Informes de la Construcción
Vol. 69, 546, e193
abril-junio 2017
ISSN-L: 0020-0883
doi: http://dx.doi.org/10.3989/ic.16.066

3D printing for construction: a procedural and material-based approach

Impresión 3D para la construcción: un enfoque basado en el procedimiento y los materiales

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ABSTRACT

3D printing for construction is stagnated at an early stage of development, especially regarding material optimization and procedural issues. These limitations are due to the specific knowledge that these technologies imply, the total cost of the machinery involved, and the lack of clear procedural guidelines. This paper presents a methodology that aims at overcoming these limitations through a workflow that allows for the ease of use of 6-axis robotic arms. A technique for the optimization of material usage is presented. A test case that shows the integration the design-to-fabrication process combining Integrated Robotic Systems (IRS) and Additive Layer Manufacturing (ALM) techniques is discussed. A structure-based approach to material optimization and smart infill patterning is introduced. A 0.4 × 0.4 × 1.5 m test part is shown as technological demonstrator.

Keywords: 3D printing; additive manufacturing; construction technology; design to production; integrated robotics; automation; material optimization.

RESUMEN

Las aplicaciones de impresión 3D para construcción se encuentran en una fase inicial de desarrollo, tanto en lo referente a materiales y piezas como a procedimientos. Dichas limitaciones se deben a la especificidad del sector, el coste de la maquinaria necesaria y una ausencia de un patrón procedimental característico. El artículo presenta una metodología innovadora para superar estas limitaciones mediante un flujo de trabajo sencillo que permita el uso generalista de brazos robóticos mediante software integrativo y un uso de materiales optimizado. Asimismo se expone la integración de diseño y fabricación combinando Sistemas de Integración Robótica y técnicas de Fabricación por Deposición. Finalmente se muestra un modelo de optimización de material y patrones de relleno inteligentes. Se expone una pieza real de 0,4 × 0,4 × 1,5 metros como demostrador tecnológico de gran escala.

Palabras clave: *impresión 3D; fabricación aditiva; tecnología de construcción; diseño de producción; robótica integrada; automatización; optimización de materiales.*

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Cómo citar este artículo/*Citation:* Nadal, A. , Pavón, J., Liébana, O. (2017). 3D printing for construction: a procedural and material-based approach. *Informes de la Construcción*, 69(546): e193, doi: http://dx.doi.org/10.3989/ic.16.066.

Recibido/*Received*: 03/05/2016
Aceptado/*Accepted*: 27/01/2017
Publicado on-line/*Published on-line*: 20/05/2017

1. INTRODUCTION

Current 3D printing processes (1) (2) focus mostly on rapid prototyping (RP). SLA (Stereolithography), SLS (Selective Laser Sintering) and FDM (Fused Deposition Modeling) techniques rely on a layer-by-layer approach to 3D printing, which presents a number of limitations that include: (i) the need for material continuity, (ii) the presence of support material in certain parts, and (iii) manual refinement needs.

Oversize approaches to 3D printing intend to scale up desktop-oriented machines. There are two main methods that focus on big-scale 3D printing: the scaffolding-based Z-printer, the bridge-crane approaches [e.g. WASP project and D-Shape printer (3)], or techniques similar to Contour Crafting (4) (5). The former requires huge amounts of material to work, and results in lots of material waste, an issue that 3D printing needs to tackle. Furthermore, these methods cannot be deployed on site, or it is unaffordable to do so. In addition to that, these techniques are rough, inaccurate and prone to geometrical imprecisions, which yield raw results that are far from acceptable to be considered as final.

Many examples make use of these technologies (6). The Radiolaria Project, for instance, consists of a scaled-up translation of SLA printers working with a nozzle that pours adhesive binder onto a layer of raw structural material. On the other hand, the WinSun Singapur Home or the 3D printed canal house by DUS Architects –see Figure 1– use the Contour Crafting methodology, where a nozzle pours concrete or a similar fused material directly in place, creating the final form or object physically (7) (8).

Although these are interesting experiments that push the limits of construction, they fail at various points: the most prominent problem of the Radiolaria Project is the amount of material that is required for the fabrication, alongside the size of the infrastructure, which makes it unsuitable for moving its production to delocalized factories. The Winsun 3D modules, on the other hand, need to provide more complex solutions that incorporate building systems, structural elements, and finish materials into the final products. Besides, it does not tackle the issue of transporting the modules onto the final site, a key aspect of modular and prefabricated construction.

Metal 3D printing is another technique related to construction that can be explored for creating full-size parts. Metal printing for small parts has already been developed through SLS techniques, although its adaptation to high-volume objects goes nowadays through the application of standard welding techniques. These open new opportunities to explore the fields of complex geometrical forms, intricate reinforcements, and temporary constructions. The MX3D project, for instance, aims at building a full-scale metal bridge in Amsterdam using 3D printing with relatively standard welding techniques. These differ slightly from the standard FDM or related printing methods in that it does not require horizontal curve-like inputs, but rather a series of points where material is fused.
As it can be seen, there are very divergent approaches, strategies, and procedures that directly relate to Computer Integrated Construction (9), and more particularly when oversized 3D printing technologies are involved. Thus, it is possible to identify exceptional opportunities to be explored regarding:

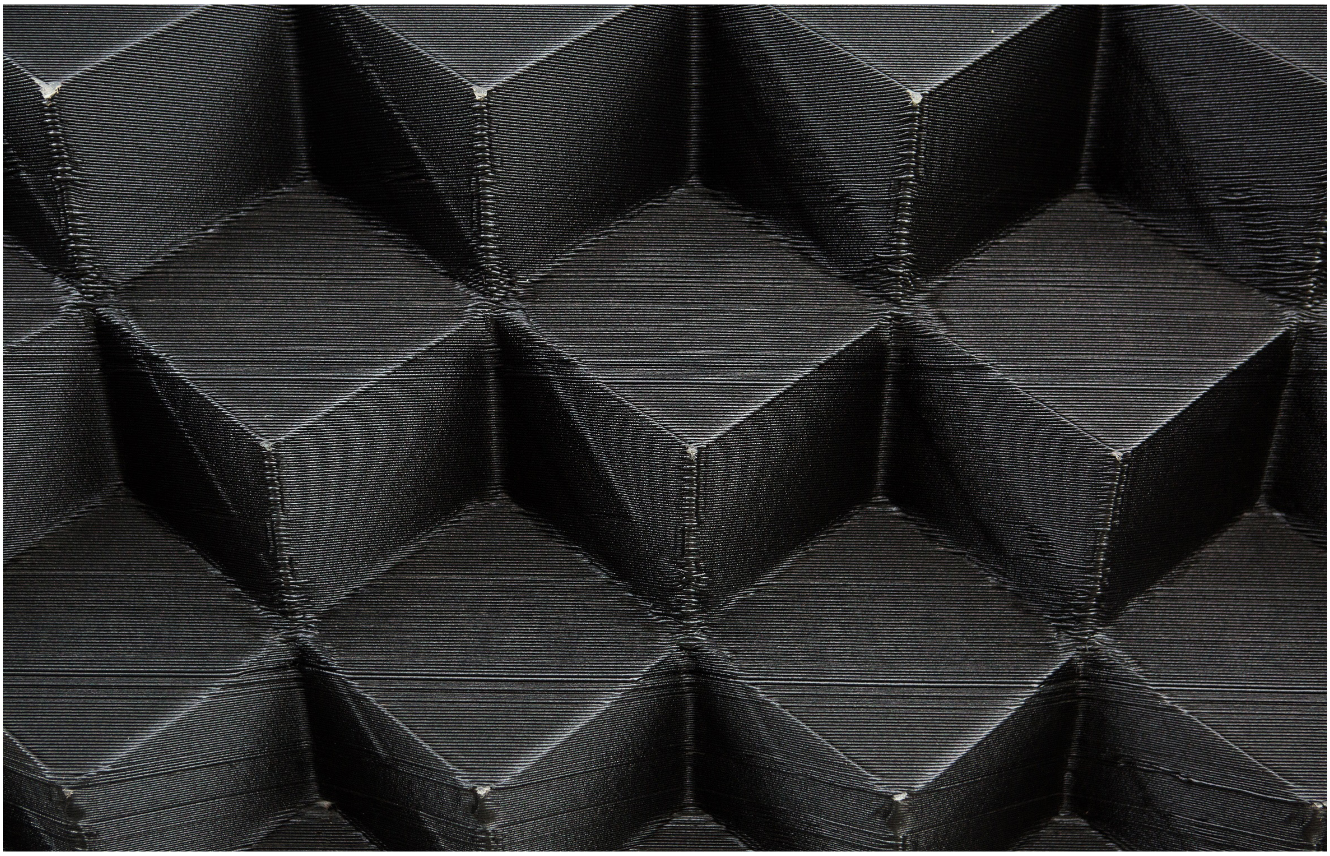

Figure 1. A module of 3D printed Canal House by DUS architects, an application of FDM to full-scale 3D printing (Picture: Martin de Bouter).

- **Standardized workflows and scalability.**
- Material **optimization,** and the use of **recycled** and environmental-friendly materials.
- Energy savings and use of **local and renewable energy** sources.
- Deployment of the **fabrication machinery on site.**
- Fabrication of **ad-hoc parts** with no extra-cost.

These issues are discussed in the following sections, where a comprehensive methodology for 3D printing applied to construction is presented.

2. STANDARDIZATION, PREFABRICATION, AND 3D PRINTING FOR CONSTRUCTION

Prefabrication is a reality deeply embedded in construction processes in developed countries, where labor force has become a highly specialized and expensive asset. The industry is nowadays capable of producing all sorts of building elements in a wide range of materials and forms: sandwich panels, precast structural parts, or even whole housing units to name just some. Casting, molding, extrusion, injection and other techniques are used to create construction and industrial parts for almost all imaginable uses.

Nevertheless, there are certain limits to what industry can offer for the construction sector. Using molds only makes sense when total part production is really high, lowering the price impact on each piece or when forms are not limited to certain geometric restrictions. Construction is different to other industries by nature, which makes it impossible to compare its serialization process to that of the automotive industry, for instance.

3D printing in the building industry, can thus be oriented towards bridging the gap between construction and customized serialization, a sort of intermediate space between industrial parts and traditional construction. Although much has been said about the benefits of 3D printing and market forecasts predict its exponential growth, it seems logical to precisely determine the range of affection of 3D printing for the construction field. Precisely where other fabrication methods cannot operate due to either geometric or size constraints, 3D printing finds its place. As a consequence, it can be applied to a number of products and methods, such as complex casting, prefabricated or monolithic structures, temporary constructions, non-structural parts, and other components that might require high degrees of customization. Besides, it can fill the need for the quick production of long series of variable parts, such as slightly differentiated façade panels present in singular buildings all over the world. The use of this adaptive panelization has been allowed itself by the implementation of easy-to-use parametric design software for architecture and construction.

This paper proposes a comprehensive approach to deal with these issues: on the one hand, it proposes an integrated design-to-production methodology to tackle big-scale part fabrication with 6-axis robotic arms for enhanced functionality and flexibility; on the other hand, it presents a material optimization tool to be integrated in the generation of 3d-printable models through customized fill patterns that respond to specific material behaviors and structural conditions.

