A Taxonomy of Design Features for Additive Manufacture

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Abstract

The use of Additive Manufacture (AM) in New Product Development (NPD) supports creativity, reduces tooling costs and enhances the development process. Despite these advantages, there is still lack of available information to empower designers to take full advantage of AM. It is proposed that a taxonomy of AM-enabled design features will serve as a rich source of information for students and practitioners. These features refer to aspects of a product's form or other attributes that would be uneconomical or expensive to be produced with conventional methods and thus better suited to be made by AM. Despite the fact that similar knowledge-based tools are available, they are largely segregated. In light of this, the paper aims to define and categorise the arrangement and classification of key reasons for using AM based on four measures encompassing orthogonality, spanning, completeness and usability. Following several iterations, four taxons were derived, consisting of user requirement, functionality, parts consolidation and aesthetics. The next stage of this research aims to incorporate the taxonomy as a design support tool for AM.

Keywords – Additive Manufacturing, Taxonomy, Design Features, New Product Development

I. INTRODUCTION

In New Product Development (NPD), fabricating complex parts using conventional manufacturing techniques remain costly and difficult to produce. Additive Manufacture (AM) offers an alternative, and has been used in numerous applications such as for consumer, industrial, medical and aerospace industries. The use of AM has a significant impact where it enables greater freedom of manufacture, reduced tooling cost and faster product development time. Despite these advantages, there is still lack of available information to empower practitioners and students to take full advantage of AM. Despite the fact that knowledge-based tools are available, they are largely segregated. Therefore, the aim of this paper is to understand and classify the key reasons for using AM, so as to develop of a taxonomy of AM-enabled design features.

Features have been defined by researchers in very broad contexts according to their application. In design, it has been recognised that features are representations of shapes and aspects of a product [1]. Features also refer to form or other attributes such as design, performance and manufacture or assembly of a part [2]. Features that concern form can be grouped as regular shaped and freeform [3]. For this research, the term "AM-enabled design features" refer to aspects of a product's form or other attributes that would be uneconomical or expensive to be produced using conventional methods; and thus would be better suited to be made using AM. A thorough review of the literature identified a total of 106 AM-enabled design features. For clarity, these features will be further categorised as a taxonomy that is now discussed.

II. METHODOLOGY

The term taxonomy is defined as a study of arrangements and is considered as a way of ordering complex phenomena to enable comparison [4]. Taxonomies have been applied for mechanical design methods, tools and theories [5], for decision support systems [6], idea generation [7], collaborative design activity [8], design requirements from customers [9], design guidance for hypermedia design [10], and for grouping freeform shapes [3]. For this research, the aim is to generate a concise taxonomy to classify AM-enabled design features based on their use.

Figure 1 shows the first iteration of the taxonomy where the AM features have been classified into internal and external design features. As AM supports freedom of design, this taxonomy was developed to group the design features by external and internal geometries. The external features tended to relate to visual appearance whereas the internal features often related to function. The second level of the taxons shows some of the examples of features grouped under the external and the internal categories. An example of internal selective reinforce feature is shown in Figure 2. However, the classification did not offer sufficient differentiation between the types of features.

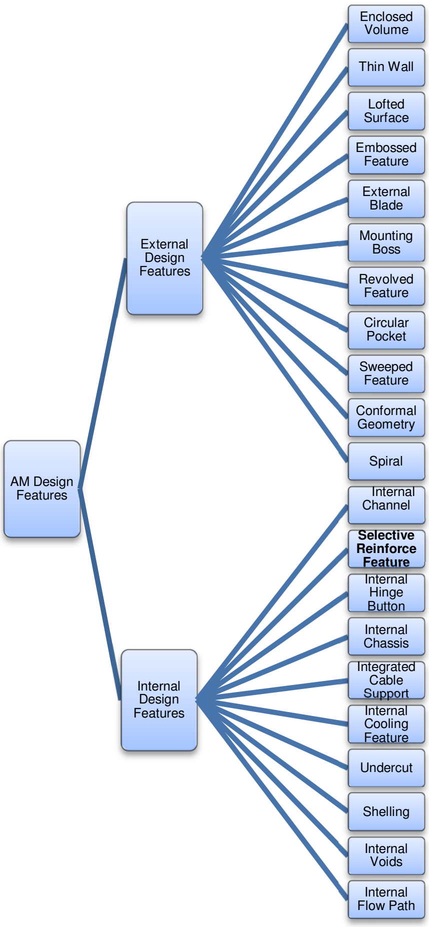

Figure 1: Taxonomy of Internal and External AM Design Features

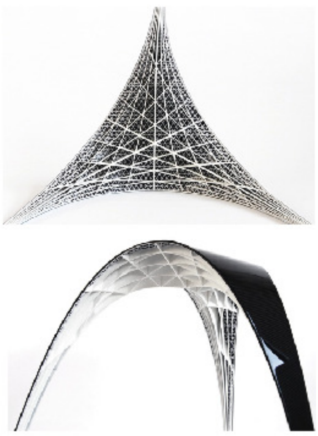

Figure 2: Selective reinforce feature.
(Image courtesy of Bram Geenen, YankoDesign.Com)

Another approach was adopted for greater distinction by grouping features according their application such as for medical, sport, consumer products, automotive, military, marine, aerospace, motorsport and fabrics (Refer Figure 3). They were further specified as customised features, consolidated features and complex geometrical features. However, this approach lead to elements that could potentially overlap and did not offer sufficient differentiation.

