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State Of The Art on Functional Fabrication

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Abstract

Digital fabrication technologies are becoming of importance to a number of knowledge areas and sectors, including medicine, entertainment, design, engineering, education, arts and architecture, due to their accessibility and versatility. These technologies are changing the design of digital models, materials and manufacturing processes which enable to build previously unachievable physical objects. Since many constraints imposed on the design of objects have changed significantly, a growing research community is working on graphical tools and techniques to enable the conception, automation, production and usage of innovative and complex designs for fabrication. In the present work, we survey the state of the art of computer graphics contributions to functional fabrication design tools and techniques. By functional fabrication we understand the design and manufacture of physical objects which functionalities exploit the capabilities of digital fabrication technologies. These functionalities include improving the mechanics of a workpiece, producing articulated models, capturing aerodynamics, planning deformable workpieces and controlling the object's appearance and acoustics. The resulting design tools are clearly taking advantage of relevant computer graphics techniques. Furthermore, they are extending these techniques to realise new physical forms as well as bringing innovation to feed into the design space.

Categories and Subject Descriptors (according to ACM CCS): I.3.5 [Computer Graphics]: Computational Geometry and Object Modeling—Modeling packages

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1. Introduction

Digital fabrication technologies are creating a revolution in making things by changing the way products are designed, fabricated and delivered to the user. These technologies include design and validation tools, as well as manufacturing technologies, such as Additive Manufacturing (AM), Computerized Numerical Control (CNC) and laser cutting machines to mention the most widespread technologies. The growth in the digital fabrication sector is evidenced by the increase in sales of equipment, technological advances, new applications, and the expiration of key patents in particular for the AM technologies. Hence, this sector is forecasted to continue to grow in the next years as advances in materials and machines are assimilated by the market.

Geometry Processing contributions to the manufacturing sector extend long before the popularisation of AM technologies. However, there has been a recent surge of interest in experimenting with the capabilities offered by newer digital fabrication technologies. Applications are currently constrained by the technical and physical limitations of the fabrication equipment, such as their ability to process only certain materials, quality of the surface finish, geometric constraints, working volume limitations, as well as production times and costs. For example, AM technologies allow for complex geometries to be produced, but the quality and tolerance of the workpieces produced by the more affordable machines can be low. CNC machining, on the other hand, allows for precise workpieces to be produced, but the level of complexity can be restricted by the tool accessibility's limitations.

While technical and physical manufacturing related challenges continue to be addressed, there is a growing need to approach the graphical challenges from a broader perspective. A relevant discussion that arises in relation to digital fabrication technologies, in particular when compared to traditional manufacturing, is that complex shapes do not necesarily require complex manufacturing process. Hence, a new generation of graphical tools aimed at designing complex shapes with specific functionalities is emerging. Current contributions from the computer graphics community concentrate mostly in developing these graphical tools and on making the fabrication process more efficient and accessible to unskilled users. Hence, recent research shows an intentional aim at lowering the barrier for non-domain experts to conceive, design and manufacture products by incorporating design and engineering knowledge into the design tools.

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This paper collects recent research results and tools that have impacted in the area of functionally aware design for digital fabrication purposes. By functional fabrication we understand the design and manufacture of physical objects which functionalities exploit the capabilities of digital fabrication technologies, such as AM technologies. These results and tools are important for the role they play in the democratization of design.

The structure of the paper is simple. We have clustered the literature contributions by their intended functional effect on the manufactured workpiece, including fabrication oriented functionality to produce articulated objects, aerodynamics, predefined deformable characteristics as well as controlled appearance and acoustics. We describe each category and review recent contributions in Sections 2-6. Thereafter, we present conclusions as well as highlighting future trends in this area.

2. Articulating workpieces

Articulated objects are interconnected workpieces that can move relatively to each other reconfiguring the overall shape of the object. In recent contributions, several proposed techniques take advantage of the information embedded in digitally animated 3D characters to define psychical articulations in a workpiece to be fabricated.