Stress analysis is carried out through 3D models characterized as finite element representations. This method enables form-finding based on material properties, organization, and behavior. The integration of the whole design-to-fabrication process combining IRS and ALM techniques (10), as well as the integrated software platform (11) that enables this solution is shown in sections 4 and 5.

This approach provides (i) feasible, (ii) technologically viable, and (iii) economically affordable solutions to large-scale part production in the construction industry by introducing another level of intelligence into the four main aspects of 3D printing:

- **Workflow**: integrating design-to-production processes.
- **Materials**: reducing the use of materials and the associated carbon footprint attached to the fabrication through a single production process (see section 4).
- **Software**: a platform that translates design ideas into machine-readable content that makes it unnecessary for users to have high levels of expertise or otherwise understand complex machines (see section 4).
- **Hardware**: 6-axis robots are easily transportable and deployable on site for construction processes and succeed in being able to move freely in 3D space without the limitations inherent to other oversize 3D printing methods. Furthermore, robots can be **easily transported** and **deployed on site**, resulting in a significant reduction of transportation costs. Finally, robot programs fit different robot sizes and models with no or little restrictions, resulting in a particularly scalable technology (see section 3).

As Figure 2 shows, current design-to-fabrication workflows require a great involvement from the user. The design-to-production workflow presented in the paper aims to reduce user involvement in fabrication processes, automating highly skilled tasks. It intends to create a single cycle that automatically relates virtual models with the fabrication itself, solving any design refinement needs and automating non-critical tasks.

This is achieved by including all fabrication requirements into small software packages that work as “interpreters” and “translators”. 3D models are read and analyzed by the software, which solves small defects or informs the user of any modifications that need to take place. The packages integrate (i) existing **3D modeling platforms**, (ii) **machine interaction** and setup, and (iii) **fabrication** or physical interaction present in any CNC paradigm (12). It is not desired to create an universal design user interface, but to take advantage of widely accepted CAD-CAM software and use them as basis for completely integrated, native tools that deal with the most obscure and abstract aspects of human-machine interactions.

3. ROBOTIC ARMS AS LARGE-SCALE 3D PRINTING TOOLS

Small-part 3D printing mostly relies on stereolitography (STL) file format standards[1]. The STL file describes a mesh that

[1] The STL is a file format developed by 3D Systems that lightly describes closed solid geometry. It is considered a standard used by almost all 3D CAD applications.

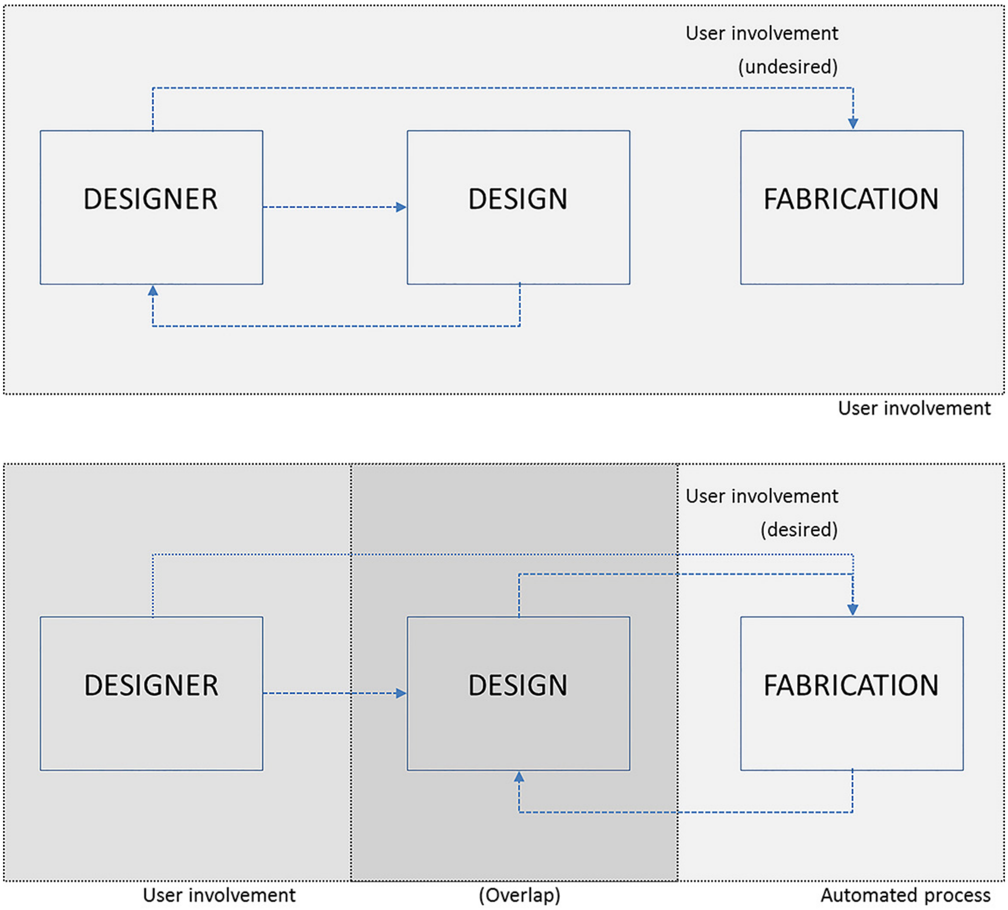

Figure 2. Current and proposed designer-design-fabrication interactions.

stores the object's geometry information. This file is sliced with a special program (Slicer), which calculates a series of contours where the binding (SLS) or fused materials (FDM) are placed. The printer software translates those contours into GCode or similar, which in turn result in layers of material.

