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Progress towards an international standard for data transfer in rapid prototyping and layered manufacturing

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Abstract

This paper discusses the informational requirements of rapid prototyping and layered manufacturing (RPLM). The study is motivated by the recent decision to embark on the development of a new Application Protocol for the international standard ISO 10303, specifically to handle layered manufacturing information.

The most common industrial use of RPLM today is for rapid prototyping, but a wider view of it as a flexible fabrication technology is taken here, to allow for future developments. Its use in building functional metallic parts under computer control has already been demonstrated, and commercial RPLM machines for building production parts are already being marketed.

The paper includes a survey of current and proposed data formats for communication between the various stages of the RPLM process. In comparing them, particular attention is given to the issue of extensibility to meet future needs. In this last respect, special emphasis is given to materials-related and other non-geometric information needed for fabricating multi-material objects and objects with graded material properties. Published by Elsevier Science Ltd.

Keywords: Layered manufacturing; Rapid prototyping; Solid freeform fabrication; Standards; STEP; ISO 10303; Data exchange; Product data exchange

1. Introduction

The paper examines the informational requirements of rapid prototyping and layered manufacturing (RPLM), and describes progress towards establishing a new electronic data exchange standard for this mode of manufacturing. Current and proposed data exchange formats are reviewed and found to have insufficient representational capabilities in important developing areas of RPLM technology. In particular, it is noted that the capture and transfer of information about material property distribution is likely to be an essential need in the future, and that no formal proposal for RPLM data exchange has so far addressed this requirement. The study provides a preliminary survey of requirements for the development of a new Application Protocol (AP) of the international standard ISO 10303, specifically for the transfer of RPLM data, which officially commenced in February 2001. ISO 10303 [1,2] is concerned with the electronic capture and transfer of product data; it is unofficially known as STEP (Standard for the Exchange of Product model data).

The paper is organized as follows. First a brief review is given on the salient aspects of RPLM processes in general. The information needed during various stages of manufacturing planning common to most of them is then discussed. Requirements for the manufacture of artefacts designed in terms of inhomogeneous and/or anisotropic materials are given particular attention, because emerging technology in this area appears to have great significance for the future of RPLM. Several possible ways of representing non-uniform materials are briefly reviewed. Existing and proposed means for data exchange in RPLM are then examined and their advantages and disadvantages discussed. The resources provided by the standard ISO 10303 are found to cover many of the RPLM data requirements established earlier in the paper, and the necessary extensions are identified. Finally, the paper outlines the current status of the recently established ISO 10303 project for RPLM data exchange.

2. Primary characteristics of RPLM processes

RPLM, also known as solid freeform fabrication (SFF), represents a class of recently developed additive manufacturing processes in which objects are constructed layer by layer, usually in terms of a sequence of parallel planar

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laminae. Many RPLM processes now exist, using a variety of materials and layering methods [3,4]. The methods may be broadly classified as follows:

- Photopolymer solidification (e.g. stereolithography, solid ground curing), in which a liquid resin is hardened layer by layer with a laser or ultraviolet lamp.
- Material deposition (e.g. fused deposition modelling), in which drops or filaments of molten plastic or wax are deposited to construct each layer.
- Powder solidification (e.g. selective laser sintering, 3D printing), in which powdered material layers are solidified by adding a binder or by sintering with a laser. Parts can be built from ceramics, nylon, polycarbonate, wax or metal composites.
- Lamination (laminated object manufacturing and solid ground curing). The first of these methods uses lasers to cut layers from sheets of paper, cardboard, foil, plastic, or ceramic [5], stacks them and bonds them together. The second uses a cut mask to expose regions of resin to be solidified by an ultraviolet lamp.
- Weld-based approaches. These methods produce a small melt pool from material delivered in the form of wire or powder mix. Components manufactured with these processes use welding and cladding deposition techniques that result in fully dense material deposition, though finish machining is usually required [6–8].

RPLM was originally used for rapid prototyping to help the designer verify part geometry, but is now increasingly used to make production tooling, including moulds for castings [9,10] and electrodes for electro-discharge machining (EDM) [11]. It also has emergent use for the manufacture of one-off and small batch production parts. RPLM processes can be used to build very complex artefacts, having intricate geometry, internal voids or multiple ready-assembled components, without any special tooling. Model transfer between CAD and the fabrication process is electronic, and the planning of fabrication is largely automatic, demanding little human intervention. However, because RPLM objects are built layer by layer, their surfaces often have a staircase appearance. They may also have inferior material properties when compared with objects manufactured by other means. Poor surface quality is sometimes overcome by performing finishing operations, such as grinding, polishing or NC machining, after an object is built.

Support structures are required by certain RPLM processes, when the object being built has overhangs or internal voids, in which case part of any layer may have no underlying layer to build it on. Supports are usually built together with the part, and are later detached and discarded.