Character animation usually requires the definition of a skeletal base consisting of rigid bodies that are connected through joints. Based on this idea, there are several interactive design systems aimed at non-experts [TCG*14, CTN*13, CLM*13] which use as input an animation to create mechanical characters for fabrication using additive manufacturing or laser cutters. In the system presented in [TCG*14], the authors enable non-experts to create linkage-based characters that are capable of compelling movements by inputting a virtual character performing a periodic motion. In addition, the system proposed in [CTN*13] take an articulated character as input and allows the user to iteratively create an animation by sketching planar motion curves indicating how different parts of the character should move. In [CLM*13], the authors propose an algorithm that takes a motion sequence of a humanoid character and generates the design of a mechanical figure that approximates the input motion. This work fabricates the links, spur gears and four-bar linkages with a laser cutter and use pre-made bevel gears and pulley components requiring their assembly.

Another set of tools allow the interactive design of articulated bodies, including robots [MTN*15], planar structures [BCT15], twisty puzzles [SZ15] and mechanical toys [ZXS*12]. In [MTN*15], the authors propose an interactive tool that allows the user to design the structure, including motors and the skeletal structure, and motion of a robot. Before proceeding to fabrication, the system automatically generates 3D printable geometry for the robot's mechanical structure. [BCT15] proposes a tool for interactively editing the shape and motion of planar linkages. This work proposes a simulation algorithm which can handle kinematic loops to provide real time feedback to the user and ensure the correct functioning of the mechanism at all times.

[SZ15] propose a system that take as an input a 3D model and a rotation axis to produce the shapes which can be directly 3D printed and assembled into an interlocking puzzle. Moreover, [ZXS*12] present a design tool to synthesize mechanical toys for 3D printing. The system takes as an input the geometry and a time-varying rotation and translation of each rigid feature component. The system generates a mechanical assembly that produces the specified motion.

In addition, [CCA*12] address the particular challenge of designing articulated models that should be posable. For this, they focus on the design of the joints for them to exhibit internal friction to withstand gravity based on user-defined rotational constraints. This design tool takes advantage of the capabilities of additive manufacturing approaches to manufacture the joints in the same process than the rest of the piece in order to avoid assembly.

Another application of articulation is that of enabling foldable and space saving components. In this area, design systems have been conceived to take as input a 3D model and generate a foldable solution using a continuous folding sequences [LHAZ15, ZSMS14, ZWC*15]. In a related area, workpieces created by folding and cutting such as pop-up cards have also attracted recent research effort [LSH*10, LJGH11, HAW16]. In [LSH*10], the authors propose an algorithm that is grounded on geometric formulation of planar layout for paper architectures that can be popped-up in a rigid and stable manner.

A different point of view when working with articulations is enabling the creation of articulated complex shapes based on the functionality desired by the user. In [KLY*14], the authors present an interactive system for designers to specify high-level functional relationships between components (e.g. part A fits inside part B, parts C and D support part E) so that the system can automatically adjust part proportions and joint parameters to produce feasible workpieces.

3. Controlling the deformability of workpieces

Designing workpieces with desired elasticity behavior is a research topic that significantly advanced in the last years. The idea is to accurately tune local elasticity properties at a fine scale to design a workpiece that, when fabricated, produce a prescribed deformation when external forces are applied to it.

There are two main strategies to design workpieces with spatially varying elasticity:

- By combining portions of different materials within the workpiece's volume using a multi-material printer.
- By changing the workpiece's geometric structures at fine scale, creating microstructures that alternate voids with material.

The approach proposed by [BBO*10] combines stacked layers of different material to meets user's specified example deformation. In a first step, several base material are analysed under different deformation poses to derive a non-linear stress-strain relationship in a finite-element model. Then, an optimization process based on a non-linear finite element simulation retrieves the combination of stacked layers that best approximates the desired deformation behaviour. Similarly, the approach proposed by [STC*13] uses multi-material printing to fabricate articulated characters. Given a 3D model in a set of input poses, the system produces a set of actuators on the surface that allows the character to match these desired poses. These actuators are fabricated by locally varying the softness of the material close to the joints.