This format has proven useful for 3 axis FDM printers, but robotic arms have a-completely different approach to movement control. The latter depend on vendor-specific hardware. All main robot suppliers in the world (13) provide integrated software and hardware solutions to design and fabricate parts for the automotive and aerospatial industries. However, each vendor provides unique, black-boxed packages that are incompatible with one another. As a consequence, there are many emerging opportunities to be explored, especially in the AECO sector (14).

Robots can be thus thought as simple 3D space "tool locators" defined as a series of joints and axes (15), which would replace the hand of a human worker. As opposed to other fabrication methods, 6-axis robots have **no inherent geometrical limitations aside their own size** –which can be scaled up by introducing tracks or external axes**.** The Space Frame project proves that it is possible to print with no support material (16), showing that robots outdo the layer-by-layer logic when they are utilized as a resource for 3D printing purposes. Thus, these machines can create spatial structures that supersede those created using other, more generic, techniques. Employing appropriate materials (PLA or ABS derived materials (17), cement-like materials, or composites) favors real-scale object production, whether for the automotive, aerospace, AECO industries, and others[2].

4. AN INTEGRATIVE DESIGN-TO-FABRICATION FRAMEWORK FOR CONSTRUCTION

4.1. Current trends in architectural modeling and fabrication

Contemporary building design methodologies implement Building Information Modeling (BIM) as building database integration platforms. BIM seeks to unite all building-related information into single, comprehensive models that allow for an interaction of the different agents involved in the construction process, and a coordination of the different disciplines that intervene therein. Nevertheless, these methodologies focus mainly on building control issues, largely ignoring the possibilities of current fabrication and construction trends.

Despite significant progress made in CAD/CAM software, the existing design-to-fabrication workflow can be still dif-

[2] According to technavio, "[...] the field of robotics technology demands continuous exploration and innovation, there are a lot of untapped opportunities [...]. This prompts many robot OEMs and new start-ups to innovate and invest in this technology. The major vendors such as ABB, iRobot, and KUKA are investing heavily in R&D to remain ahead in the market.

ficult to traverse for architects, designers, and builders. Design conception continues emerging from 2D sketches which are ultimately converted into 3D CAD models. This can be achieved through traditional 3D CAD modeling, or by capturing an existing physical part with a scanning device. Either case, designers and fabricators need to use specific proprietary software packages that require qualification which is sometimes overkill for 3D printing applications, as they present unnecessary complex features. Furthermore, these skills are normally beyond the scope of the training of architects, engineers, and designers. As a consequence, the process suffers from a detachment between designer and final building parts.

The current tendency to use parametric software in architecture and design has led to various attempts to deal with this undesired situation. HAL (18), Firefly, Robots.IO (19), and others intend to bridge the gap between design and production through Grasshopper[3]. Nevertheless, this adds another level of complexity to the equation, since it replaces the previously mentioned CAM software with an even more complex visual programming interface for Rhinoceros.

4.2. An integrative software-based framework

This process makes it possible to benefit from the advantages of real-time model checking in order to reduce project time and costs significantly while increasing productivity and quality. A completely integrative software and hardware interaction is proposed by translating different geometry types into robot instructions.

The software consists hence of two cores, (i) a geometry-calculation and a (ii) translation engine. The former calculates the robot tool path in the host CAD program, while the latter translates this result into machine-readable code for each robot model via an Inverse Kinematics (IK) engine (20) (21). In addition to that, the software performs basic checks for the user to visualize during the conceptual phase whether a design can be fabricated. Finally, the software creates the necessary files and protocols required to move the robot.

This approach constitutes a milestone for the standardization of robotics-oriented fabrication (22) and the evolution of the processes thereby implied.

Alongside those methodological advantages, the approach implements:

- Real-time design checking, minimizing or even eliminating flaws prior to execution and fabrication. It implements advanced error prevention, collisions, singularities, and range detections.
- Cost prediction and material usage, including:
  - Time needs
  - Manufacturing costs
  - Material needs and presets
- Easy interaction and maximized information, a key standardization aspect.

As Figure 3 shows, user involvement decreases gradually from design to production. Designers focus on creating comprehensive designs that match their expectations without worrying about fabrication. The hereby presented software provides a solution to ease the modularity and expandability of the whole integrated simulation process (23).

4.3. Form-finding: material optimization through structural patterning systems

Oversized 3D printing has a great potential concerning material cost saving, as those account approximately for a 60%-70% of total construction costs. A novel method for material usage optimization through a structure-oriented infill pattern system that implements the physical properties of materials is presented.

The software provides options for easy, ready-to-use **presets for diverse materials** that can be modified, classified, and extended by the user. These presets incorporate the following behaviors:

- hardening times,
- maximum robot speeds, and TCP rotations,
- structural printing settings.

In addition to comprehensive material conditions, it is important to point out the logic of infill patterns used in 3D printed parts. As opposed to standard, non-structural, space-packing infill patterns employed by vendors and freeware alike, the system presented in this paper offers a compelling **material optimization approach**. Material usage minimization is not only an industrial demand and a feasibility must, but also one of the greatest contributions of 3D printing technology. Furthermore, minimizing material reduces the building energy footprint at all levels.

This strategy supports the structural analysis of parts, yielding stress-responsive patterns (24). The algorithm works in a multiphase manner, including (i) input parsing, (ii) translation of 3D models into spring-like models, (iii) exporting to the Processing stand-alone calculation software (25), (iv) material characterization, and (v) the use of the physical logic to determine actual material thickness. The technological demonstrator has been built in PLA due to financial restrictions. ABS and PLA with carbon fiber have been tested.

For construction purposes, concrete is quickly gaining adepts (26) in the field of large scale 3D printing (27) and has also been considered for simulations of big-scale parts. Parts have been tested against self-bearing conditions mainly, although a variety of different forces may be implemented. The algorithm is being developed to comply with the restrictive regulations that apply to structural concrete in the region of Spain, including all in the EHE-08 (28). It is planned to use concrete for further test parts.