Any RPLM process is characterized by a 'build volume'. This determines the largest single artefact that can be fabricated at one time. In fact, it is a widespread practice to manufacture multiple artefacts, simultaneously maximizing the proportion of the build volume that is occupied by the objects being built. For some RPLM processes, this economizes on the wastage of expensive fabrication material by minimizing the amount that is unused and discarded after each run of the RPLM processor.

A major prospective use of RPLM is for manufacturing heterogeneous objects. These may be made of more than one material, contain embedded devices, or have continuously graded material properties. RPLM, unlike conventional manufacturing processes, in principle permits complete 3D control over material properties. New design methods such as homogenization for structural topology design [12] specify varying material properties throughout the volume of the designed object; RPLM provides a means for producing such artefacts. Suggested applications of such 'functionally graded materials' include [13,14].

- Increased wear resistance for machine parts by use of resistant surface material.
- Use of heat-resistant ceramics on the surface of gas turbine blades, grading to titanium in the interior for strength.
- Manufacture of surgical bone implants with ceramic surface material to ensure good bonding, grading to metal in the interior for strength.
- Design of electrical components by control of electrical properties at a local scale.
- Time-dependent controlled release of ingested drugs through variation of the internal composition of pills manufactured by RPLM.

3. Data transfer requirements for RPLM

The design and manufacture of an RPLM object are often performed in separate organizations. Hence it must be possible to transfer design data to the RPLM manufacturer, preferably electronically, to enable process planning and product fabrication. Since a single organization may manufacture parts using several different RPLM technologies, a unified set of data transfer protocols is desirable for the entire class of processes. Although distinct RPLM processes use specialized equipment, most of them use a tool that is moved under computer control to add material to the part. Process planning for RPLM determines the tool paths and process parameter settings for the manufacture of a particular object from a given material by a particular RPLM process [15]. The basic steps, and their informational requirements, are as follows:

1. *Choice of object orientation during the build process.* This requires knowledge of the 3D shape of the artefact. The objective may be to minimize build time or support requirements, maximize surface quality (e.g. avoid staircase effects in functionally important regions), or to optimize in terms of some weighted combination of such simple criteria. More complex possibilities also exist.

For example, the structural properties of the built object are affected by the orientation and thickness of the layers within it, and by the spacing of deposition paths, since the RPLM process gives rise to small-scale material inhomogeneity. These factors in turn will be affected by the choice of process and material. The optimization of structural properties of an RPLM artefact could therefore also be an objective at the orientation stage, but this would require material and process information in addition to pure geometry. The output of the orientation task is simply a transformation to orient the part model appropriately.

2. *Support structure design*. Here, the 3D object model is needed. Support regions for any orientation can be found by calculating the 'shadows' it casts on the slicing planes. The output of this task may be a modified 3D shape model that includes the support volumes; alternatively, the supports may be represented only at the level of 2D slice data.
3. *Part slicing*. Given the oriented part model and its support volumes, this is a purely geometrical process of determining the details of the layers to be laid down. Its input is the 3D object model, and its output is a set of 2D slice contours, but if graded materials are used these must also contain 2D material distributions derived from a original 3D distribution specified at the design stage.
4. *Path planning within each slice*. The input to this stage is the shape of the slice, any 2D material distribution specified for it, and details of the path planning strategy if any choice is available. For lamination methods as described earlier, it is only necessary for the path to traverse the boundary of the slice. As they use uniform laminae, these methods cannot handle graded materials. However, the use of fibre composite layers will require material orientation to be specified. For other methods, an area fill strategy must be used with or without a boundary traversal. The path planning output is a geometric representation of the generated paths, with information on material composition if this varies within the slice. Criteria for path planning may include minimization of build time and requirements on part stiffness and strength—different scanning strategies give different material properties.
5. *Packing of artefacts into the workspace*. As previously mentioned, the simultaneous manufacture of multiple artefacts is often desirable. On the assumption that the preceding operations have already been performed for each artefact type concerned, the task then arises of packing a set of oriented objects into the processor workspace in an optimal way. The data requirement for this task is simply the shape and orientation information for each artefact type.

Expanding the fourth point, the structural properties of the part are affected by tool paths because the bonding strength between newly deposited material and previously hardened material may depend on the spacing of adjacent tool paths and the time interval between their traversal by the tool. Further, it may be noted that path choice affects post-manufacture distortion. In some processes, molten or unsolidified material shrinks as it hardens on top of a previously solidified layer; this generates residual stresses and consequent distortion of the part. A suitable choice of tool paths can minimize this effect.

The tasks described are common to most RPLM processes. Their common informational requirements establish the possibility of standardizing RPLM data transfer.

Other planning tasks in RPLM include process parameter selection, a very method-specific task, less suitable for a standard approach. Further, most RPLM techniques require post-processing of the built part (e.g. finishing operations to improve surface quality, or curing following stereolithography to remove unsolidified material). Most such process-specific activities are currently not automated and involve no electronic data transfer; they are not further considered here. The exceptions are those methods that employ NC machining for part finishing. However, they can in principle use standards that already exist in that area.

