Rapid Prototyping: A Tool for Product Development

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ABSTRACT

This paper discusses the current status of layer-based manufacturing Rapid Prototyping (RP) technology and how it is being successfully implemented as a tool for product development (PD). A brief introduction to RP is given, focusing on the limitations of existing technology. Future trends for RP development are then discussed with further consideration for software issues in future applications.

Keywords: Rapid Prototyping, Product Development, Industry Overview

1. INTRODUCTION

This paper is an overview that assumes that some readers may only be vaguely familiar with layer-based manufacturing, Rapid Prototyping (RP) technology. RP is a term that has been used in a number of different contexts and therefore it is necessary here to describe the technology, both to set the scene and to clarify the terminology used. The purpose of this paper is to state what RP is and why it is useful to use it as part of the development process for new products. This objective is further strengthened by discussing how this technology itself is developing in order to fulfill the needs of manufacturers.

1.1 What is RP?

Rapid Prototyping is a term used to represent a range of technologies that can fabricate 3-dimensional objects in a single stage, directly from their CAD descriptions. There are a number of other terms that are associated with RP that can be used to further describe the technology: -

- *Free Form Fabrication:* This term emphasizes the fact that RP is largely 'geometrically independent' in that any increase in the complexity of form does not necessarily make it more difficult to build.
- *Automated fabrication:* This links RP with other, similar technologies like NC machining to emphasize the fact that parts are largely produced without human intervention. Since RP replaces traditional model making skills, this can be considered a huge advantage in terms of increased manufacturing speed, throughput and reduced demand on skilled labour.
- *Layer-based additive manufacture:* RP simplifies the complex 3D fabrication process by reducing it to a series of finite thickness 2D forms or layers and adding them together.

The RP term has been the subject of much discussion and controversy. RP is also used to describe processes in software, business, and electronics sectors. The general definition relates to being able to create objects, models or systems in a speedy manner so that further development is subsequently streamlined. RP is therefore a relatively ambiguous term that is also linked to the more general theme of rapid product development. Some people would prefer not to use the term 'prototyping' because it restricts the scope and applications can indeed be outside of the prototyping arena. However, despite all this ambiguity RP was the first term used to popularize this technology and as such it has stuck.

The final definition of layer-based manufacture is the key to how RP really works. Models are created by bonding layers of material together. If the layers are sufficiently thin then the models will closely approximate the original intended design. Most RP processes use layer thicknesses in the order of 0.1mm and this seems to be sufficient to suit many applications. RP is becoming a well-accepted technology in the manufacturing sector, with many different industries (e.g. kitchenware, electronics, toy-making, jewelry, automotive and aerospace, etc.) making use of these capabilities. The term 'additive' manufacture also distinguishes RP from NC machining, which uses a stock material and removes, or subtracts, material to reveal the final shape. With RP you start with just a substrate and add material in layers until the part is completed.

The process starts with the original native CAD file (fig 1), which must be translated into a STereoLithography (STL) file, which is a triangular faceted surface representation. STL is a *de facto* standard that is used by all RP machines and sliced according to the machine capabilities. Prior to this, however, the data may be pre-processed to include machine-specific requirements. The slices correspond to the layer thickness of the machine and parts are built from the bottom up. The first layer is built on to a platform, which is indexed down for each layer. Each layer is therefore considered as a 2D extruded form and therefore the layer thickness is critical for accuracy and surface roughness. We can view this process as reduction of a complex 3D construction to a series of simpler 2D steps. A significant problem with this is that all parts must be physically supported at all times during the build process. With some RP machines this means a pre-processing stage to add support structures to the STL file prior to slicing. It also means that cleaning of RP parts (the post-processing stage) can become a time-consuming manual task.