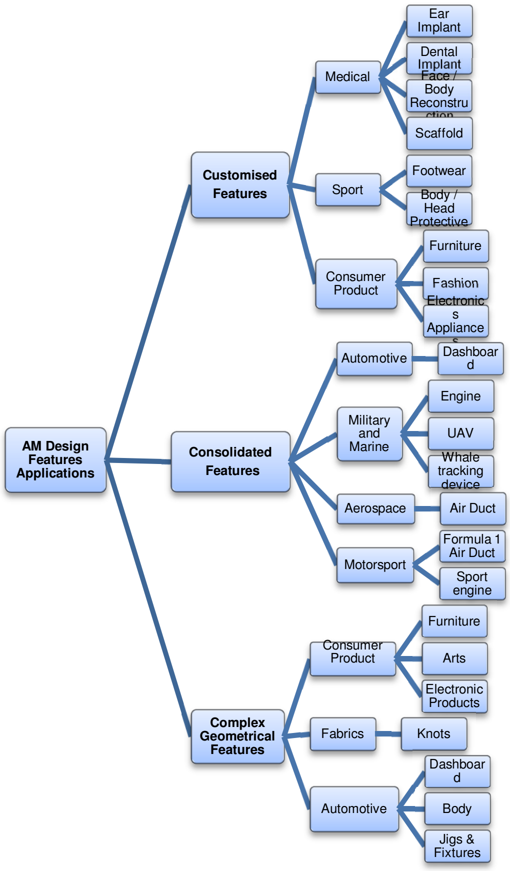

Figure 3: AM areas of application design features

To allow for greater disparity among the taxons, another round of iteration grouped the features according to functionality and complex geometry. As shown in Figure 4, the elements under functionality comprised of fastening or holding features, weight reduction features, embossed features, size variations features, personalised parts or product, consolidated parts, dual functionality product and dual material product. In turn, features under complex geometry were grouped as instant assembly, internal structuring, shape optimisation and profile features. Despite allowing for greater diversity of elements, it was also found that this version did not offer enough differentiation between each feature.

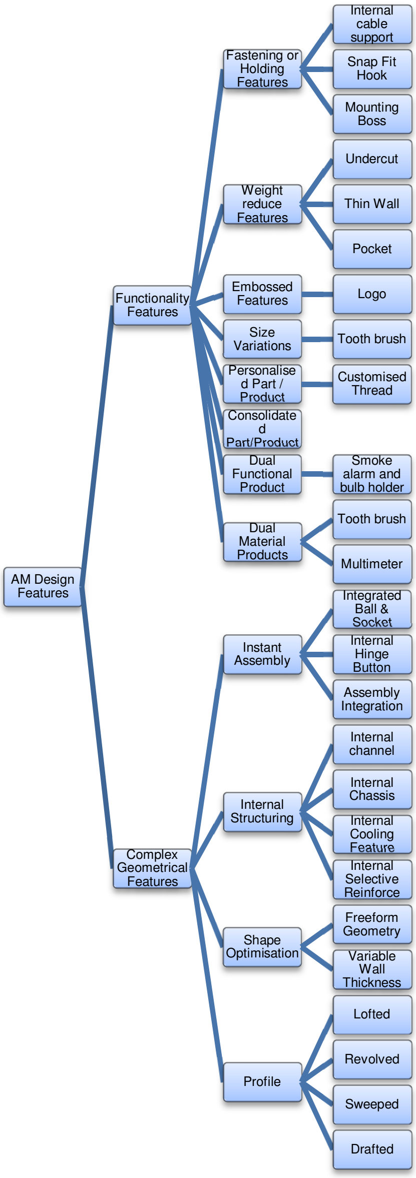

Figure 4: Taxonomy of AM functionality & complex geometrical features

The final iteration of the design feature taxonomy centered on the reasons for using AM, such as user fit, improved functionality, parts consolidation, and aesthetics or form requirement (Refer Figure 5). From the four groups, fifteen sub-categories were further generated that will be explained in the next section.