The following sections analyse various aspects of RPLM information in more detail.

3.1. Geometry-related input needed for RPLM

The most basic input to a RPLM process planning system is the description of the shape of the object to be manufactured. Additionally, tolerance information, surface finish, material data, etc. should ideally be used in performing certain process planning tasks. However, the process planning modules of most RPLM systems currently accept only shape information. Several types of shape representation exist.

- Computer aided design (CAD) models used to generate input for RPLM are usually surface models or boundary representation (Brep) solid models [16]. Either of these may be regarded as composed of bounded regions of different surfaces forming a large composite surface, and may in general be composed of combinations of planar and curved surface elements.
- *Polygonal* or *faceted* models are defined in terms of planar surfaces alone, the object boundary being represented by a mesh of polygonal facets. If the facets are all triangular, the model is consistent with STL, the most commonly used input format for RPLM process planning systems. Most CAD systems can compute and output such approximate triangulated surface or solid representations (specifically, STL files), the chord-height deviation between the true object surface and the triangular facets being controlled according to the user's requirements on approximation accuracy.
- Other shape representations (including 'point clouds', image data generated by computer tomography or

magnetic resonance imaging) usually require post-processing into faceted surface or other CAD-related representations for input to RPLM.

As RPLM moves closer to becoming an accepted production process, accuracy requirements on the shape models transmitted to the fabrication system are becoming more stringent. The proposed new RPLM data transfer standard should certainly include a faceted model capability for upwards compatibility with current practice, but it should also look to the future and provide for the transfer of exact geometry as defined in the originating CAD system. This will, in turn, make it easier to enhance the shape model by the inclusion of the surface finish, tolerance and feature information discussed later. All such information fits uncomfortably in a faceted model, and some of it (notably shape tolerances such as cylindricity) make no sense in a faceting context.

In addition to the overall shape of the artefact to be built, 2D representations of the individual slices are also needed as input for the path planning stage. At present, path planning is usually performed in the same system that calculates the slice shapes, so that there is no need for a standardized representation for the slice data. However, as will be shown, there is some motivation for performing the slicing and path planning functions in separate systems. This indicates the desirability of a standardized slice format.

3.2. Assembly data needed for RPLM

As mentioned earlier, ready-assembled artefacts may be fabricated in a single RPLM process, and it is therefore appropriate to provide for the representation of assemblies in the proposed standard. Furthermore, the capability of RPLM for fabricating multiple artefacts simultaneously in a single process indicates a need for the representation of *sets* of artefacts, each of which may in turn be an assembly of individual components. These topics are explored further in the following paragraphs.

The one-pass fabrication of complete assemblies (including working mechanisms such as functional bearings and gearboxes) has been demonstrated by many RPLM systems. In most cases, a single material has been used, but in the future the use of multiple materials for different parts may be anticipated. Some of the advantages of this mode of assembly manufacture are obvious; the assembly operation is eliminated as a separate manufacturing process, and in many cases the use of fastening devices can be dispensed with. The modelling requirements for assembly fabrication in RPLM include, as a minimum, assembly representation as a collection of positioned and oriented parts. However, consideration must also be given to the desirability of capturing inter-part relationships, possibly in terms of assembly features, which allows the modelling of kinematic degrees of freedom between parts—important for mechanism design—and the association of tolerance and fit data where part interactions occur.

Currently, in the RPLM fabrication of multiple artefacts, the items to be manufactured in a single operation are either (a) input in a single consolidated file as though they were just one non-decomposable object, or (b) input as multiple separate files. This is because there is no logical capability in the current input file representation for distinguishing between cases of one or many objects. It will be more desirable to provide such a multi-object representation capability, which will allow greater flexibility in adding or subtracting individual items to or from the collection to be fabricated. It will also allow (for example) reorientation of selected items in a collection, which is not possible in the consolidated file approach mentioned earlier. Accordingly, we propose that the concept of an *assembly set* should be available in the proposed new standard.

3.3. Tolerance data needed for RPLM

Tolerance and surface finish information cannot be handled by currently used data input formats, but they are clearly required for the future, particularly when RPLM reaches the status of a regular production technology. Tolerance information may be taken to cover the standard forms of engineering tolerances as associated with various elements of the model. These include tolerances of size, location and form, together with datum elements where appropriate. However, a more important form of tolerance information in the present state of the art is concerned with surface finish. In the RPLM context, this relates particularly to the ‘staircase’ effect resulting from building the object as a set of layers with (nominally) perpendicular edge faces. Good surface quality on an RPLM part requires minimization of the staircase effect. Most RPLM systems deposit material in only one direction, and reduction can be achieved in principle by slicing the part at smaller intervals. This has little effect on the accuracy of vertical or near-vertical faces, but may significantly improve the surface quality elsewhere. More generally, the slice thickness may be varied non-uniformly during the build process to get the best results, an approach known as adaptive slicing. This is well suited for parts with

- horizontal faces—which can then be built at their nominal design height rather than at an approximate height determined by a uniform slicing strategy, and
- thin horizontal protrusions—which may lie between uniform slicing levels and hence be missed entirely.