It is possible to change deformable properties of a fabricated workpiece by changing its geometry. An implementation of this strategy has been proposed by [STK*14, STBG12]. Given a target shape, the shape of a deflated balloon is deformed such that it matches the desired shape when it is inflated. This approach only allows for the optimization of a single target shape and it is not capable of optimizing for a global deformable behaviour. The approach presented by [PTC*15] allows for the design of deformable workpieces made out of interconnected rods. The target elasticity behaviour is obtained by varying the section's shape and the size of each individual rod. Rods are then interconnected to form an hexagonal dominant mesh where density and anisotropy of the elements can be variated to approximate efficiently the input surface and to match a specific defamation behaviour. Such system is capable of matching efficiently complex global target deformations including combinations of shearing, stretching and bending.

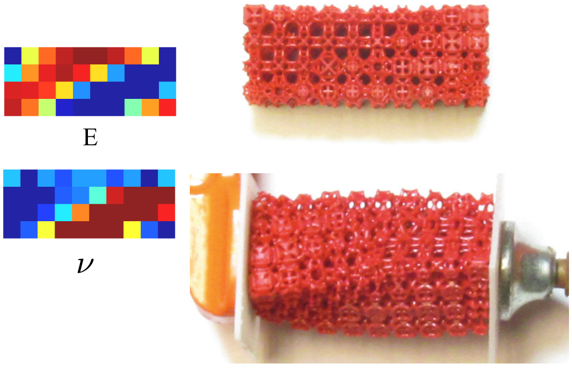

Figure 1: *Example of printed object with deformation behaviour.*

By varying small-scale structures one can adjust a variety of material properties, from elasticity to permeability. Importantly, these properties can be varied nearly continuously over the object, something that is not commonly done in traditional processes. Several approaches have been proposed in material engineering to generate microstructures that match a specific elastic behaviour [Sig95, RHX13]. The result is normally a single-scale structure, with the scale controlled by the resolution of the simulation grid or other types of regularization.

A more sophisticated and versatile approach has been recently proposed in [PZM*15] and [SBR*15]. The idea is to assemble workpieces by combining different small scale microstructures. Each microstructure is classified in a dictionary according to the elastic tensor it mimes. Different variations of microstructures are procedurally generated and analysed using finite element analysis, until the space of possible elastic tensors is properly covered.

Continuous and fine-scale variation of material properties within a volume was impossible to achieve with traditional manufacturing techniques. Hence, thanks to the continuous increase of accuracy and versatility of additive manufacturing technologies, this kind of technologies is very promising for the near future. Moreover, some of these technologies allow for the fabrication of auxetic objects, an elastic behaviour that is not common in nature.

4. Enhancing structural properties of workpieces

Experts are often concerned with designing the structural properties of a given workpiece. These properties could affect the workpieces' stiffness, lightness and cooling effect to mention some of the properties that could be enhanced by the shape design of the workpiece. Most non-domain experts lack the formal training in structural mechanics to support them in the design process. To address this gap in knowledge, several techniques and tools are being proposed to optimise the workpiece's shape for its mechanical properties. Such techniques modify a given shape to reinforce its physical realisation given the specific restrictions of the domain of application. We classified the proposed techniques in two broad classes regarding the scale of the fabricated workpiece, taking as reference the human scale, we grouped contributions into workpieces that aim to be sized smaller than human scale and bigger than human scale. The latter one is mainly represented by contributions in architecture.

4.1. Structurally functional cellular shapes

Additive manufacturing technologies allow a large number of pore network designs to be physically realised in a scale not previously possible. Porous materials, also referred to as cellular materials, are extensively studied in material science for their functional properties. Digitally fabricated workpieces can learn from these materials to design shapes that inherit such functionalities.

Material reduction in fabrication when using additive manufacturing is relevant for its efficiency and affordability. Yet, keeping the control over the strength-to-weight ratio of the fabricated workpiece is mandatory.

