped with two laser beams working in parallel. Currently such dual laser systems are available for processing thermoplastics and sand. Significant development efforts have been directed towards process optimization to widen the range of applications of SLS and LST.

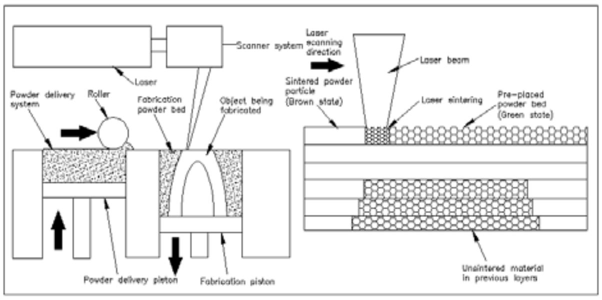

Figure 7. Selective laser sintering (SLS)

1.2.3.2 Laser engineering net shaping (LENS)*:* The LENS process involves feeding powder through a nozzle on to the part bed while simultaneously fusing it with a laser. The powder nozzle may be on one side of the bed or coaxial with the laser beam. If it is to a side, a constant orientation to the part creation direction must be maintained to prevent solidified sections from shadowing areas to be built. When the powder feeder is coaxial, there may be inaccuracies in the geometry of the part and the layer thickness if the beam and the powder feeder move out of alignment. Because the stream of powder is heated by the laser, fusion to the previous layer is facilitated. Other systems have also been developed based on the same principle, in particular direct metal deposition (DMD) and Aero Met laser additive manufacturing

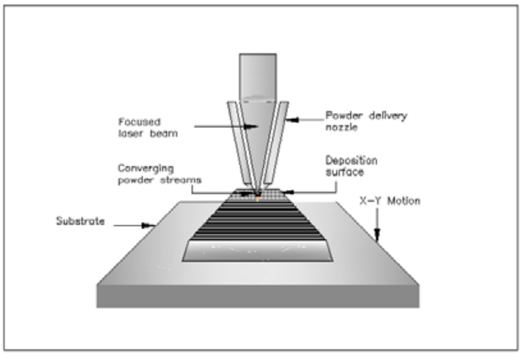

Figure 9. Laser Engineering Net Shaping (LENSTM)

1.2.3.3. Solid foil polymerization (SFP): The part is built up using semi-polymerized foils which are soluble in monomer resin. On exposure to UV light, the foil solidifies and bonds to the previous layer. It also becomes insoluble. Once the cross-section has been illuminated, a new foil can be applied. The areas of foil that do not constitute the eventual part are used to support it during the build process, but remain soluble and so are easy to remove. No commercial systems are available yet.

1.2.3.4Electron Beam Melting (EBM): The fundamental idea behind the CAD to Metal technology is to build up metal details in layers of metal powder, each of which is melted by an electron beam to exactly the geometry defined by the computer model.

The part is first designed in a 3D CAD program. The file is transferred to pre-processing software where the model is sliced into thin layers. The parts are built up layer-by-layer by the Electron Beam Melting (EBM) process in a vacuum chamber. On completion of the CAD to Metal Process the net-shape part is cleaned and can be finished as necessary by conventional methods. The electron beam is generated in an Electron Beam Gun situated on the top of a vacuum chamber. The Electron Beam Gun is fixed and the beam is deflected to reach the entire building area. The electrons are emitted from a filament, which is heated to high temperature. The electrons are then accelerated to half the speed of light in an electric field. The beam of electrons is controlled with two magnetic fields. The first acts as a magnetic lens and is responsible for focusing the beam to the desired diameter. The second magnetic field deflects the focused beam to the desired point on the building table.

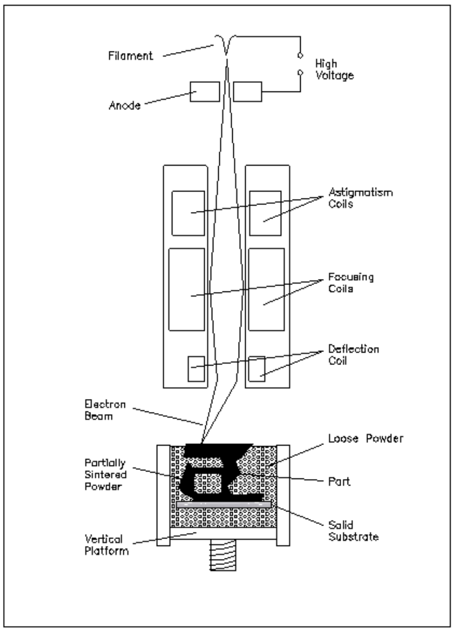

Figure 10. Electron Beam Melting (EBM)

II. APPLICATIONS

RP models are becoming widely used in many industrial sectors. Initially conceived for design approval and part verification, RP now meets the needs of a wide range of applications from building test prototypes with material properties close to those of production parts to fabricating models for art and medical or surgical uses. In order to satisfy the specific requirements of a growing number of new applications, special software tools, build techniques and materials have been developed. Five examples in different application areas are described in this section.