Adaptive slicing requires a shape model of the part, plus information on the desired minimum cusp height on the manufactured part. This height may vary from region to region of the part, depending on its functional requirements. Particular RPLM machines usually have a maximum and a minimum allowable slice thickness, which may vary from one material to another. Thus, both method-specific and material-specific constraints may have to be imposed on the calculations. When adaptive slicing is not available, it is still necessary to determine the uniform slice thickness that best meets the surface finish criteria required on the part.

In general, scan strategies that include a boundary traversal in addition to a fill pattern give a better finish, because they avoid the occurrence of the secondary staircasing in the slice contours that may arise (for example) from simple zigzag scanning. This effect results from the finite width of the RPLM tool. Other scan strategies in use include paths that are offset inwards from the slice contour by multiples of the tool radius. This has advantages in the manufacture of hollow structures, because it requires many fewer reversals of tool direction than a conventional raster fill strategy. There are consequent savings in the time taken for tool repositioning (during which material deposition or solidification is not taking place) and in acceleration and deceleration for direction changes.

3.4. Feature information

Feature information may be desirable in the transmitted model for a variety of reasons. Various researchers have proposed the association of tolerance or surface finish data with specific features in an RPLM artefact, as a way of identifying regions of the surface needing special treatment during manufacture. The specification of assembly features may also be useful, as mentioned earlier, especially when a ready-assembled product is to be fabricated. As far as it is known, the use of feature information in RPLM has not so far progressed beyond the research stage. However, work in this area needs to be tracked, and provision made for the transfer and use of feature information when its advantages have become accepted in a production context.

3.5. Material information needed for RPLM

Material information, not available in any RPLM data transfer format in current use, will be needed in the future for a variety of purposes. The primary reasons are as follows:

- Slicing calculations require material data because the minimum and maximum allowed layer thickness varies for each process and often for each material.
- RPLM objects can be manufactured having discrete regions composed of different materials, or with embedded components. A special case of multi-material parts is that of multi-colour parts.
- As mentioned in Section 1, design methods are becoming available for the optimal design of objects with functionally graded materials, and these may be manufactured by RPLM.
- Other research [17] has demonstrated the embedding of reinforcing fibres in the deposited material to give RPLM objects with directional material properties.

A key missing element in the RPLM product design and manufacturing environment is the capability to create a 3D CAD model that can represent a product's solid interior, in terms of material micro-structure or continuously variable material properties. The authors believe that no standard representational scheme provides such a capability. Research is needed to fill this technology gap, which may otherwise raise a barrier to important new developments in RPLM technology. The following sections of the paper briefly summarize the state of the art for this important topic.

For the representation of material macrostructure, what is ideally needed is some means of defining a function whose domain is strictly limited to the interior and boundary of a 3D object. However, for most realistic mechanical engineering objects, there is no simple parameterization of the object interior. The choices available in such cases are:

- Construction of an *exact boundary-based parameterization* for the interior and boundary of each specific object. In general, this will be very complex.
- Discretization of the object's volume into simple parameterizable elements. These will usually be polyhedral, and the boundary will in general have to be approximated.
- Use of a simple parameterization whose domain does not conform to the object's boundaries, either approximately or exactly.

Progress with these three approaches is outlined in what follows. It may be that all three are needed, since the nature of the design system used for defining objects with continuously variable material properties will determine the most appropriate formulation to use. Some of the earlier methods proposed are examined in Ref. [18] in more detail.

3.5.1. Exact boundary-based parameterizations of object interiors

Methods of this type make use of implicitly defined surfaces expressible in the form $f(x,y,z) = 0$. One can think of the surface as being the zero contour of the function $f(x,y,z)$; other contours may be defined by $f(x,y,z) = c \neq 0$. Since (at least for small positive or negative values of c) the distance of these contours from the surface increases with $|c|$, f may be regarded as measuring distance from the surface, in a generalized sense.

Park et al. [14] use a global blending technique to build a single implicit function f that represents the entire boundary of a modelled object. They then define material gradients inside the object, in terms of the variation of f with increasing distance from the boundary. This method is suitable for dealing with functionally graded materials in surface layers of an artefact, but it is not immediately clear how it could be used for general material distributions in the interior. From the standard point of view there is the further problem that no current standard represents shape in terms of the type of implicit functions used in this method.

A related method under development by Rvachev et al. [19] avoids this last disadvantage by deriving the function *f* directly from a Brep solid model. Each face of the model is first automatically expressed as a single implicit function using the properties of a class of *R-functions* having properties analogous to Boolean logical functions ([20]). The faces may then be similarly composed into a full Brep model. Finally, a generalization of an interpolation method attributed to Shepard (see Hoscheck and Lasser [21]) is used to interpolate continuous distributions (e.g. of material properties) specified on boundary elements of the model. The gradients defined by the functions *f* associated with each such boundary element provide the distance functions required by the generalized Shepard method.