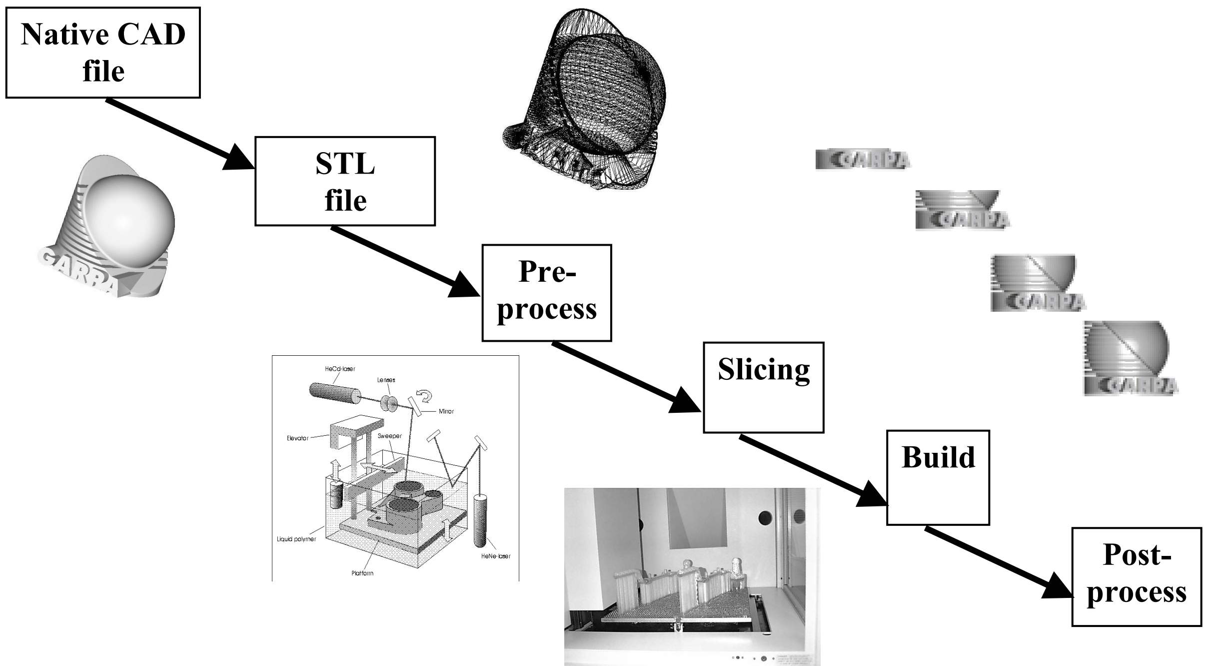

Fig. 1. Representation of the RP process chain

1.2 Why is RP important for Product Development?

D.T. Pham presents one of the most appropriate diagrams to explain the benefit of RP as part of the product development (PD) process. Pham refers to this as Time Compression Engineering, and the concept is reproduced in figure 2 [16]. Obviously this is a somewhat stylized representation, aiming to prove the point that technological solutions can now provide you with an opportunity to perform tasks concurrently, thus saving time in the process. It is clear from this diagram that there is a need for significant levels of data and platform sharing as well as permitting iteration and feedback. RP fits into this framework very well. Firstly, it can assist in consolidating the conceptual design process ①. RP models can also be used to assist in the analysis process by providing test models②; the results of which can be fed back into the detailed design process. Models can also provide assistance to the tool designers and fabricators by providing reference to the final parts. They can assist in the tool-making process by providing patterns for soft tooling ③ and, in some cases, hard tooling that can be used to accelerate the product release process by providing a bridge to full-scale manufacture ④. So we can see prototyping moving further downstream in the product development process to further reduce the time to market.

Terry Wohlers writes an annual state of the industry report that has catalogued the development of RP in recent years [19]. This report has demonstrated numerous examples of how RP has been implemented to enable the concurrent processes illustrated in fig 2. However, it is interesting to note that the number of machines is still only around 15,000 worldwide. Compared with the hundreds of thousands or even millions of companies developing new products around the world, this can only represent the tip of a very large iceberg in terms of the overall market potential. This is notwithstanding the possibility of completely revolutionizing the way manufacturing is carried out in what is becoming termed as Rapid Manufacture. This subject will be discussed later on in this paper.

