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Research

Prototyping Vitruvius, New Challenges: Digital Education, Research and Practice

Abstract. This paper discusses a key subject of research at ISCTE-IUL. Digital fabrication in architecture offers new perspectives and design innovation in three main areas: academia, research and professional practice. In order to investigate these new challenges and its contributions to architecture in Portugal, a group of multi-disciplinary researchers organized a symposium that presented a state of the art in digital fabrication. The main points were the creation of the Vitruvius FabLab–IUL laboratory and the definition of appropriate new lines of research in digital fabrication.

Keywords: digital fabrication, digital architecture, fablab laboratories, digital tools

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Introduction

Over the past decades, the development of new technologies and the emergence of sustainable/integrated digital tools for visualization, representation and fabrication have played crucial roles in architectural design, as a new paradigm at various levels: education, research and architectural practice. The digital revolution has transformed not only the process of architectural thinking but also the making. Architecture schools around the world are creating digital fabrication laboratories to provide their students with the skills to support new learning processes, scientific innovation and development linked to architectural practice and the building industry. Digital technologies have released a multiplicity of new career opportunities for graduates and advanced architectural education. Digital methods enable architects to create complex parametric modeling geometries; generate construction information directly from design; test its performance virtually and physically; and produce full-scale models of their designs. Thus, it has been necessary to introduce new architectural curricula in academia and new strategies to approach technology, implement digital thinking, and foster collaborative environments and digital methods. The main goal has been to explore the new digital technologies and their contribution to solving some of the challenges presented to society and architecture. Social responsibility requires greater sensitivity to innovation. Digital design sensibility must encompass the school culture [Cheng 2003]. The progress of architectural practice

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is characterized by two forces, one driven by the spirit of time and the other by innovation. Nevertheless, there is still a long way to go. In other words,

> the connection between a physical visual order and digital order is not fully understood, but at the same time the situation indicates many things can no longer be coded in the same manner as earlier. Architecture is evolving into far more of an infrastructure capable of taking on a variety of spatial and functional programs, than the actual physical edifice. In this light, critical thinking becomes an essential instrument in a research based architectural education [Fjeld 2008:7].

The variables are unlimited and involve the consorted efforts of all, especially academia and industry. Other important issues are the technological limitations and future directions.

In order to investigate these processes and their contributions to architecture in Portugal, ISCTE-IUL organized a symposium that would allow a state of the art in digital fabrication. The main topics were the creation of the Vitruvius FabLab–IUL laboratory, and the identification and definition of new advanced architectural education according to new lines of research appropriate to digital fabrication. The event was organized in cooperation with the industrial companies and had the participation of internationally renowned researchers in the field of manufacturing and digital architecture. The aim was to bring together professionals and non-professionals to reflect and discuss the work that has been developed in the area of new technologies, interactive architecture and digital fabrication.

This paper has four sections: the first section introduces the digital fabrication challenge. The second section describes the state of the art of digital fabrication and the symposium contributions, which are presented as papers in the present issue of the *Nexus Network Journal* (vol. 14, no. 3, Winter 2012). The next section, describes the area of expertise in digital fabrication at ISCTE-IUL and the first steps of research at Vitruvius digital fabrication laboratory. The final section discusses the results and future work.

A digital fabrication challenge: teaching/learning, research and practice

> *The architect should be equipped with knowledge of many branches of study and varied kinds of learning, for it is by his judgment that all work done by the other arts is put to test. This knowledge is the child of practice and theory. … There are three departments of architecture: the art of building, the making of time-pieces, and the construction of machinery. … All these must be built with due reference to durability, convenience, and beauty* [Vitruvius 1960: 5, 16, 17].

As Vitruvius reminded us, the relationship between conception and production is very important. This relationship has played a vital role in the development of both areas throughout history. But in the beginning of the twenty-first century, these matters assume new contours. The digital revolution has completely reconfigured this relationship, creating a direct link between the two based on the processes of computer numerically controlled (CNC) prototyping [Kolarevic 2003].

Tools once limited to non-creative areas are now part of everyday life for architect students, researchers and professionals. CNC combined with digital design tools make it possible for the designer to directly transfer design information to fabrication machines (milling, laser cutting, robots and 3D printers). Nowadays, the design process (academic, research, practice) is no longer conceivable without the aid of information technology.