The R-function method (RFM) in principle enables the representation of continuous material property distributions, without the use of meshing or other form of decomposition, inside any volume bounded by implicitly defined surfaces. It therefore has good potential for modelling material properties in the design and manufacture of RPLM objects. However, it currently has no associated design method, it needs extension to work with CAD models containing parametric surface elements, and its computational complexity is very high. Further, the constructed R-function does not in general provide a uniform measure of distance from the part boundary. Nevertheless, the fact that RFM handles exact shape representations using the simple algebraic surfaces provided in every CAD system (e.g. planes, cylinders, cones, toruses, etc.) encourages its further investigation for possible use in an RPLM standard.

3.5.2. Volume discretization approaches

The most elementary form of cellular decomposition uses *voxels*, cuboidal cells forming a regular 3D grid, (see, for example, Wu et al. [22]). Typically, the grid is imposed over the object and all cells more than 50% occupied by material are considered to be part of the object. The physical properties associated with each voxel are usually taken to be homogeneous in its interior. Thus a voxel-based material model will have a discontinuous material distribution and a boundary exhibiting staircase effects, incompatible with the requirement noted earlier for increased accuracy in shape modelling for RPML.

The *octree* approach to decomposition [23] is more sophisticated than pure voxel decomposition. It uses small cells near the boundary to achieve acceptable resolution there, but larger ones in the interior of an object model to minimize the overall number of cells. However, the basic octree approach suffers from the same disadvantages as the pure voxel method.

Irregular decompositions of the finite element type provide alternative possibilities for the modelling of material distributions. One such proposal is made by Jackson et al. [13], who suggest a design technique for graded material objects in which an initial CAD solid model is first meshed into tetrahedral elements using standard CAD system FE mesh generation capabilities. The material composition in the model is represented in terms of a vector-valued function which may be denoted by $\mathbf{M}^n(\mathbf{x}) = (m_1(\mathbf{x}), m_2(\mathbf{x}), \ldots, m_n(\mathbf{x}))$, where $\mathbf{x} \in \mathbf{E}^3$ represents a point in the domain of the object, n is the number of different materials to be combined in the RPLM process, and $\sum m_i(\mathbf{x}) = 1$, so that $m_i(\mathbf{x}) \geq 0,\ 1 \leq i \leq n$, expresses the relative concentration of material i at the point $\mathbf{x}$.

Jackson et al. [13] prescribe material composition in terms of distance from some geometric feature (for example, an axial line for a rotational object) or from the surface of the object. Currently, only piecewise constant and piecewise linear material property variations have been considered. A more recent paper by Kumar and Wood [24] describes a design approach based on the use of hexahedral elements.

The discretization methods described provide only stepwise or faceted approximations to the object boundary, which is often where the greatest accuracy is desired in both geometry and material representation. This is a significant disadvantage. A further possibility is to discretize a solid model into a set of disjoint triparametric volumes, which will in general have curved boundaries. However, there is no satisfactory known method for generating such decompositions from general CAD models.

3.5.3. Non-boundary conformant parameterization

Heterogeneous solid modelling (HSM) is the name given to a method developed by Kumar and Dutta [25] for the representation of multi-material objects. In a sense this is also a discretization method, though the way the object boundaries are treated is different. Essentially, the object model is decomposed into disjoint volumetric elements (specifically, *r*-sets as defined by Requicha [26]) and a parameterization is chosen for each element on the basis of its shape. The material distribution in each *r*-set is defined in terms of this parameterization; it is taken to be C^∞ continuous within the *r*-set, and to apply only in the interior of the set. Thus, the boundary of an *r*-set may coincide in part with the exact boundary of the CAD model, but this may not coincide with any isoparametric surface of the material distribution function defined in it, unless the boundary of the *r*-set has a particularly simple geometric configuration. Although the mathematical formulation is slightly different, the mode of representing material properties at an interior point is equivalent to that described earlier for mesh-based methods. The limiting case where each *r*-set is occupied by a single pure material can obviously be handled by a suitable choice of material distribution functions.

Patil et al. [27] give examples of the use of the HSM approach. The best choice of coordinate system depends on the basic shape of the underlying *r*-set. For example, regions that are approximately cuboidal or approximately cylindrical will have their material distributions represented in cartesian or cylindrical coordinates, respectively.

The HSM method provides material distributions that are continuous in each *r*-set, but not in general between the *r*-sets composing an object. Furthermore, except in simple cases it does not provide a direct way for defining material distributions in the interior of *r*-sets in terms of distributions on their boundaries.

The work of Kumar and Dutta [25] has been further extended by Shin and Dutta [28] where a constructive representation scheme for heterogeneous objects has been outlined. This scheme focuses on the construction of complicated heterogeneous objects, and it guarantees desired material continuity at the interfaces between *r*-sets through the use of geometry-independent and geometry-dependent material composition functions. Provision is made for easy update or modification of the constructive models.