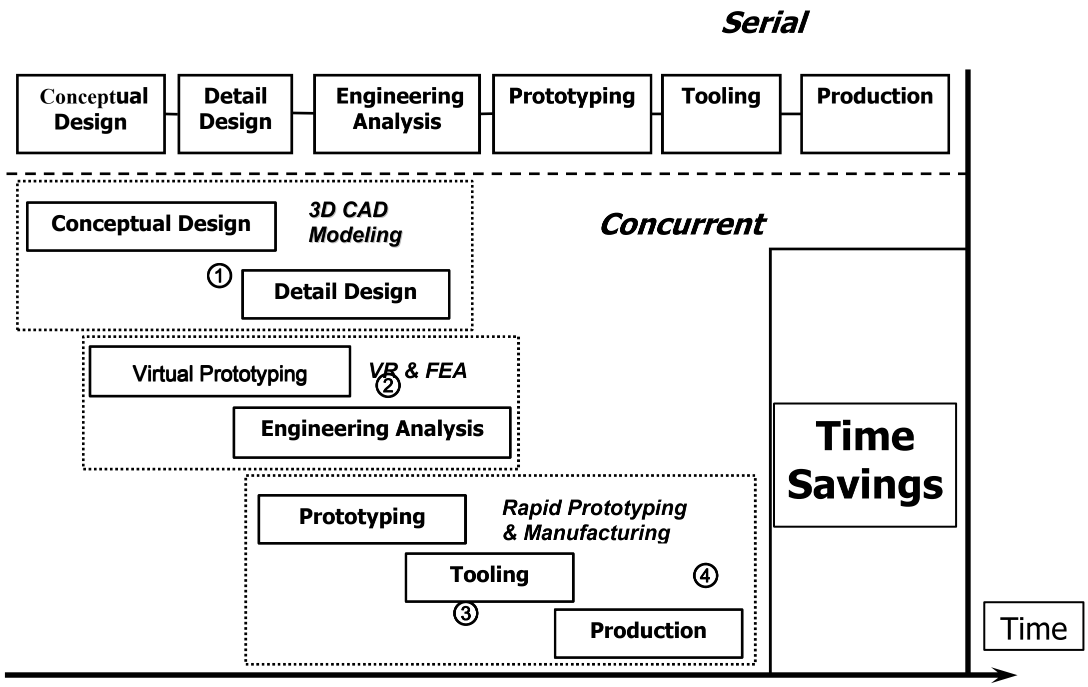

Fig. 2. Time Compression Engineering, showing the contribution of RP to this process (after Pham [16])

2. CURRENT LIMITATIONS OF RP

There are many different ways in which the part layers can be made and consequently there are numerous different RP machines and manufacturers. It should also be noted that RP technology has many limitations and it is appropriate at this stage to list the most common: -

- *Layer thickness:* 0.1mm layer thickness is still too thick for many applications. The best layer thickness commonly available is around 0.02mm, but users must be made aware that reduction in layer thickness means more expensive machines and a slower build process. All RP parts exhibit a characteristic 'stair step' texture, most evident on sloping surfaces and therefore manual surface finishing is required for many models.
- *Part accuracy:* In addition to layer thickness, there are a number of other accuracy issues that affect the building of parts. In particular one can expect an RP machine to have a minimum wall thickness for shell-type parts. Normally this will be a few millimeters. Repeatability of RP processes is generally good (in the order of a few microns), but part shrinkage due to material and process constraints can lead to tolerances in the few tenths of a millimeter range. In addition, many RP processes require overhanging and isolated regions to be supported. These supports must be removed at a later period. Normally, where the supports were in contact with the final part, there is a surface roughness that affects the overall part accuracy.
- *Part size:* Geometrical independence is not strictly true in that models are restricted by the working envelope of the machine. Many RP machines are in the order of 300mm cubed and the largest are around 500mm cubed. Some applications may therefore require construction of parts in sections or for them to be made to scale.
- *Materials:* Much of the part fabrication process in RP is dependent on the ability to combine layers together. This forces severe constraints on the materials suitable for a particular process. The majority of

RP processes build models from polymeric materials since this represents satisfactory material properties without the need to resort to very high temperatures and/or forces.