This is due to the increasing need to quickly and flexibly fabricate tailored architectural solutions, as well as the complexity of the physical structures and the processes of assembling them. The modern paradigms of repetition, standardization and customization pose new questions regarding both the emerging aesthetics and the future production means for a new practice [Vicent and Nardelli 2010]. As Michael Meredith puts it,

> in this new production context, increasing importance has been given to the role of parametric design, a process based not on fixed metric quantities but on consistent relationships between objects, allowing changes in a single element to propagate corresponding changes throughout the system. In parallel, developments in scripting have opened the way to algorithm design processes that allow complex forms to be grown from simple iterative methods [2008:8].

Recently, relevant research in the field of natural structures has focused on generating complex geometries and the emergence of prototyping, providing additive technologies for these purposes. Fab(a) thing is a project that opens up new paths for the design process [Malé-Alemany et al. 2011]. This has become a means for delivering geometrically precise and useful prototypes within short periods of time [Oxman 2011].

The digital fabrication technologies are pointing to new ways to foster the communities of researches and individuals to develop sustainable tools based on open source hardware and software and self-learning processes. According to Mark Burry,

> Digital design is now fully assimilated into design practice, and we are moving rapidly from an area of being aspiring expert users to one of being adept digital toolmakers". The final intention is that any person, anywhere, could produce its own devices [2011:8].

However, knowledge related to digital issues is not taught at an equivalent level in architecture schools and the challenges are large. Preparing students and professionals of architecture to meet these challenges requires appropriate responses, based on the desire to reconcile historical and cultural identity within a global community.

State of the art of digital fabrication

CAD/CAM technologies are being used in architecture and building technologies to foster innovation and introduce original approaches to the design and building processes. Digital fabrication brings new possibilities to the design-through-fabrication processes, alleviates geometry constraints on mass production strategies and enables the production of custom components without increasing labor [Shelden 2002: 46].

As stated by Malcolm Mitchell and William McCullough, new tools often "seem strange and are understood in contrast to their predecessors" [1994: 464]. In fact, digital fabrication tools are still being affected by this appearance of novelty in architecture. However, over time their use has become commonplace both in education and practice in architecture. Today the benefits of digital fabrication in architectural research are becoming well understood and the contributions of the experiments undertaken are accepted to the extent that technologies are becoming more approachable and transparent. The use of digital fabrication in combination with other digital methods such as generative design systems, parametric design and shape grammars in the design practice allow the development of new and diversified solutions. Thus the possibilities brought about by the new technology-based methods of design and fabrication enable the emergence of solutions that were frequently impossible to achieve via other, non-computer-aided methods.

The emergence of CAD technologies in the 1980s changed some aspects of the design process but focused essentially on the representation of architecture with the systematic use of 3D models and realistic renderings. At the time, representation of the building was done by traditional 2D drawings. This kind of representation was seen as a necessity to inform the final construction, but was often untested as a valid construction method. Physical models were almost replaced by virtual models during the "digital fantasy era" and there was almost no relation between virtual models and real construction [Celani 2010]. During the 1990s Mitchell and McCullough [1994] witnessed the initial uses of digital fabrication and 3D scanner in architecture, previously used by the naval and aerospace industries, with experiments by Gehry [Shelden 2002].

Although Gehry introduced innovations in the materiality of architecture, the architecture and manufacturing processes which involve working with prototypes is not a new subject. In fact Gaudi, Buckminster Fuller, Mies and other architects used models to test their ideas [Kolarevic and Klinger 2008].

Since Gehry's first experiments, several digital fabrication laboratories, or workshops, were created in universities, industries and offices. These laboratories are fully equipped with computer-operated machines able to manufacture almost everything from integrated circuits to entire houses [Diez 2012]. According to Celani [2012] initially these labs mainly produced scale models using 3D printers, but researchers soon found new hypotheses for production of full-scale prototypes and started to orient their research to post-industrial methods.

Nowadays the connection between the concept and the fabrication phases is increasing and both are cross-referenced to exchange information and enhance the object's performance. Visualization, geometrical manipulation and simulation make it possible to anticipate incompatibilities and design errors that can be corrected on time. Being able to simulate the building's performance during the design process as well as work with real environment parameters creates buildings which are more connected to the environment and have better performance. The simulations and analyses of building performance informs its final form, which means that, all the other aspects aside, form is being informed mainly by performance [Klinger 2012].