3.5.4. The representation of material microstructure

Only a few remarks will be made on this topic, which represents a significant problem in its own right. Microstructure in most LM objects results from filament-wise accretion of material [29]. For the purpose of illustration, suppose that the material hardens after deposition over some finite period of time. The bonding of adjacent strands will then be affected by the degree of hardening that has occurred in the first strand by the time its neighbour is laid down. One governing factor is the speed of deposition, and another is the area fill strategy used, which will determine the time difference between the deposition of adjacent filaments at any given point of adjacency. Furthermore, the bonding of filaments in one layer to material in the layer below may also be affected by the hardening time and the time-periods involved, in a similar manner.

Bonding strengths between filaments will affect overall part strength. Additionally, there is likely to be material variation even within filaments as a result of the hardening process, which may occur from the inside out and therefore lead to inhomogeneity of properties at the scale of individual filament radii.

Clearly it will be a complex task to capture such small-scale variations within the entire manufactured object, and none of the techniques discussed earlier appear immediately useful for the purpose. Nevertheless, these variations are important in that they affect the structural properties of the artefact, and their capture is likely to be necessary for the future. For the moment it seems best to concentrate on the macroscopic variation of material and leave the microstructure for the longer term. One point that may be made is that an RPLM system has to generate scan paths (analogous to NC cutter paths in numerically controlled machining). It is these scan paths that give rise to the particular microstructure in a specific RPLM object, and they potentially provide the basis for the capture of that microstructure. The standard ISO 10303-42 (‘Geometric and topological representation’), discussed in Section 3.5.5, has the capabilities required for scan path representation, but further research is needed to find the most appropriate means of using them in modelling this small-scale aspect of material distribution.

3.5.5. Summary of the material representation situation

It would be premature at the moment to propose any means of standardizing the representation of material microstructure. Analysis methods making use of such information are likely to be developed in the future, and it is best to wait and see what form of representation is found to be best for that purpose.

The requirement for modelling material macrostructure is a more pressing one, because there is now significant research work in progress on this topic. However, even here no dominant method has yet emerged, and matters are complicated by the fact that the corresponding design methods for graded material objects currently use a variety of representations. As mentioned earlier, it may therefore be appropriate to allow for the use of any of the methods described that are compatible with the ISO 10303 resources. At present this rules out the method of Park et al. [14], though if that method is implemented commercially it may be possible to extend the STEP resources appropriately. All the other methods described earlier for representing material property distributions are compatible with ISO 10303 as it is at present.

4. Existing and proposed RPLM data transfer protocols

We now give a brief survey of some current and proposed formats for data transfer in RPLM. Ideally, any such format should be comprehensive in terms of information coverage, efficient in terms of data volume, and free from errors or ambiguity. So far, we have not attained that desirable situation, as will be shown. In particular, the transfer of material distribution information is not possible with any of the current formats. Data transfer is becoming increasingly critical for RPLM as accuracy requirements become more stringent [30].

4.1. The STL format

Although it was developed specifically for the stereolithography process, STL has become the de facto industrial standard for the transfer of data to RPLM process planning systems. It represents a 3D shape in terms of a triangulated approximation of its boundary.

The advantages and disadvantages of STL have been discussed exhaustively elsewhere, for example, see Refs. [31,32]. To summarize, STL files are conceptually simple and easy to generate, but they have disadvantages of file size and numerical accuracy, are subject to a variety of error situations and lead to inefficient slicing algorithms. However, despite its proprietary nature and its associated problems, STL is currently almost universally used as a neutral (system-independent) format for the transfer of RPLM shape models. Most STL file errors arise from the limitations of triangulation algorithms, and can now be corrected by automatic or semi-automatic means. The large file size does not pose severe difficulty in the present state of data storage technology. On the whole, it may be said that STL has served the RPLM industry well in its early years, and it is likely to continue in widespread use for some time to come.

Nevertheless, it is evident that STL cannot handle future requirements imposed by the recent developments in RPLM technology discussed earlier. These, with their need for more accurate models and the representation of material data, motivate the development of an alternative, more comprehensive, means of RPLM data transfer. Several suggestions have been made for this purpose [31], but none has so far met with enthusiasm from the RPLM community. The situation has recently been changed by the publication of the international standard ISO 10303 described later, which has strong potential for application in RPLM.

4.2. STEP—Standard for the exchange of product model data

STEP, or more formally ISO 10303 [1,2], is an international standard for the exchange of product life-cycle data, covering design, analysis, manufacture, maintenance and disposal. STEP has been built on experience gained with earlier computer graphics and product data transfer standards,[2] and its scope is continually expanding to cover new classes of products and new phases of the product life-cycle. At present STEP is most highly developed in the area of mechanical artefacts, but it is intended eventually to cover a wide range of manufactured products, from micro-electronics to cars and ships.