- *Part strength:* Since parts are built in layers, which are then bonded together in some way, it is likely that these bonded regions represent weaknesses in the overall structure. Even within the material range of a particular process, it is commonly found that the mechanical strengths of parts made are slightly inferior to parts made with the same material in other manufacturing processes (e.g. injection moulding).
- *Speed:* RP is not as 'rapid' as many people realize and would like it to be. Parts generally take a matter of hours, to perhaps a couple of days to fabricate, depending on the chosen process and size of part. Whilst this is a significant improvement on conventional model making approaches (with the addition of improved accuracy, material properties, etc.), there is always a demand for further increase in speed. Many potential users may not be prepared to wait for models to be made in this time frame.
- *Cost:* Of course, the capacity to create models quickly, accurately and reliably using RP technology must come at a price. RP technology is still something of a novelty and machines are generally constructed in small volume production. Many of the higher end machines are over US$200,000. Having said that, the prices of all machines are steadily coming down and smaller machines that are focused more at the concept modeling sector, generally with limited properties, are approaching a cost similar to many high-end computer products (i.e. around US$30,000). Many concept-based applications can be addressed using these lower-cost machines.
- *System integration:* Currently, RP machines are considered to operate as stand-alone. Whilst most machines are networked to assist file transfer, machine operation and part output requires a significant amount of manual labour.

This means that, as researchers and developers, we have plenty of work to keep us busy. For example, systems are being developed that can make parts with micron-scale layer thicknesses. Other machines are focusing on producing parts with a wider variety of materials, namely bio-materials and metals. Ink-jet printing technology is widely used in more recent RP machines, with the major benefits of controllable precision and increased speed of build. Add to this research into incremental improvements in existing technology and system integration and you have a huge amount of potential for achieving the ultimate goal of rapid manufacture.

3. FUTURE TRENDS

It is quite easy to see why RP is a technology that has aroused the interests of many researchers. Whilst it is a technology in common use in industry, it is still relatively new and represents a significant milestone in manufacturing technology. It is a technology that directly links to CAD without the need to focus specifically on the fabrication process, thus providing a mechanism to produce parts automatically. This section discusses the various ways in which RP is developing in order to overcome one or more of the limitations mentioned above.

3.1 Development of existing technology

Obviously, the RP vendor companies wish to reduce the cost of their machines in order to make them more competitive and widespread. Incremental improvements of the RP machines include reduction in layer thicknesses, faster scanning speeds, and larger build volumes. Improvements in materials include the ability to withstand higher temperatures, reduced shrinkage and produce higher resolution parts. Cost reduction is primarily achieved by streamlining the production process and selling more machines. Whilst vendors have taken advantage of improvements in associated technologies (e.g. computer systems with greater data processing capabilities), the machines bought today employ the same techniques developed when RP started to emerge in the late 1990's. What might be termed 2nd generation RP technology is now starting to encroach on the commercial market. These are the results of RP research being carried out with RP technology in the last 10-15 years and are described briefly in the following sections.

3.2 Rapid Tooling (RT)

RT is an objective that RP vendors have been trying to achieve for many years. The basic rationale used by most systems employs RP parts as patterns for casting. In 'soft-tooling' the pattern is used in conjunction with rubber moulding technology to provide short production runs. This has been successful commercially for a number of years and companies routinely use this approach to test new products prior to decisions on making significant financial (and time) commitment to large-scale production.

'Hard-tooling' based on RP, on the other hand, is still a relatively unfulfilled objective. A number of companies have introduced methods for creating steel parts, based on RP technology. An example process is Laserform [13], owned by the most well-known RP vendor; 3D Systems. In this case a metal/polymer composite is created in the RP machine and further furnace processing results in a fully dense metal part. This, and similar processes, can result in good quality parts, but are considerably more involved and often require additional capital investment to the RP machine.

An alternative approach appropriate to all RP technologies is to create an investment-casting pattern using RP. This approach requires the manufacturer to have access to foundry facilities with an understanding that the RP parts being used do not behave in exactly the same way as conventional wax or foam parts. As with the previous 3D Systems examples resulting parts can only be near-net shape, thus requiring conventional machine-tool processing in most cases to achieve acceptable accuracy and surface finishes.

More recently there have been a number of direct metal RP systems (e.g. the ProMetal system [17]). Nearly all parts are made using a powder feed approach, using laser or similar beam technologies to locally melt the powder. Using powders means there is generally no problem with supports, which would be very difficult to remove from a metal part. However, there will always be a powdery surface to the part, which will require additional machining for tight-tolerance and surface-critical features.