2.1FUNCTIONAL MODELS

One of the RP processes that is widely used for producing polyamide-based models for functional tests is SLS. The SLS production of polyamide parts is generally cost effective when a small number (1–5) of parts is required. Patterns for investment and vacuum casting RP technologies are widely used for building patterns for investment and vacuum casting.

2.2 MEDICAL OR SURGICAL MODELS

RP technologies are applied in the medical/surgical domain for building models that provide visual and tactile information. In particular, RP models can be employed in the following applications.

2.2.1. Operation planning: Using real-size RP models of patients' pathological areas, surgeons can more easily understand physical problems and gain a better insight into the operations to be performed. RP models can also assist surgeons in communicating the proposed surgical procedures to patients.

2.2.2. Surgery rehearsal: RP models offer unique opportunities for surgeons and surgical teams to rehearse complex operations using the same techniques and tools as in actual surgery. Potentially, such rehearsals can lead to changes in surgical procedures and significantly reduce risks.

2.2.3. Training*:* RP models of specimens of unusual medical deformities can be built to facilitate the training of student surgeons and radiologists. Such models can also be employed for student examinations.

2.2.4. Prosthesis design*:* RP models can be used to fabricate master patterns which are then replicated using a biocompatible plastic material. Implants produced in this way are much more accurate and cost effective than those created conventionally.

2.3 ART MODELS

Another growing application area for RP technologies is art and design. Through building RP models, artists can experiment with complex artworks that support and enhance their creativity. Initially, the high cost of RP models meant strict limits on the size of the models. However, recently, with the introduction of concept modellers, which are relatively inexpensive RP machines for quickly producing design models, it has become cost effective to employ RP techniques in many artistic applications. Taking into account the accuracy of art models and the RP materials available, the technological capabilities of concept modellers are more than adequate for the majority of art applications

2.4 ENGINEERING ANALYSIS MODELS

Computer aided engineering (CAE) analysis is an integral part of time-compression technologies. Various software tools exist, mainly based on finite element analysis (FEA), to speed up the development of new products by initiating design optimization before physical prototypes are available. However, the creation of accurate FEA models for complex engineering objects sometimes requires significant amounts of time and effort. By employing RP techniques it is possible to begin test programmes on physical models much earlier and complement the CAE data. Four applications of RP models for engineering analysis are described below:

2.4.1. Visualization of flow patterns*:* SLA models were used to optimize the cross flow jacket of a V6 high performance racing engine. Sixty sensors were installed in the model to monitor local flow temperature and pressure conditions. The coolant flow patterns were visualized by accurately injecting very small air bubbles. The flow patterns were recorded by high-speed video.

2.4.2. Thermoplastic tension analysis: By employing the THESA method, RP models of real parts can be used on test rigs for structural analysis. This method allows temperature changes in the test parts to be directly correlated to the load. The effect of a particular load on the temperature patterns is analysed using thermal imaging.

2.4.3. Photo elastic stress analysis*:* Photo elastic testing is employed to determine the stresses and strains within physical parts under specific conditions. This method is based on the temporary birefringence of a transparent material subjected to a specific load . SLA models exhibit the required birefringence that can be observed by irradiating the test samples with polarized white and monochromatic light. Results from photo elastic analysis of SLA models can be transferred to functional metal parts by employing fundamental similarity laws. It is also possible to 'freeze' the stresses and strains by warming the loaded model to a level above the resin glass transition temperature and then gradually cooling it back to room temperature.

2.4.4. Fabrication of models for wind tunnel tests: RP techniques can be used to produce wind tunnel models, which are not subjected to significant loads For example, the strength, accuracy and surface finish of models produced using SLA, SLS, FDM and SGC technologies are sufficient for tests of non structurally loaded parts. In addition, SLS models produced using steel powder or metal models fabricated from RP patterns are adequate for lightly loaded applications

III. FUTURE TRENDS

Research in the fields of RP and RT is just over 10 years old. In spite of this, significant progress has been made in widening the use of these technologies and in the development of new processes and materials. To achieve long-term growth in these fields and realize their full potential, a number of challenges remain. These challenges could be grouped under the following categories.