As a result of the above, the boundaries between otherwise separated building parts are blurred. In traditional construction, building elements are differentiated not only ac-

[3] Grasshopper TM is a parametric tool for Rhinoceros developed by David Rutten at McNeel & Associates that implements a visual programming interface where functions are black-boxed into a series of components. These components are associated to one another in order to create algorithms.

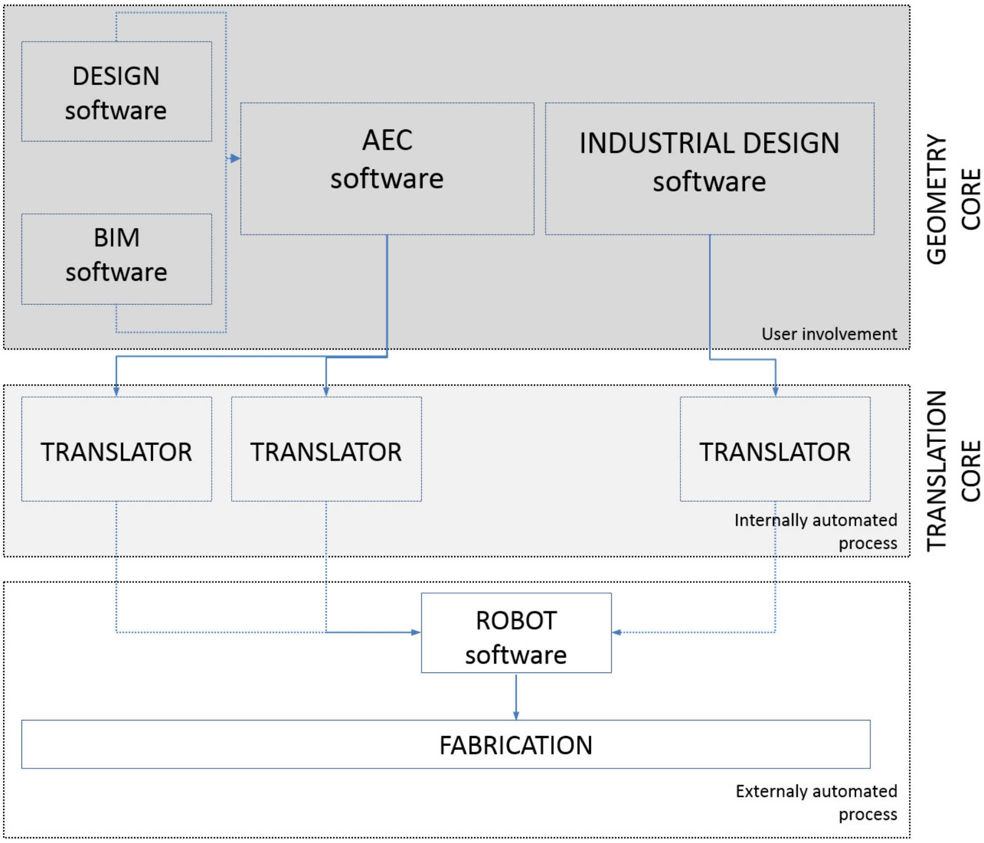

Figure 3. Proposed workflow: automation of non-critical, fabrication-related tasks.

cording to structural or architectural organizations, but to actual construction phasing. 3D printing optimized structural patterns could put an end to these differentiation and account for the synergetic relationship between performance and material integrity, one that can ultimately blend the physical experiments that classify form according to load applications and the digital realm where these may be simulated and studied prior to the designer's decision making. Pursuing further this strand of logic, the notion of form-finding attributed to Frei Otto (29) would acquire a more comprehensive meaning.

5. SOFTWARE DEMONSTRATOR

The demonstrator brings all above mentioned features into a single package that accounts for the whole design-to-production process. The software is a plugin for the CAD Rhinoceros software, and includes the following capabilities:

- User-friendly integration in the host User Interface (UI).
- **Definition of build parameters, material constraints** and wall description through:
  - Wall thickness,
  - Extrusion thickness –related to the nozzle diameter and layer height.
  - Reinforcement density, which defines the infill.
- **Robot selector**: from within a limited yet expandable library that consists of a series of pre-defined models from the main vendors.
- **Simulation preview** controls for (i) coarse and (ii) fine visualization allowing the user to understand the simulation of the building process. In the present development, geometry is programmed as mesh/polyline conduits to provide more responsive previews. Results are shown in Figure 4.
- Geometry **output** as both polylines and/or meshes for use by the designer as native Rhino objects.
- Export **robot code** depending on the robot vendor.

6. RESULTS

The proposed methodology has been tested through a series of large-scale pieces printed using the integrative software platform developed ad-hoc for Rhinoceros. The prints evidence that the methodology works as desired for FDM-similar techniques, and that it can be extended to real construction projects.

The platform has been tested on different machines and run under several operating systems. Diverse designs have been produced according to the above described process and tested using two different ABB robots. The same printed head, electronics, and setup were adopted for tests running on both machines. The experiment shows that the employment of different controllers had no impact on the workflow methodology and yielded exact results. Although printing times vary slightly due to different robot controller's hardware specifications, the operational experiments prove that the technology is easily scalable and works on different robot models with little or no need for specific configurations. PLA parts were printed, although concrete-like materials can be easily adapted.