The fabrication of models, prototypes or building components through digital fabrication uses subtractive, additive and formative technologies by modelling, dividing, machining and assembling surfaces.

CNC cutting, both 2D and 3D, is a subtractive technique that may use laser-beams, plasma-arcs or water-jets. It consists in cutting complex geometries in a very rigorous way. Multi-axis milling machines are also subtractive technologies since they remove parts of a solid material and may create textured surfaces.

Additive technologies, often referred as rapid prototyping, make it possible to create a 3D model by overlapping layers of material (polymer, metal and clay, among others). Due to the small size of 3D printing machines this technology has a limited application in the architectural design processes, being limited to small components. However the use of robots to assemble components or to print construction material is also an additive technology and its use is being widely investigated nowadays [Bonwetsch 2012; Malé-Alemany et al 2011; Webb and Pinner 2011; Kestelier 2011]. Instead of using representation drawings to manufacture a building and its components, like CNC fabrication technologies, the use of robots requires a different type of computing which "generates the design out of the fabrication parameters and the sequential fabrication steps" [Bonwetsch 2012].

To change the shape of a material we may use formative technologies, which apply forces to the material in order to get the desired final shape. Bending, extrusion, thermoforming and molding are some examples of formative technologies [Pupo et al 2009: 441]. Due to the high price of machinery the use of this technology in architectural reearch is still residual and mostly industry-oriented.

Along with these new ways of creating complex surfaces, patterns or forms there is an increasing interest in research in construction materials. This research is focussed on concepts like biomimetics, morphogenesis, generative systems, complexity and emergence among others. The work carried out by Neri Oxman at MIT within the initiative "Materialecology" is a great example of research in computational form-generation inspired by nature [Oxman 2010].

Kolarevic and Klinger [2008:3] emphasise the fact that projects growing out of research in digital fabrication exploring mathematics logics of surface modelling are dependent on software that is entirely surface-oriented in its underlying mathematics. Decisions made during design, prototyping, fabrication and assembly rely on codes, scripts, parameters, operating systems and software. This situation creates the need for teams with multidisciplinary expertise and different skills, from IT to architecture, design, material engineering, biology and mathematics, among others.

The Internet has considerably increased the possibilities of collaboration between different realities, expertise, cultures, etc. A paradigm emerged with the awareness that knowledge relies on the interdisciplinary and international collaboration between networks of experts, researchers, practitioners, students and ordinary people. These networks are usually based in online blogs, chats or forums that act as repositories of experience and code.

According to Neil Gershenfeld, the creator of MIT's FabLab network, fabrication laboratories are places to make (almost) anything anywhere [Gershenfeld 2005]. They empower people, especially in developing communities, to design and create tools to solve local problems.

Digital design and fabrication technologies combined with customized prefabrication may create innovation in materials' manufacturing industries because of the possibilities for customization and the fast design-to-production process [Mitchell and McCullough 1994]. Digital technologies allow for a further embedding of information within design processes, including information such as material properties, environmental parameters, user's data, time, construction regulations and construction methods. A process of design based on the use of several local parameters results on a customization of the final product.

The use of digital technologies in the manufacturing and building industries connects designers to manufacturers, enabling an optimized, more efficient process which does away with the traditional constraints of industrial standardization [Sheil 2013]. According to Sheil, today's bespoke architecture is a customized architecture produced by mechanical processes which takes account of specific parameters to mass-produce unique pieces.

Several research projects oriented to industry innovation have been completed during the past years. Examples are: rethinking the use of cork in architecture by José Pedro Sousa [2010], rethinking ceramic tiles by Duarte and Caldas [2005], translucent metal panels by Patterns [Kolarevic and Kevin 2008: 49]; construction system of reinforced concrete panels by Alvarado [2009]; new directions for stone by Studio Gang architects [Kolarevic and Kevin 2008: 81], among others.

Although CNC manufacturing allows the production of components in a very accurate way, the process of assembly is usually carried out through by traditional manual methods which means that typical tolerances are re-introduced into the new manufactured objects [Shelden 2002: 47]. The use of robotics in the assembly process reduces or removes this lack of accuracy and allows a complete correspondence between the design and the on-site final product. The work of Gramazio and Kohler and their team at ETH emphasizes construction as an integral part of architectural design by controlling and manipulating the building process with robots [Bonwetsch 2012].