In [MDLW15], the authors propose to optimise the structural properties and appearance of a shape, the latter being controlled by a user-provided pattern example. In their formulation, appearance is defined by examples and optimised as an objective while structural properties serve as constraints. The technique outputs rigid shapes using a specified quantity of material while observing optional constraints such as voids, fills, attachment points, and external forces. The method proposed by [CBNJ*15] uses a single explicit representation to represent the structure and, at the same time, is able to handle topology changes. The stress-relief algorithm proposed in [SVB*12] automatically modifies a shape considering fragile areas of the model. The structural problems are detected and the shape is modified by combining three approaches: hollowing, thickening, and strut insertion. In [ZPZ13], the authors present a method that identifies structural problems in objects designed for fabrication based on shape and material properties, without specific assumptions on loads and manual load setup. The proposed technique consists of solving a constrained optimisation problem to determine the worst load distribution for a shape that will cause high local stress or large deformations.

In [LSZ*14], the authors introduce a hollowing optimisation algorithm based on the concept of honeycomb-cells structure. Honeycombs structures are known to be of minimal material cost while providing strength in tension. The authors formulate the problem as a strength-to-weight optimisation and cast it as mutually finding an optimal interior tessellation and its maximal hollowing subject to relieve the interior stress. Voronoi diagrams are used to compute irregular honeycomb-like volume tessellations which define the inner structure. In [WWY*13], an automatic solution to design a skin-framed structure is presented. The frame structure is designed by an optimisation scheme which significantly reduces material volume and is guaranteed to be physically stable, geometrically approximate, and printable.

In [MRA14], the authors propose a solution to the problem of, given a volume boundary, to automatically define a parametrized shape that is suitable for additive manufacturing given any volume cell subdivision. In [MMRC15] a similar reasoning is used to propose the adaptive voids algorithm, an automatic approach to generate a parameterised adaptive primal and/or dual cellular structure infill. The output of this approach can potentially be applied in various applications, including design and engineering, architecture, clothing and protective equipment, furniture and biomedical applications. In [WLC10] a solid modelling framework is proposed that takes advantage of the architecture of parallel computing on modern graphics hardware. Solid models in this framework are represented by an extension of the ray representation - Layered Depth-Normal Images (LDNI), which inherits the good properties of Boolean simplicity, localization and domain decoupling.

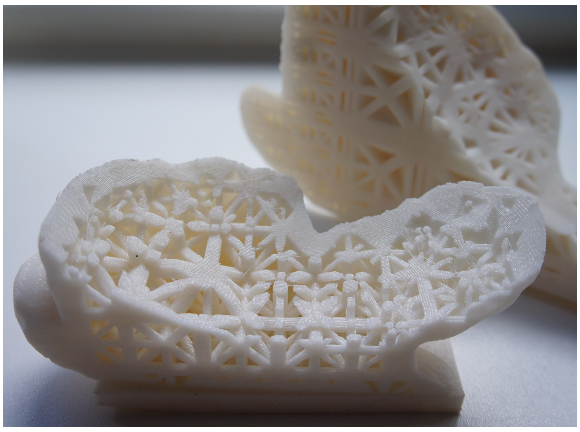

Figure 2: *The Stanford bunny printed in ABS using an open cellular structure infill.*

Porous materials are of great relevance to many fields including implants design and bio-materials. For instance, porous titanium implants are a common choice for bone augmentation. Moreover, implants for spinal fusion and repair of non-union fractures must encourage blood flow after implantation so that there is sufficient cell migration, nutrient and growth factor transport to stimulate bone in-growth. Hence, modelling porosity of bio-materials is critical for developing implants. There are many efforts in this area, including [SRSS05], where the authors explore a representation of model density and porosity based on stochastic geometry for the modelling of porous and heterogeneous materials. In [ZJY*13], the authors investigates how the design factors can be used to alter the implant architecture on multiple length scales to control and even tailor the blood flow.