Big-scale plastic parts displayed base fixation problems. High speeds do not allow for a proper base formation, suffering from instability and vibrations when reaching heights above

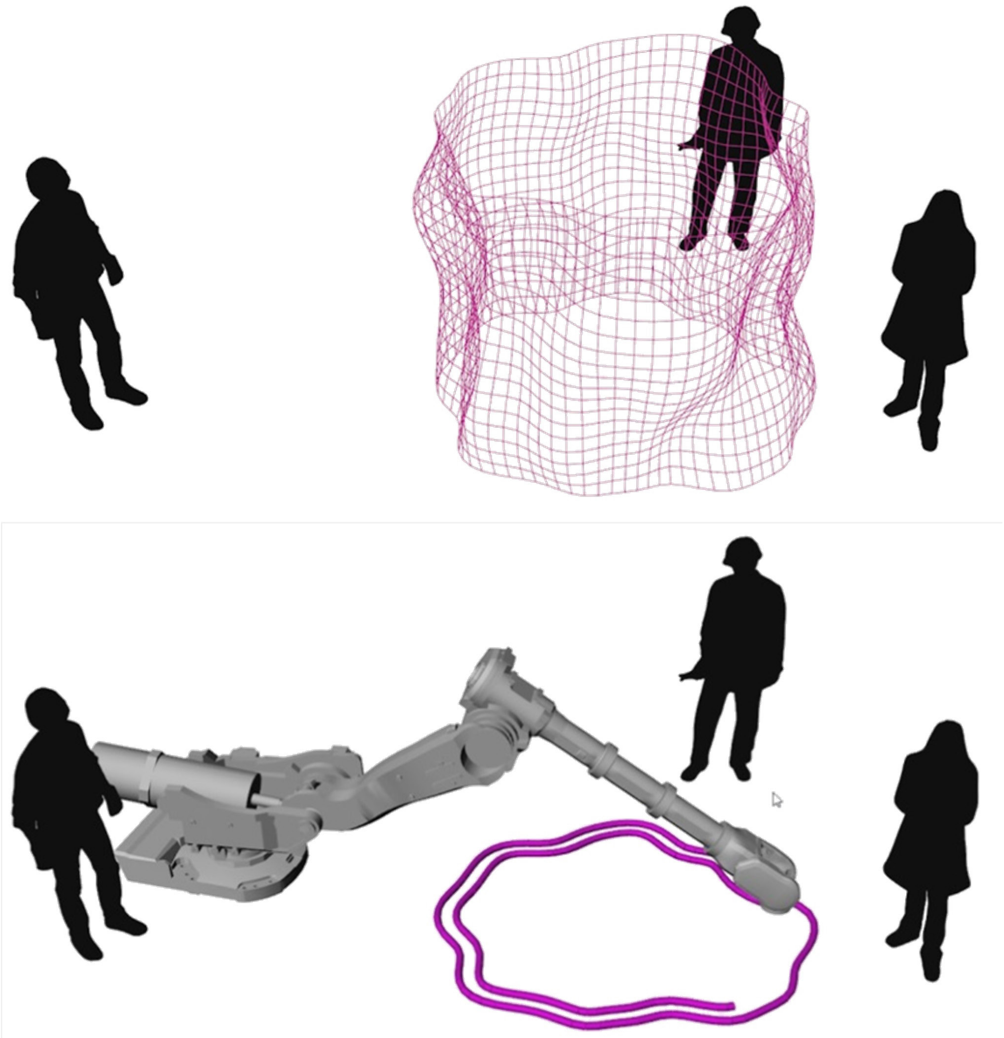

Figure 4. Current state of the technological demonstrator showing simulation in host interface with an ABB IRB 4600.

Table 1. Part configuration.

	Nr Layers	Total Length (mm)	Base Length	Movement Instructions	Base Movement Instructions
Part 1	2001	1401880	73707	53139	2906
Part 2	4001	2732171	80208	47996	1124
Part 3	10001	7438970	317	40004	412

Table 2. Part print results and printer/robot configurations.

	Standard FDM printer					
	Speed Base (mm/s)	**Speed Part (mm/s)**	**Part Modules**	**Time per part module (s)**	**Printing time (s)**	**Printing time (h)**
Part 1	35	45	N/A	N/A	34581	9,6
Part 2	N/A	N/A				
Part 3	N/A	N/A				
	IRB 120					
	Speed Base (mm/s)	**Speed Part (mm/s)**	**Part Modules**	**Time per part module (s)**	**Printing time (s)**	**Printing time (h)**
Part 1	100	100	18	0,2	14042	3,9
Part 2	100	100	16	0,2	27364	7,6
Part 3	N/A	N/A	14			
	IRB 1600					
	Speed Base (mm/s)	**Speed Part (mm/s)**	**Part Modules**	**Time per part module (s)**	**Printing time (s)**	**Printing time (h)**
Part 1	50	100	18	0,1	14757	4,1
Part 2	50	100	16	0,1	28125	7,8
Part 3	50	150	14	0,1	49598	13,8

40 cm. To solve this problem, the prints were set up with variable printing speeds. The preferred speed for the first 100 layers –although this number may vary depending on the layer height– was 50 mm/s, while 150 mm/s or was optimal for complex geometries above that. 200 mm/s or higher can be used for bigger prints or other effects. Tables 1 and 2 show 3 parts for comparison.