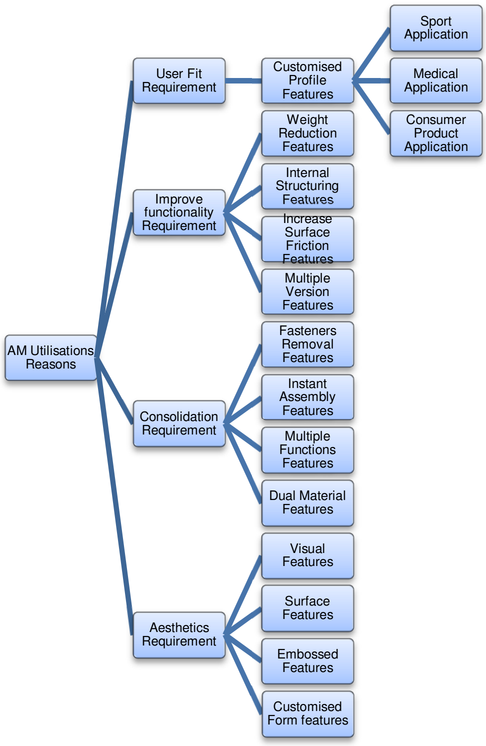

Figure 5: Taxonomy of AM reasons of utilisation

A. User Fit Requirement

User fit requirements can be defined as when parts or products have been customised to accommodate user requirements through the application of customised AM enabled features. From the perspective of AM, the user fit requirements were applied in three application areas namely sport, medical and consumer products.

The types of design features that were grouped under the three user-fit application areas, (namely sport, medical and consumer products) are shown in Table 1. In some cases there are features that appear to be applicable to more than one category. In this case, the author has to decide the appropriateness of the application group that the feature has to be included and verify this with the co-authors. Due to space limitation all the images of the design features could not be included in this paper.

AM Reasons of Utilisation	Application	Design Features
User Fit Requirement	Sport	Body Contour
		Air Ventilation
		Boot Studs
		Hand Grip Contour (1 examples)
	Medical	Ear Canal Contour
		Tooth Contour
		Convex Concave Skull Contour
		Jaw Contour
		Limb Contour
		Knee Contour
		Bone Contour
		Spinal Contour
		Leg Contour
	Consumer Product	Hand Grip Contour (2 examples)
		Wrist Contour (2 examples)
		Body Contour (3 examples)

Table 1: User Fit Requirement Design Features

B. *Improve Functionality Requirement*

As shown in Table 2, the improve functionality requirement were further expanded to include weight reduction feature, increase surface friction features and multiple version features. It list all the design features for each of these expanded categories of applications.

Product functionality improvement can be defined as methods that are used to improve part or product functionality using AM enabled features. The design features collected and grouped under this category are features that could be added into a product design to improve part or product functionality using AM. The product functionality improvement came from four approaches, i.e. weight reduction, increased surface friction, internal structure and multiple product versions.

AM Reasons of Utilisation	Application	Design Features
Improve functionality	Weight Reduction Features	Undercut
		Thin Wall
		Variable Wall Thickness
		Selective Internal Reinforcement
		Hollow Structure
		Honey-comb Structure
		External Ribbing
	Increase surface friction features	Textured Surface
		Circular Array
		Honey Comb Structure
	Internal Structuring Features	Internal Cable Route
		Internal Flow Path
		Internal Blade Geometry
		Internal Cooling
		Internal Shelving (avionic enclosure)
		Internal Shelving (fuel Injector)
		Internal Cable Support
		Encapsulated Spring
	Multiple Version Features	Customised Thread
		Size Variation

Table 2: Improve Functionality Design Features

C. *Consolidation Requirement*

As shown in Table 3, the consolidation requirement was further expanded to include fasteners removal features, instant assembly features, multiple functional parts and dual material. Consolidation requirements can be defined as the combination of parts, their functions or materials making use of AM. The design features collected and grouped under this category are features that could be added into a product design to combine various parts, to combine or have several functions or to combine its material from the perspective of AM. The consolidation can come from four approaches, i.e. instant assembly features, fasteners removal features, multiple functional parts and dual material features.

AM Reasons of Utilisation	Application	Design Features
Consolidation	Fasteners Removal Features	Locking Groove
		Hook Clip
		Snap Fit Clip
		Slide Opening & Closing
		Snap Fit Hook
		Mounting Boss
	Instant Assemblies Features	Multiple Link
		Living Hinge
		Foldable
		Torus
		Interconnected
		Encapsulated Spring Lock
		Encapsulated Track & Ball
		Slide Feature
		Circular Living Hinge
		Foldable Living Hinge
		Integrated Ball & Socket
		Internal Hinged Button
		Enclosed Volume
		Ready Assembled Gear
		Interwoven
		Encapsulated Bearing
		Ball & Socket
		Self Centring
		Interlock
	Multiple Functional Parts	Tape Dispenser
		Smoke Alarm & Bulb Holder
		Whistle & Buckle
	Dual Material	Over Moulding (Brush)
		Over Moulding (Razor)
		Over Moulding (Sat Nav)
		Over Moulding (Damper)

Table 3: Consolidation Design Features

D. Aesthetics and Form Requirement

As shown in Table 4, the aesthetics and form requirement were further expanded to include embossed feature, surface features, visual feature and customised form. It list all the design features for each of these expanded categories of applications.