RT is therefore an achievable goal for RP but requires process integration in order to make it work effectively. With advancements in high-speed machining, the benefits can be difficult to justify in terms of cost.

3.3 Rapid Manufacture (RM)

RM is a much more viable long-term possibility for RP. In RM, the justifications resulting from changes in product development are stacked in favour of RP. Product life cycles are becoming shorter, designs are becoming more complex, and markets are demanding greater variety and customized features in products. Polymers are the material of choice for most products, which is also the most common RP material. Decisions for RM are therefore made in terms of cost, time and volume. If a small number of parts is wanted in a short period of time, then RP can become RM. Numerous case studies can now be found to demonstrate this fact.

A good example of RM comes from Phonak, who produce hearing aids [15]. The NemoTech process uses a combination of reverse engineering of ear impressions, specialized software, and the Selective Laser Sintering (SLS) RP technology. This makes it possible to produce custom hearing aids that fit inside the outer-ear canal. The fit is very comfortable for users, who claim improved, high quality performance. To make individual moulds for each hearing aid would be time consuming and cost-prohibitive, so RP technology comes out as the only viable solution.

Wohlers cites a number of similar cases in his report [19], including a study carried out at the University of Loughborough in the UK, which analyses the cost implications of using RP as a manufacturing method in place of conventional injection moulding. There are a numerous caveats concerning adopting this approach, but on cost alone RP can become RM for any technologically suitable production runs up to a few thousand parts.

3.4 Multiple Material Systems

Returning to the discussion on RT, an interesting characteristic of some RP systems is the capability to produce parts with multiple material properties. Since RP is a layer-based technology, it has long been the concern of system vendors to reduce the layered effect. Most evident in the form of a characteristic 'stair-stepping', many RP parts exhibit mechanical, surface and other volumetric defects that will vary according to the position and orientation the part was built within the machine. Obviously this is a problem, but if the behaviour can be predicted then this heterogeneity also represents a potential advantage over other manufacturing processes.

A number of RP processes, like the LENS system from Optomec [14] and the SDM process developed at CMU [10], have the capability to vary the material feed of different materials into the build region. Since parts are made by 'selectively' building up material, there is the opportunity to control how that material is added: -

- *Composite materials:* By mixing filler materials together but without alloying them, it is possible to make composite material structures taking advantage of the constituent material properties. This can lead to stiffer, harder, or more heat resistant parts but the planar nature of the layers still represents a major source of mechanical weakness. If the layers do not represent the directionality of, for example the stiffness required using carbon fibre-reinforced components, then the performance of the part will be compromised. The development of the curved-LOM process illustrates how this can be overcome to a certain extent by curving the layers rather than using planar additive fabrication [12].

- *Functionally Gradient Materials:* If a beam is built with steel on one side and copper on the other, the interface between the two materials represents a significant problem. Physical bonding of the materials, thermal and chemical effects will lead to stress, bending, cracking and corrosion. Instead of having a clear junction between the two materials, grading them by varying the ratio across the boundary can alleviate some of these problems. Injection moulds for example can have the durability of steel at the mould surface, whilst benefiting from the heat transfer properties of the copper to assist in the cooling process. Gradient blending can reduce the possibility of delamination. Of course there are still material affinities to deal with relating to temperature, chemistry, etc.
- *Multiphase perfect materials:* Taking the previous examples to an extreme, RP represents a technology that can produce multiphase perfect materials [3]. This is a process of choosing material compositions and geometries to meet the requirements of a particular performance-related task. For example, animal bone has a combination of materials combined in specific ways to solve the task for supporting the body. There are dense fibrous cortical bone regions to provide support and stiffness in particular load directions. There are less dense cancellous bone regions that assist the mechanical behaviour of the bone whilst also providing nutrients to the system. Furthermore there are layers of cartilage at the joint interfaces that provide smooth motion. RP systems do not have such capabilities as yet, but the capability to specify the material properties in different regions can be exploited to this effect.

This represents the true 'cutting-edge' of RP research.