STEP has a three-level architecture, with conceptual, application and physical layers. The conceptual layer contains Integrated Resources (IRs), sets of related data entities that can be specialized to describe different domains of interest. For example, one IR (ISO 10303-42—‘Geometrical and topological representation’) contains entities for describing the geometry and topology of an object. In the application layer, subsets of the IR data entities are specialized for particular product classes and life-cycle stages. This results in a series of Application Protocols (APs) that prescribe the scope and representation of the data that can be exchanged for that purpose. The third (physical) layer of STEP architecture defines how the data elements are mapped into a physical file format (ISO 10303-21), or how it may be accessed in a data repository (ISO 10303-22).

Development of an ISO 10303 AP specific to RPLM has recently received official approval. The project is currently in the process of scoping the effort, identifying appropriate resources to use and determining what new resources will be needed. Some existing resources have immediate application in the new AP; for example, ISO 10303-42 defines geometrical and topological facilities that allow the capture of geometric models of several different types, as detailed later. One AP that already uses this resource is ISO 10303-203 (‘Configuration controlled design’), which specifies data for the exchange of mechanical engineering design data between different types of CAD systems, a common need in multi-tier supplier situations. The types of model representation supported by ISO 10303-42 include wireframes and surface models with or without topology, faceted Breps, advanced Brep solids (with curved surfaces) and 2D and 3D CSG shape representations. The faceted Brep capability includes that of STL, but uses a more efficient and less error-prone format. The wireframe facility could be used in RPLM, for the capture of slice contours and tool paths.

Several further STEP IRs are also relevant to RPLM. All of the ones listed below have been published as parts of the overall ISO 10303 standard except the last, which at the time of writing is being prepared for publication.

- ISO 10303-44 (‘Product structure’) specifies means for modelling assembly structures, which are relevant in RPLM since assemblies can be fabricated with all components in situ.
- ISO 10303-45 (‘Materials’) provides representations for material properties, covering requirements identified earlier.
- ISO 10303-47 (‘Shape variation tolerances’) covers another of the desired RPLM capabilities.
- ISO 10303-49 (‘Process structure and properties’) provides a basis for the transfer of process-related information in RPLM (if that proves possible or desirable).
- ISO 10303-50 (‘Mathematical constructs’) contains the means for transferring mathematical functions for the representation of such physical phenomena as electromagnetic or flow fields, or more specifically in the RPLM context, material distributions.

4.3. Slice formats for RPLM

The use of models with exact rather than faceted geometry allows increased accuracy. This implies that slicing may best be done in the CAD system where the design model originates, because that provides all the necessary capabilities for accurate geometric computation. In this case, a neutral format is needed for the transfer of the resulting slice data from the CAD system into the RPLM process planning system.

A slice format must enable the capture of all the geometrical data of the layer, including the layer thickness. Also, it must have provision to store material and process-related information, if necessary. The method chosen for the representation of 3D material distributions will need to be specialized for use in 2D slice representation. This can be done in an obvious manner for all the 3D methods surveyed earlier. Although there is currently no formal or industrial

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[2] Including the ANSI standard Initial Graphics Exchange Specification (IGES), which is accepted as input by some RPLM systems.

standard for slice data, a few proposals have been made in this area:

- Common Layer Interface (CLI) and Layer Exchange ASCII Format (LEAF)—these were developed by two European consortia as system-independent slice formats. Both define layers in terms of closed bounding contours and a thickness, and both also represent hatch patterns for the definition of support and filling structures. CLI defines only line-based geometric information. LEAF is more comprehensive; it includes keyword definitions and vendor or machine-specific details, together with such things as the radix of the number system used, units, and the ranges of values. LEAF describes layer contours in terms of 2D polylines and circular arcs.
- SLC formats—these encompass several different proprietary slice formats, all using polyline approximations to represent slice contours.
- SDR—this provides a representation of an assembly of objects as a stack of sets of polygonal contours. The objects can be reoriented in 3D and a new corresponding SDR representation generated [33].
- STEP—the STEP IRs provide all that is needed for defining contours and fill patterns, using polyline approximations or exact geometry. STEP also has relevant non-geometric capabilities, as mentioned earlier.

To summarize, there exists no widely used format for 2D slice data to supplement the almost universal use of STL for 3D models. However, STEP has the best potential for transmitting additional information beyond geometry because it already contains the necessary resources, though these need to be specialized for RPLM use.

Some researchers have suggested that a standardized 2D slice format be used to replace the usual 3D model transfer completely [34]. In such a departure from current methodology, the 3D model would exist only in the CAD system. Determination of build orientation, generation of support structures and calculation of slice data would take place there, using that model directly, rather than in the RPLM system as is usually the case at present. Thus only the 2D slice data would need to be transferred. CAD systems provide powerful and accurate geometric capabilities that are directly applicable for all of these purposes. The use of a CAD model with a precise geometry representation would enable the generation of slice data without the current loss of precision stemming from the use of a faceted model. This will lead to more accurate part fabrication with improved surface finish. It may also lessen the time taken for process planning, because similar accuracy using STL or some other faceting approach would demand a fine level of discretization, requiring very large files and increasing the chance of errors in triangulation and slicing. Other advantages of the pure 2D approach are that

- In most cases, correction of faulty geometry is easier in sliced data.
- A slice format may be better for use with parts defined by scanned or image input data, because it avoids the difficult task of creating a full 3D model.