AM Reasons of Utilisation	Application	Design Features
Aesthetics or Form Requirement	Embossed Features	Embossed Alphabets (Headphone)
		Embossed Alphabets (Car door Handle)
		Logo
	Surface Features	Double Mesh
		Weave
		Interlace
		Circular Array
		Fingerprint
		Alphabets Element
		Lattice
		Spike
		Perforated
		Replicated
		Overlapping
		Twelve-sided dodecahedron
		Alphabets Feature
	Visual Features	Transparency / Translucency
		Net Shadow Effect
		Circular Shadow Effect
	Customised Form Features	Curve Element
		Loop
		Organic Form
		Flames
		Growth patterns of trees
		Floating Element
		Human Body Sculpture
		Wave
		Spiral
		Swept
		Free form Geometry
		Bio mimic
		Interwoven Form
		Gyroid
		Tree Root

Table 4: Aesthetics or Form Requirement Design Features

The aesthetic and form requirements can be defined as methods that could be applied to improve product appearance. The design features collected and grouped under this category are features that could be added into a product design to improve product appearance from the perspective of AM. It includes approaches such as embossed features, surface features, visual features and customised form. More details about the types of features contained in the thirteen sub-categories that form the second level taxons are given in the following sections.

III. RESULTS

To ensure that the classification is clear and concise, the taxonomy was internally evaluated by the authors. The aim of the validation was to confirm that orthogonality, spanning, precision and usability were present within the taxonomy [9], [11]. The validation of the taxonomy by the author was made through the four criterions suggested by Gershenson:

- To check the orthogonality, questions such as 'is there any overlap between the taxons' was considered?'
- To check spanning and precision, questions such as 'what is lacking in the taxonomy?' and 'are the subcategories appropriate was considered?'
- To check the precision, question such as 'what categories require more information was considered?'
- Finally, to check the usability, questions such as, as, 'is this taxonomy of value in describing AM design features was considered?'

As for this research, the second level of the taxon i.e. the reasons for AM utilisation was based on the findings from earlier research by the author [12]. This indirectly validated the second level of the taxon. The third level of the taxon that contains the thirteen sub categories of application was developed based on the grouping of the 106 AM design features collected. Due to the level of knowledge and not much experience with regards to designing for AM, it was decided that the validation of the taxonomy with student designers would not be appropriate. Due to time constraints, level of expectation and interest of professional designers to a product specific CAD tool that could support their specific product design for AM, it was also found that the validation of the taxonomy with professional designers would also not be appropriate. Due to these justifications, the final taxonomy was validated firstly by the author and the co-authors' who has extensive knowledge and experience in AM and product design.

For orthogonality, each of the four taxons and its fifteen sub categories were clearly distinguished to ensure it was not repeated in other groups. In terms of spanning, relevant literature and websites that provide examples of AM enabled design features were surveyed. It was found that little work has been done to provide an inclusive and collective source of reference for AM enabled design features used by designers. And as AM systems improve, more categories could be added to form a more comprehensive taxonomy. In terms of precision, 106 AM enabled design features were collected from relevant literatures to generate the taxonomy. While it may be difficult to fully ascertain that the taxonomy is complete or exhaustive, it can be justified through successful categorisation of the data [13]. Finally, usability was checked by questioning whether the structure could be well understood and if its description was clear and concise. This was further achieved by ensuring a structured layout with the addition of visual examples.

In summary, four matrices encompassing orthogonality, spanning, precision and usability that has been described above were adopted, resulting in a taxonomy that is clear and concise.

IV. SUMMARY

This paper explores the development of the taxonomy by identifying and organising AM-enabled design features. The final taxonomy comprises four key reasons for using AM, namely user fit, improved functionality, parts consolidation, and aesthetics or form requirement. These groups form the top level of the taxonomy comprising of 106 features. User fit requirement was further sub categorised into applications for sport, medical and consumer products. Other sub categories were weight reduction, increase surface friction, internal structural, multiple version, instant assembly, fasteners removal, multiple functional parts, dual material, embossed features, surface features, visual features and customised form features. For validation, four matrices encompassing orthogonality, spanning, precision and usability were adopted, resulting in a taxonomy that is clear and concise. It was found that little work has been done to provide an inclusive and collective source of reference for AM enabled design features used by designers. And as AM systems improve, more categories could be added to form a more comprehensive taxonomy. The next stage of this research is to implement the information as a design support tool for AM.

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