3.5 Micron-scale RP

Another area of great excitement is that of micro- and nano-scale fabrication. There are many technologies focused on being able to create objects on a nano-scale. However, we cannot really say that these are RP technologies since they require significant amounts of design and planning and technical constraints. All this goes somewhat against the RP principle of 'plug and play' where the designer does not have to worry too much about the fabrication process when creating the design. Micro-scale RP is, however, very viable.

The only RP technology that has been successfully scaled down to a micron level is stereolithography (SLA). The advantage of this process is that the liquid resin photoreactive polymer can be presented at a very low viscosity prior to polymerization. This makes it possible to generate such thin layers (around 10 microns). In-plane resolution is achieved by the use of very finely focused optic systems, which can even be in the form of masking technology [18]. However, it is not merely a case of reducing the size of all the machine components. For example, very small parts will have very fragile features. Mechanical spreading of the resin to ensure the layer is flat cannot be done for fear of damaging the part. Similarly, since it uses liquid resins, SLA is a technology that requires support structures. Removal of parts from the build platform as well as removal of the supports themselves represents a significant problem when the parts may only be 1 or 2mm in size. The support geometry is therefore significantly different from conventional SLA.

However, there is increasing interest in this technology to assist the electronics (for connectors, waveguides, etc.), jewelry and optics industries, etc. The demand is unlikely to be great compared with the rest of the RP industry, but one can envisage a lucrative service industry fabricating prototype micro-parts and tooling.

3.6 Non-manufacturing applications

RP was a technology developed to solve the problems of manufacturing industry. The types of materials, machine dimensions and processing speeds are generally compatible with product development as it is carried out today. However, there are a number of potential applications outside of this industry: -

- *Medicine:* Already a number of examples used in this paper have alluded to applications in medicine. Applications in medicine are not merely confined to medically-related manufactured products. RP models have proven to be extremely successful aids to diagnosis and planning for complex surgical cases. For example models are routinely used in planning the separation of conjoined twins [4]. Many applications are therefore created from individual patient data. However, it is interesting to note that whilst linking RP to medical imaging data (CT, MRI, etc.) seems a logical and natural development of this technology, there are numerous cost, speed and materials (specifically biocompatibility) issues that must be resolved before it is widely used in this application sector.

- *Architecture:* The main issue surrounding the use of RP for architecture is effective communication. Models are routinely used at various stages of the architectural design process [8]. However models, by definition, can never become the final product. Buildings are too large and too complex to be made using RP (although a system is currently under development that uses RP techniques for construction of full-scale buildings [11]). Architects therefore make decisions on what details they wish to focus on by using models to make certain statements and assess certain aspects of the design. As a result, they would like an RP system that has the aesthetic capability of representing multiple material (although not necessarily mechanically). Currently there is one colour RP system commercially available from the ZCorp Company [2]. Whilst this technology is improving in its ability to represent colours, multiple material representation is not just about colour, but also texture, translucency, etc.
- *Art:* Using RP for artistic modeling (sometime referred to as digital sculpturing [6]) is not the same as in the previous example of architecture. Here, artists are attracted to RP because it provides a different artistic media compared to others (like clay, marble, etc.). As well as the aesthetic impact of RP materials, it has been recognized for many years that the technology has the capability of creating parts that would be difficult or even impossible to fabricate any other way. Objects trapped inside other objects, fine detail and precisely defined surfaces are all relatively easy to create using RP. RP has therefore become a particularly popular tool for artists who base there designs on mathematical equations [5].

Certainly there will be new applications that can benefit from RP technology. One possible conclusion of this is to see the obviation of manufacturing technology as we know it. Fabrication may eventually end up in the home, where application is limited only by the imagination of the user.

4. SOFTWARE ISSUES

Obviously CAD is a critical element in any system involving RP. RP is driven directly from the CAD file of the product generated. This CAD representation must consist of fully-enclosed surface model data or else the resulting RP part may be compromised. In the past this caused problems for early surface modeling systems and produced best results from solid modeling packages. Nowadays, RP is an accepted output route for most CAD systems and part quality is rarely affected by the package used. With more widespread use of RP in manufacturing, attention has been directed towards effective integration with other technologies. There are numerous software solutions to assist in running RP systems as noted in [7]. Two of the key areas where there is considerable activity are discussed in the following sections.