4.2. Structurally functional architectural shapes

Efforts in recent years have focused on simplifying the design of complex architectural structures. Fabricating large scale architectural structures is a very challenging task and poses severe constraints both on the construction process and on the physical stability of the resulting structure. Computational geometry is helpful to solve some of these issues at the design stage by simplifying significantly the overall construction process. This class of algorithms, which are usually referred in the literature as *architectural geometry*, can be considered another example of functional fabrication technologies. In this case the geometry of the final structure is modified to optimise a performance or to conform to fabrication constraints.

Most of the design methods proposed in the literature are concerned with the optimization of grid-shells. Grid shells are a modern response to the ancient need to cover long span spaces. Their supporting structure is made up of beams which are connected at joints, while covering panels only acting as a load.

Most contributions in this field are concerned with the optimization of geometric properties of 3D meshes approximating a free-form surface. Many works address the planarity of faces, such as the construction of planar quad meshes [LPW*06, LXW*11, TSG*14a, YYPM11, ZSW10] or planar hexagonal meshes [LLW15]. Planar faces are highly desirable in architecture since bending glass panel may be an expensive operation. Other methods try to build meshes from a restricted number of tiles or moulds [EKS*10, FLHCO10, SS10]. This fundamental problem, in the architectural community referred to as rationalization, may significantly reduce the cost of the manufacturing process.

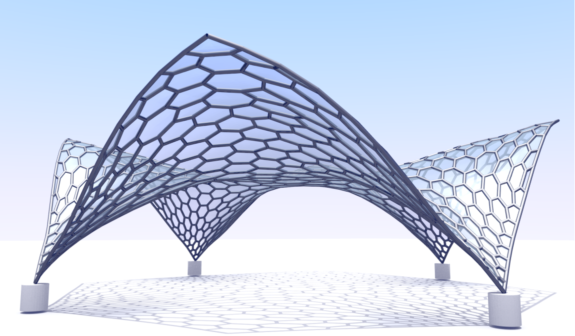

Figure 3: *A polygonal tessellation whose elements are sized and aligned according to the stress tensor field.*

A more recent trend of research aims at optimising static performance of the grid shell. In *compressive structures*, such as grid shells, the principal stress comes mainly from axial forces. A purely compressive grid-shell provides the optimal load distribution and can be obtained only through a form-finding process

[VHWP12, TSG*14b] or by modifying the connectivity of the grid shell keeping intact the shape of the structure [PTP*14, PTP*15].

In [DPW11], the authors deal with another important aspect, namely long-range parts and supporting structures. They restrict their work to the so-called hexagonal webs which correspond to a triangular or tri-hex decomposition of a surface. [DBD*15] present a computational framework for interactive shape exploration of discrete geometric structures in the context of freeform architectural design.

New design tools allow creating and interactively exploring self-supporting freeform designs. However, the physical construction of such freeform structures remains challenging, even on small scales. In [DPW*14], the authors propose to replace the commonly used dense formwork with a sparse set of temporary chains that guide the construction of such structures.

5. Achieving balance of workpieces

When considering physical rigid models and their dynamic properties resulting from mass distribution, the weight of each part must compensate each other, balancing the design in its intended, stable pose. Digital 3D models can stand in impossibly balanced configurations that could suggest a feeling of dynamism and movement or produce a pleasant aesthetic configuration. Materialization breaks the illusion, the laws of physics do apply and real models topple instead of standing.

In ”Make it stand“ [PWLSH13] the authors propose an approach to assist users in modifying existing 3D models for balancing static models at rest, to create novel, balanced designs by a combination of voxel carving and deformation to control the centre of mass. The proposed technique redistributes weight by jointly optimizing the interior and the surface shape of the workpiece. The interior volume is approximated with a voxel grid, each voxel being tagged as full or empty.

Global stability is typically required in furniture design. Furniture usually consists of assemblies of elongated and planar parts. Overall stability is usually achieved by connecting the parts together using glue, nails, hinges and screws. A number of recent techniques and tools aim to assist the user in the modelling phase to produce shapes that incorporate the knowledge to deliver physically feasible designs. In SketchChair [SLMI11], the user sketches a profile which is automatically extruded into a chair that can be fabricated from assembled laser-cut wood panels. In [UIM12] the authors propose an interface automatically suggesting to the user how to modify the current design so that it would meet specific fabrication requirements, such as stability and durability.