Further experiments yield printing times up to 5 times faster using robots than standard FDM techniques. Figures 5, 6 and 7 show two printed parts and a close-up detail of a complex geometrical instance. Please note the finish quality of the piece, similar or better than that of the commercial printers, and able to reach a layer density up to 0.1 mm or less. The part occupies a total volume of 0.4 × 0.4 × 1.5 meters

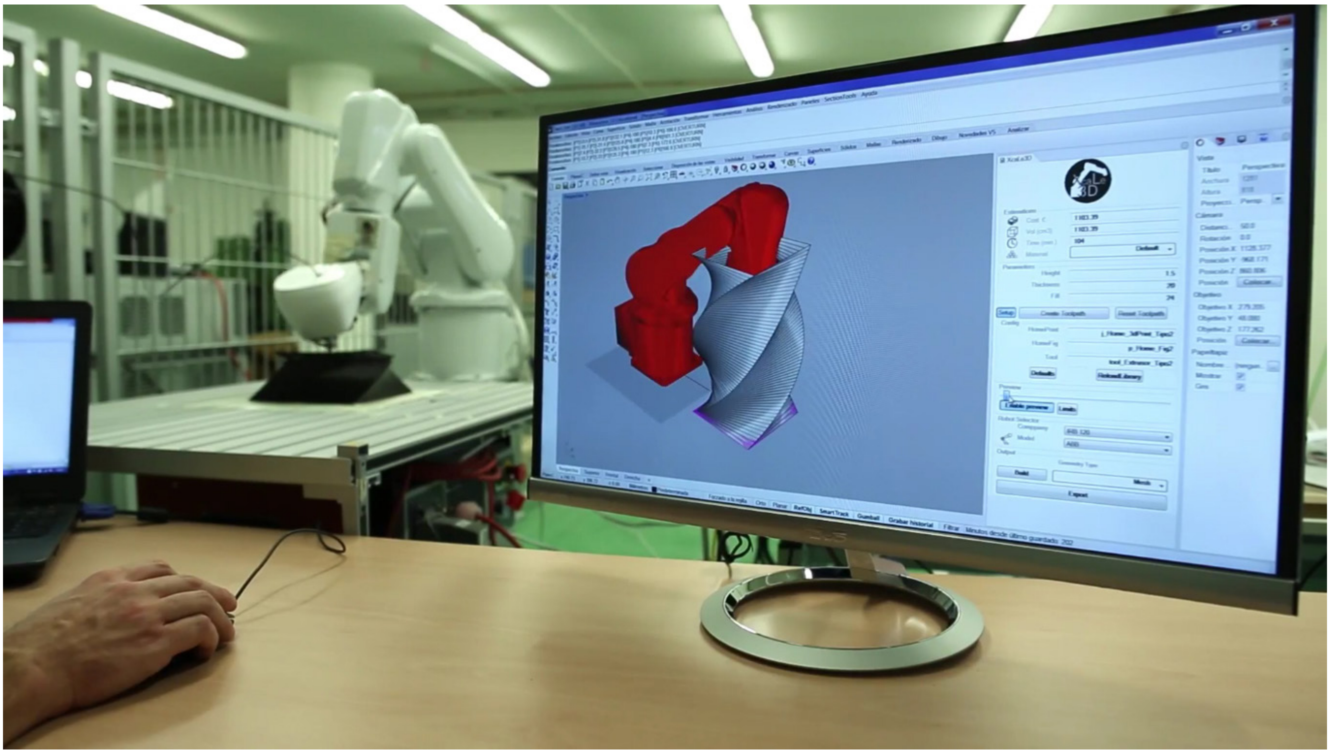

Figure 5. Plugin software operating an IRB120 robot.

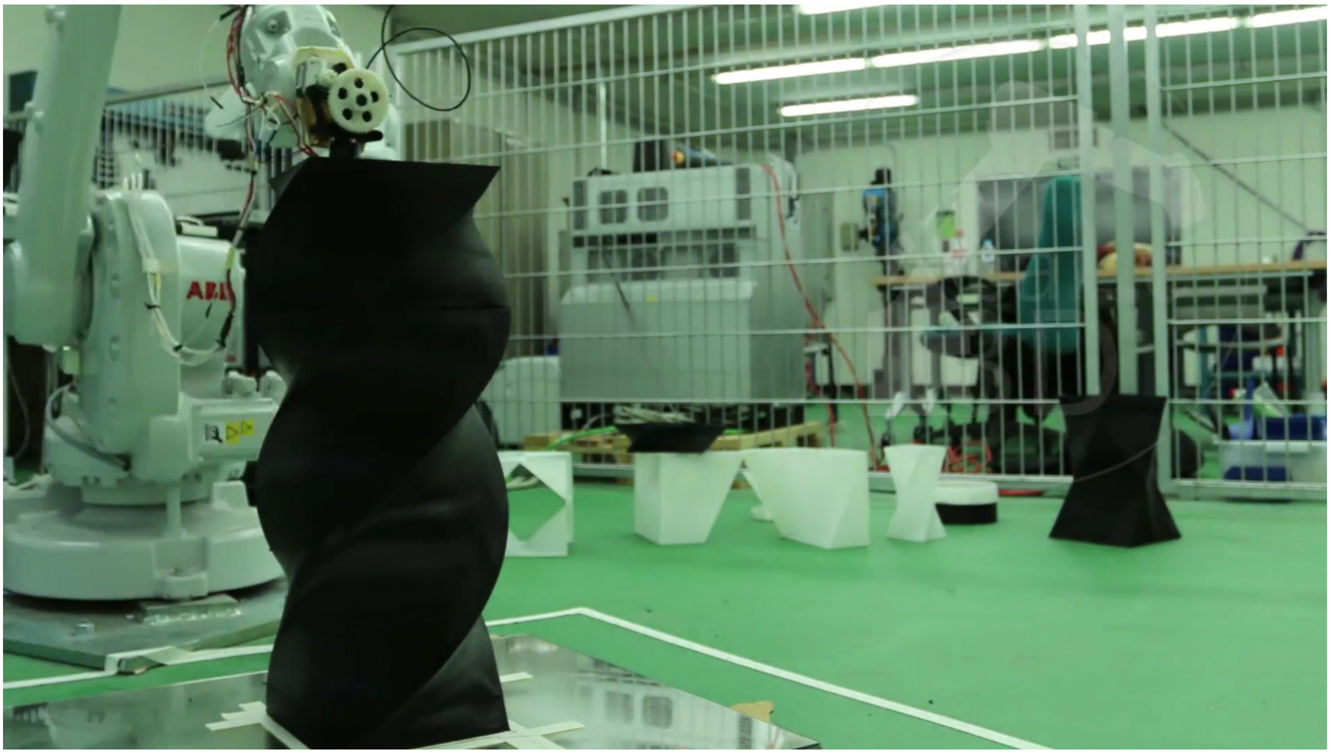

Figure 6. Printing the part with an ABB IRB 1600 robot.