4.1 Representations

The *de facto* standard for RP model representation is the STereoLithography (STL) file. This is a simple facetted representation that uses triangles to approximate the model surfaces. The size of triangles used can be varied according to the maximum allowable deviation from the actual surface. If this deviation is close to the RP machine accuracy limits then faceting as a result of the STL file would not normally be noticed on the resulting part. The STL file represents something of a lowest common denominator that makes it relatively easy to make good quality output regardless of the RP machine used. Slicing is easy to calculate by just intersecting a plane with the model triangles. It is possible to use the additional information of triangle facet direction to determine the internal and external surfaces, but this is more commonly calculated by looking at the nested curves generated in 2D. The machines have their own slicing algorithms that are process dependent. Whilst it may be more efficient to slice the model directly from the CAD file, this would cause problems with model file transportability. However, the STL file poses some constraints that may limit the development of RP technology, for example: -

- *Feature based systems:* There are systems that can adapt some of their parameters according to the model being built. For example, some systems can vary the layer thickness so that vertical surfaces can be manufactured using thick layers whilst more complex curved and sloping surfaces can be fabricated using thinner layers. The objective here is to optimize build speed without compromising build accuracy. Other systems have been developed that will not necessarily build the components in a purely homogeneous, layer-wise fashion (e.g. Shape Deposition Modeling and Contour Crafting [10,11]). In these cases the STL file may not be the best way to determine the build process, requiring greater knowledge of the design than a simple geometric representation.
- *Heterogeneous systems:* STL is a surface representation. The systems under development that have heterogeneous properties cannot use existing STL files since they are defined in terms of the solid structure. Even the colour system from ZCorp cannot properly create a coloured model using STL files

alone. A modified version of STL can apply a colour tag to each triangle, but there is no real reason why triangles should be just one colour. VRML has been used and can be directly applied to the model, but so far only limited implementations exist as discussed in [9], which illustrates the difficulty in this area. Most probably there will need to be a new standard developed to deal with heterogeneous solid modeling, some of which are described in [7].

4.2 Technology Management

RP technology is designed to operate for long periods of time unattended whilst the build process is being carried out. Totally ignoring the system can however result in dire consequences as a build can go wrong and many hours of operation can be wasted. Good control software ought to have a top level system that monitors the quality of the output regularly so that the machines are kept in good condition and parts are produced reliably. This may be expensive to achieve automatically so some operators use remote camera monitoring systems [1]. It is also interesting to note that a fast, reliable build time estimator is still not commonly available for most machines.

Whilst RP is viewed as a form of automation, there are in fact quite a number of manual tasks that must be carried out. Machines need to be set up. Parts must be unloaded from the machines. Post-processing of parts can require a lot of manual labour if they are for presentation purposes. Similarly parts used in additional process chains generally require manual treatment. In addition, material management is often an important issue, requiring the operators to keep an eye on the part quality as a measure of how good the raw material is. Unacceptable part quality can mean a need to replace the raw material. This means that operating RP technology is a mixture of good machine skills coupled with good manual skills. Such rare individuals who possess both qualities must not only be well rewarded but kept productive. Since RP is supposed to be a versatile technology, the process planning software ought to reflect this versatility. This is issue is described in detail in [7].

5. CONCLUSIONS

RP is a technology that can be used for many different applications, both manufacturing and non-manufacturing based. It can enhance and optimize the product development process. Whilst there are still many outstanding technological issues surrounding development and application of RP technology, it has already proved that it can be a valuable addition to the range of automated systems available to manufacturers.

This paper has presented an overview of RP technology, followed by discussion on the contribution it can make to product development. It has then gone on to discuss various limitations of the technology and how researchers are attempting to address these. Finally, there has been a brief discussion on how software needs to be developed in order to further enhance the technology.

It can be concluded that RP has made a good introduction and has a bright future in making PD more effective and efficient. Rapid Tooling assists this in current applications, but one should maintain a watching brief on the development of the exciting area of Rapid Manufacturing, which is ultimately set to revolutionize the way we manufacture products to meet the demands of modern consumers.

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