Interlocking mechanisms are an alternative approach to achieve global stability. In [FSY*15] the authors present a computational solution to support the design of a network of interlocking joints that form a globally-interlocking furniture assembly. For the reader interested in this specific area of application, this paper offers a good picture of the subject.

In ”Spin-it“ [BWBSH14], the authors present an algorithm to generate designs for spinning workpieces by optimizing rotational dynamics properties. As input, the user provides a solid 3D model and a desired axis of rotation. Then, the proposed technique modifies the mass distribution such that the principal directions of the moment of inertia align with the target rotation frame. The output is a model with voids inside its volume.

In a related area, the authors in [WW16] present a system for creating floating workpieces. The method presented optimizes for buoyant equilibrium and stability of complex 3D shapes, applying a voxel-carving technique to control the mass distribution.

6. Capturing aerodynamics on workpieces

The aerodynamics of a workpiece depends much on its shape. The knowledge on how to design a shape that behaves aerodynamically as intended is complex. Therefore, it requires highly skilled designers and engineers working together to design and manufacture efficient structures, such as aircrafts or windmill helices. Design tools under this category aim to incorporate this knowledge to enable designers to creatively explore the design space while restricting the shape to ensure its aerodynamic properties. Most of the work in this area has been done to design flying toys [UKSI14, MUB15].

In [UKSI14], the authors work on the inverse problem of optimizing a given input shape to enhance its aerodynamics guided by an observed behaviour learned from a vision system. The optimization is efficient enough to run in real time, providing guidance when using the interactive glider design tool. The technique can guide the user to deliver a hand-launched free-flight glider airplane. In [MUB15] the authors provide an intuitive user interface to interactively design three-dimensional kites. The system engine called “OmniAD” has the same overall concept of optimizing a given input shape to enhance its aerodynamics guided by an observed behaviour learned from a vision system, but its input parameters are omnidirectional, that is, allows the evaluation of aerodynamic forces, such as drag and lift, for any incoming wind direction.

7. Enhancing the appearance and acustics of workpieces

The appearance of a surface is affected by a vast numbers of physical attributes at a different scale, including the molecular properties affecting wavelengths, the micro-surface roughness affecting reflectance and the mesoscale effect of sub-surface scattering. The recent advances in the fabrication technologies allow for the first time to control, drive and predict the reflectance behaviour in a direct way. A recent survey [HIH*13] discusses all the specific aspects of the problem of creating physical workpieces with controllable appearance characteristics, including the relationship of this problem with display technologies. In this section we will shortly review the works oriented to provide specific appearance capabilities using fabrication technologies.

The first significant attempts of controlling appearance by means of digital fabrication are illustrated in [WPMR09] where the authors present a technique for the creation of specific highlight shape by means of explicitly defining and fabricating the micro-geometry surface. This approach was followed by [LDPT13] where by assigning different ink combinations to fabricated facets with different orientations, the authors are able to define bi-scale material that can reproduce a wide variety of reflectance including anisotropic ones. Similarly in [RBK*13], the authors adopt microsurfaces consisting of very small transparent plastic domes whose normal distribution approximates the desired one that are layered atop a (mostly) diffuse colour layer, yielding a complete reflectance model. Moreover, in [PRM14], the authors propose the use of multi-material 3D printing to fabricate objects with embedded optical fibers, exploiting total internal reflection to guide light inside an object.

Beyond surface reflectance, there is the problem of manufacturing physical workpieces with a desired inner translucent appearance. In [DLG13], the authors present a solution for fabricating a material volume with a desired surface BSSRDF by stacking layers from a fixed set of manufacturing materials whose thickness is varied spatially to reproduce the heterogeneity of the input BSSDRF. A similar approach was presented in [PRJ*13] where instead of using fixed materials, the authors exploited mixtures of different pigments suspended in a clear base material.