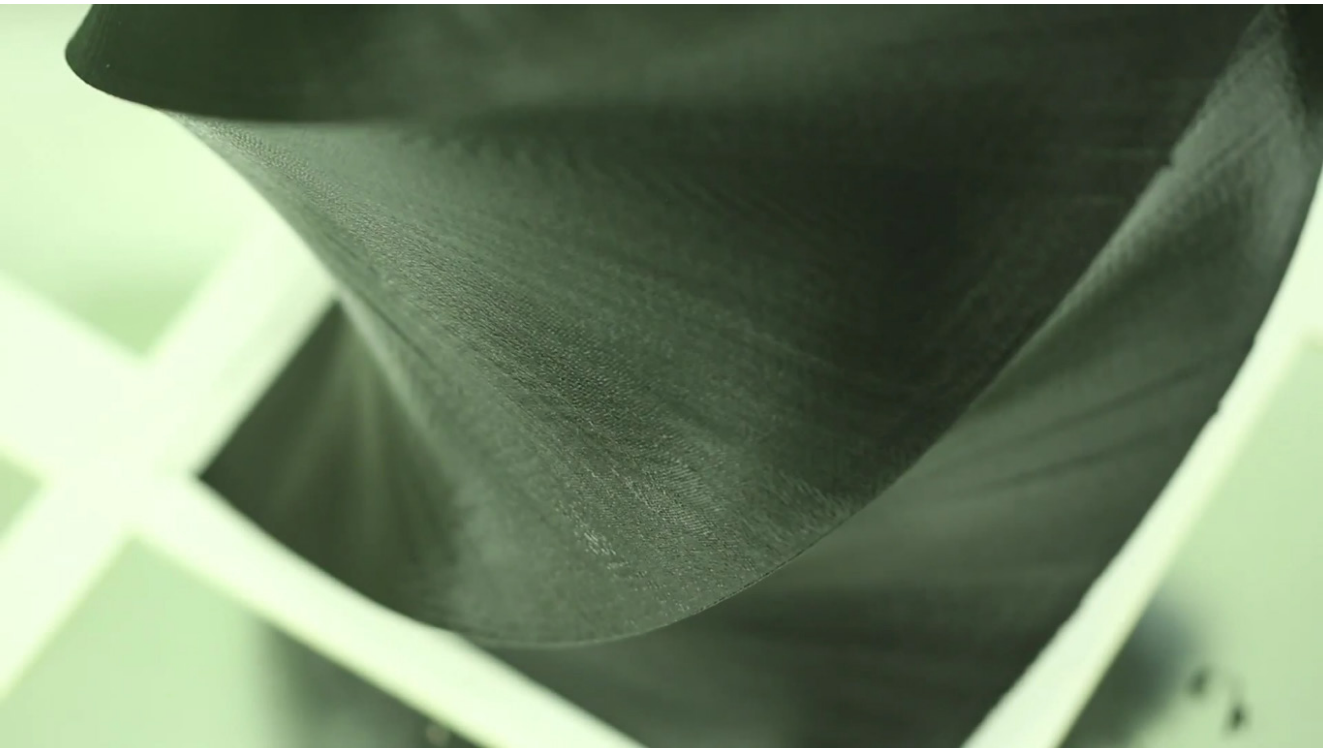

Figure 7. Close-up showing finish quality of the 0.4 × 0.4 × 1.5 m part with a 0.1 mm of layer height resolution.

and has been printed using an IRB 1600 at a printing speed of 150 mm/s. The part is displayed here as proof of concept.

7. CONCLUSIONS

This paper has presented a framework for an integrated Design-to-Fabrication process and a material-based approach to infill formation. The integration is realized as a series of connectors or “translators” using Rhinoceros as a test case. Another piece of software is developed in order to carry out the actual translation and validate the result with a variety of ABB robots, demonstrating the interoperability between software tools supporting the design, model management, and performance evaluation prior to physical fabrication. Finally, a structure-oriented algorithm for infill patterning creation is discussed and presented. The overall performance of the combined software, hardware, and material study outmatches that of the standard 3D printers in each of the comparison fields: speed, volume, and finish quality.

Although the present research offers a compelling approach to 3D printing for the AECO related industries, a number of key issues regarding construction and sustainability can be explored thanks to the inherent advantages of the 3D printing technique, namely:

- Waste control, zero-waste production, and reduction of building footprint at construction time through a minimization of operation costs (30) and an increased optimization of time, and energy footprint.
- Use of organic materials, and recycled building materials for non-structural and structural parts. Organic materials, as opposed to traditional materials, can be relatively easily obtained from their raw material counterparts (31) and are recyclable.
- Reduction of human errors in building sites through the automation and mechanization of the process, which account for more than 80 % of total defects in housing construction (32) (33). Safety would be affected positively.
- On-site deployment: using robots on-site allows for access to local and renewable energy sources. Furthermore, transportation impact is lowered or eliminated, thus its associated expenses and carbon footprint.
- Detail enhancement, finish quality through a re-qualification of tooling and labor force.

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