Two disadvantages in replacing the 3D format by slice data are that

- Once the model is sliced, it is impossible to make general changes to the build orientation without losing accuracy. It is easy to modify the build configuration by translating or rotating the slices parallel to the x,y-plane. For other re-orientations slice regeneration is needed, and this cannot be done without incurring errors [33].
- Most current RPLM technologies fabricate parts in layers, but some deposit material in 3D, and they clearly demand some approach other than slicing.

5. Progress towards a STEP application protocol for RPLM

Two workshops were held at the US National Institute of Standards and Technology (NIST) to discuss standardization issues in RPLM. Participants were drawn from industry, academia and government. Two consensus recommendations emerged [35]:

- STL, the *de facto* data transfer standard for RPLM, should be improved to meet short-term RPLM requirements, and
- a new STEP AP for RPLM should be developed in the longer term.

Following up on the second recommendation, several meetings of an ad hoc interest group in RPLM were organized at meetings of ISO TC184/SC4. This interest group then submitted a proposal to the International Organization for Standardization (ISO) for the development of a new ISO 10303 AP for RPLM data transfer. This was accepted on the basis of an international mail ballot in November 2000, and several countries have agreed to commit human resources to the project. Meanwhile, some preliminary work has already been done at NIST, in collaboration with the University of Michigan, on the use of existing STEP resources in the new AP and on the modelling of material distributions.

6. Conclusions

RPLM processes involve multiple tasks, each with specific data requirements. Various file formats are in use or have been proposed for transferring data between those tasks. Most are restricted to the exchange of geometry data, though there is an increasing need for the transfer of additional types of information. STL, the current de facto standard, allows the transfer of approximate 3D shape information alone. This is inadequate for the future, because of the increasing importance of non-shape information and model accuracy in RPLM. In the authors' view, extending the STL specification will not give a good long-term solution. The ultimate survival of STL is called into question by

- The prospect that RPLM will become suitable for production use (apart from its current applications for moulds and dies) in the medium-term future. Such use will place a premium on the transfer of exact product geometry from the CAD system, together with information on tolerances, surface finish and materials.
- The possibility that some phases of RPLM planning will migrate into the CAD system, raising the need for an alternative standardized slice format.
- The prospect of using RPLM for the generation of parts with embedded electronic or other components, multi-material parts, or parts in which the material properties vary in a continuous manner. These parts will demand completely new capabilities in RPLM data transfer.

Regarding the last issue, the methods described earlier for the representation of material distributions are all, with minor exceptions, compatible with the capabilities provided by ISO 10303, both as regards geometric representation and the representation of the mathematical functions involved. In the mesh-based case it will also be necessary to use some of the standard's finite element capability, as specified in ISO 10303-104 ('Finite element analysis').

These considerations have led us to initiate the development of a STEP AP for the transfer of RPLM data. Existing STEP resources cover most necessary types of information, including shape representation, assembly structure, material specification, process parameters, tolerance information and mathematical functions. 3D shape data can be transferred using STEP's faceted Brep (a direct replacement for STL), or as an advanced Brep solid with topology information and general curved surfaces. Additionally, STEP resources can be used to represent slice contours in terms of lines or general curves; thus both 3D and slice data can be defined in the same standard. The major required capability lacking in STEP is that for modelling inhomogeneous and non-isotropic materials, but suggestions have already been made for one new resource suitable for this purpose [27].

The development of a new AP for ISO 10303, aimed at the transfer of RPLM data, will be a timely expansion of the coverage of the STEP standard into an important emerging area of manufacturing. Many of the STEP resources needed for this effort already exist as components of an international standard that is increasingly being adopted by industry. They have the advantage that they have been tested and refined in practical use, and can be imported wholesale into the new AP. Their existence should greatly assist the rapid development of the new AP.

The most immediate concern is that determining the scope of the first release of the new AP, and prioritizing the capabilities that should be added in the second and subsequent releases. Should its first release aim at shape representation alone? If so, should exact shape representations be included? Should a standard slice representation be provided? Should an assembly capability be available? A tolerance/surface finish capability? These and similar questions must be answered in the near future to enable work to get started on the generation of the definitive standard document. It is probable that consideration of the features and materials representation aspects of RPLM data transfer will be deferred until at least the second release of the AP. That would be reasonable, because it is here that the most work will be needed in the development of new STEP resources. The potential importance of new developments in these areas implies that relevant research and commercial implementations must be carefully tracked while the initial AP development is in progress. Additionally, the new standard must be designed to be extensible to accommodate these and other future requirements.

7. Disclaimer

Commercial product or company names in this paper are given for informational purposes only. Their use does not imply recommendation or endorsement by the National Institute of Standards and Technology.

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