3.1. Productivity/cost of RP machines: To benefit truly from the 'direct' fabrication capabilities of RP processes, especially when the serial production of parts is targeted, their productivity should be increased and machine costs reduced significantly. Currently, there are two main approaches to addressing these issues. With the first approach, productivity is raised by increasing the number of channels used for data transfer (multiple one-dimensional channels) without modifying the working principles of a process. The second approach is to develop a new generation of RP machines that are specially designed for serial production and employ new mechanisms for data transfer (multiple/arrays of one-dimensional channels or two-dimensional channels) and/or new physical principles. It is expected that long-term growth in the RP industry will come from applications that are impossible/very dificult, costly and time consuming to implement with conventional manufacturing techniques. Therefore, new RP machines should address the specific requirements of these applications. For example, these new machines should allow improved accuracy and surface finish of RP parts, multi-axis deposition of material, direct building of multi-component assemblies, fabrication of materially graded structures (in density and composition) and manufacture of mesoscopic components and devices. Furthermore, it is expected that wider use of RP machines for rapid manufacturing would lead to reduction of their cost

3.2. Materials: One of the main limitations of RP processes is the limited variety of materials and their properties, and also their relatively high cost. Significant research efforts are focused on the development of a broader range of materials that simulate very closely the properties of the most commonly used engineering plastics. In particular, much research is being conducted on the development of new materials with high rigidity, high impact strength and high tensile elongation at breaking. Also, a range of materials for fabrication of investment casting patterns with low ash content, high impact strength and good surface finish are currently under development. Recently, the fabrication of multi-materials and heterogeneous objects has attracted the attention of the research community. This is quite understandable because RP is well suited to building such objects. Functionally gradient components could be manufactured from different constituent materials exhibiting continuously varying composition and/or microstructure. Developments in this area will make possible the fabrication of objects with multiple and conflicting functionality. Progress in the area is directly linked with the development of new CAD tools that are suitable for designing heterogeneous objects.

3.3. Process planning: Although process plans for building complex RP parts are reduced to containing only three operations (these usually being building parts, inspection and finishing, which can include painting) compared to the many steps required by conventional material removal processes, the process planning tasks associated with layer manufacturing require special attention. These tasks include selecting the part orientation, identifying the support structures needed, slicing and deposition path planning and the specification of process parameters. Existing approaches to addressing these problems fall into two categories: algorithmic and decision-support solutions. The algorithmic approach relies on geometrical reasoning mechanisms to find solutions for these tasks. For example, this approach is used to determine the part orientation in respect of some user-defined criteria (minimization of the support structures required, avoidance of trapped volumes, improving part quality and engineering properties), to study the influence of different deposition patterns and process parameters on part properties, to identify overhanging features requiring support structures utilizing STL file facets, solid models or slice data, and to develop new techniques for slicing (adaptive slicing and slicing of heterogeneous objects). The second approach employs decision-support methods to perform tasks that require quantifying the tradeoffs between competing goals. Such process planning methods employ multi-criteria optimization techniques, analytical models and heuristics. With increases in part complexity and the wide range of available RP materials and RP machines, there is a need for more advanced process planning tools, in particular tools that could relate process variables to part quality characteristics and address the process specific requirements associated with the fabrication of parts from heterogeneous materials.

3.4. RP data formats and design tools: The stereo lithography (STL) format was introduced in the early years of RP technology and is considered a standard for interfacing CAD and RP systems. The STL format has a number of drawbacks that are inherent in the representation scheme employed. The use of other standard formats for product data exchange such as IGES, HPGL, STEP and VRML have been considered in place of STL, but as problems remain these alternative formats are not widely accepted. Work on the development of new formats continues in order to address the growing requirements of RP and RT applications for more precise methods of data representation. Also, in recent years, with the emergence of RP processes for fabrication of heterogeneous objects, there is an increasing interest within the research community in developing new CAD tools that enable objects with varying material composition and/or microstructure to be designed. Currently, a number of CAD systems for constructing such objects are under development employing voxel-based methods, generalized cellular decomposition, finite element based methods and constructive methods. As already mentioned, advances in this area are directly linked to research and development in technologies capable of producing materially graded structures.

IV. CONCLUSION

Rapid prototyping method is very useful tool which can accelerate the way of product from the idea to market. Generative principle of rapid prototyping methods enables to produce parts of any geometry. These processes are practically unlimited in their ability to form complex shapes, they can produce both positives (parts) and negatives (dies and molds) . Recently this technique was used for the separation of Siamese twins who was boned by the attaching of the skull portion as shown below

RP modeling for surgical planning to separate Siamese twins.
(Courtesy, Biomedical Modeling, Inc.)

It is a very significant discovery in medicine and the first step on the way to making other complex human organs. Further development in RP in tissue engineering requires the design of new materials, optimal scaffold design and the input of such kind of knowledge of cell physiology that would make it possible in the future to print whole replacement organs or whole bodies by machines. There are also many new trends of applying RP in orthopedics, oral and maxillofacial surgery and other fields of medicine. RP technology can make significant impact in the field of biomedical engineering and surgery. Physical models enable correct identification of bone abnormality, intuitive understanding of the anatomical issues for a surgeon, implant designers and patients as well.

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