Figure 4: *By controlling the diffuse colour during the fabrication process the subsurface scattering effect that reduces the perception of small scale geometry can be counterbalanced.*

Related to the issue of controlling the appearance, we can also mention [CGPS08] where the authors face the problem related to the fact that 3D printed materials have a significant subsurface scattering behaviour that often reduces the perception of details and fine scale geometry. Hence, they propose to simulate and counter balance the impact of these effects by procedurally changing the diffuse base component of the object in order to better match the desired properties. [STTP14] propose an algorithm that solves for the shape of a transparent object such that the refracted light paints a desired caustic image on a receiver screen.

[BAU15] present a solution for accurate colour reproduction by an error diffusion halftoning approach to achieve full color with multi-jet printers.

Finally, current research effort is focusing on reproducing the acustic properties of fabricated objects. In [BLT*15], the authors optimize the shape of arbitrary 2D and 3D objects through deformation and perforation to produce sounds when struck which match user-supplied frequency and amplitude spectra.

8. Conclusions

In the present work we have reviewed the recent contributions on functional fabrication tools and techniques. The design tools reviewed have been developed achieve functionalities of a workpiece, including balance, articulation, aerodynamics and appearance.

We chose not to review the many contributions aiming to improve the specific technical properties of the digital fabrication process itself. Although we recognize the importance of these technical contributions we point out the ongoing advances on the manufacturing technologies. Effort is being done in getting the best of the technologies in hybrid approaches, that is, approaches that combine two or more manufacturing technologies [ZDNN13, LKK*14, NZDS15] as well as high-resolution, low-cost multi-material printing over larger printing volumes [SARW*15, VWRKM13]. These advances, while enabling complex shapes with truthful appearance, pose an enormous computational challenge. This challenge includes the amount of data and formats required both for describing and manufacturing the high-resolution workpieces. For instance, most existing software to support digital fabrication is designed to handle only a few million primitives with discrete material choices per object.

As observed during the review, the proposed tools and techniques aim to encode knowledge on structural, functional, mechanical properties and manufacturing processes to support the design of a workpiece. This knowledge is typically only available to experts. Hence, this trend is indicating a clear direction for the democratisation of digital fabrication technologies for non-experts and amateurs. This direction is supported by the increased access to fabrication technologies in the Maker Movement and the availability of FabLabs and other similar initiatives all over the word. Cloud computing and other technologies for securely storing and transferring huge data for fabrication will be increasingly required to support these communities.

Effort towards simplifying the creation of complex yet functional workpieces emerged from the field of topology optimisation. It consists of techniques for designing shapes that meet structural needs while optimising a prescribed functionality. A key ingredient in topology optimisation is shape representation which drives shape topology changes. Hence, future research in digital fabrication will continue to be closely linked to the research challenges in related fields including shape and solid modeling and geometry processing.

Another interesting aspect is that the reviewed research explores two, often contradictory, aims: i) the ability to explore freely the design space by not restricting the designer to prescribed shapes; and ii) restricting the shape to ensure a prescribed functionality after fabrication. These two goals sometimes do not easily fit together. Hence, tools often find a compromise between enable freedom of creation and enhancing the functionality of a given shape. The review shows that most research enhances the properties of a given shape or allows an interactive design process, thus restricting designers to freely explore the rich design space enabled by digital fabrication technologies. Achieving a good balance between design freedom and high-level functionality will continue to be a research challenge in the years to come. Moreover, much attention has been placed on learning from biological systems to imitate their capacity for evolution, simplicity; strength and self-assembly [Tib12].

Another design challenge includes encoding hidden information as part of the fabrication process. [WW13] presents a system to embed information inside digitally fabricated objects for imaging in the Terahertz region. Applications for these technologies include location encoding, pose estimation, object identification, data storage, and authentication. Addressing challenges in this area will enable to create workpieces which are, not only functional, but can enable other applications such as the Internet of Things.

In conclusion, this review has shown that the research area of functional fabrication looks strong and that the pioneer research communities working in this area have many challenges to tackle in the years to come.

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