In architectural practice these digital technologies are being used at several scales of intervention. Besides Frank Gehry's innovations in almost all aspects of digital design and fabrication, other practitioners are exploring technologies in some very interesting ways. Offices like Jean Nouvel, Zaha Hadid, Foster and Partners and Amanda Levete architects, are among the best practices in these areas.

In the Galaxy Soho project Zaha Hadid explores complex geometries and their translation into construction through design and fabrication technologies. The Louvre Abu Dhabi project by Jean Nouvel used digital design and fabrication technologies to test strategies for extreme environment conditions. Similar explorations were carried out by Enrique Ruiz-Geli and Cloud 9 with projects like Villa Nurbs which explores the limits of NURBS technology as well as CAD/CAM and Media-ICT with its CAD/CAM manufactured facade. Foster and Partners, in collaboration with Loughborough University, have recently investigated large scale free-form construction using additive technologies [Kestelier 2011].

None of the above practices in architecture were driven by cost constraints and were only made possible because they were unique projects for private real estate developers. In contrast, there are several initiatives in designing customized housing. Within these projects we highlight the Instant House developed in MIT [Sass and Botha 2006] and FACIT houses designed by Bruce Bell. The Instant House is an experimental project combining prefabrication with digital fabrication with the goal of creating customized housing made of wood derivates for emerging communities. FACIT houses are digitally designed and manufactured on a CNC router using plywood. The goal is to create a cost-effective, bespoke house using digital technology.

Mark Burry used digital design and fabrication methods to complete the Sagrada Familia, Gaudi's unfinished masterpiece in Barcelona. Burry's pioneering methods involve parametric design, material computation and high-tech digital fabrication in stone and concrete.

Diez [2012] states that today's architecture is full of unique, inimitable and iconic creations which try to make a statement in the territory. This approach to the use of CAD/CAE/CAM technologies enhances the least desirable attributes of these technologies and constitutes a serious error. The point of view of Amanda Levete

Architects [2011] on using digital technologies is that the great freedom in form-making comes with great responsibility.

Symposium Digital Fabrication – A State of The Art

The “Symposium Digital Fabrication – a State of the Art” was held at ISCTE-IUL on the 9-10 September 2011. The aim of this symposium was to define the state of the art of digital fabrication in architecture and other areas such as design, fine arts and building construction.

Symposium
Digital Fabrication
a State of Art

Sep 9th-10th

Conferences by

Kevin Klinger
Ball State University

Tomas Diez
Institute for Advanced Architecture Catalonia

Bob Sheil
Bartlett School of Architecture

Gabriela Celani
UNICAMP

Tobias Bonwetsch
ETH Zurique

Workshop by
José Pedro Sousa
FAUP/DARQ/OpoLab

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Sara Eloy
Hugo Coelho
Maria João Oliveira
Luís Carvão

A este evento foram atribuidos pelo Conselho Regional de Admissão da Ordem dos Arquitectos, 3 créditos ao simpósio e 8 créditos ao workshop

Apoios | Sponsors:

The fusion of architecture, computing and manufacturing enabled by the use of CAD/CAM technologies has, in recent years, broadened the scope of research in architecture and transformed traditional approaches to the architectural issues.

At this symposium we challenged the participants to explore how computing can improve the design and performance of architecture, how the experience and perception of space can be enriched through the integration of emerging technologies, how the shape can be generated parametrically and evolve and, above all, how to take advantage of digital modeling and manufacturing to produce differentiated physical objects.

Digital manufacturing is still poorly understood and used by architects in Portugal, with only a small number of researchers actively involved. Given this background, the symposium aimed at a wide dissemination among non-specialists and a specialized audience in architecture, fine arts, engineering and construction, in order to make evident the potential of this approach, especially in regard to the architectural object.

The presence of some of the most respected international experts in the field of manufacturing and digital media allowed a reflection and debate on the role of these technologies in current practice and education.

Two decades after the first attempts at utilizing digital fabrication in architecture, this symposium provided an account of today's progress and experimentation across the globe. Works from Europe with Bob Sheil, Tobias Bonwetsch and Tomas Diez, from Brazil with Gabriela Celani and from the USA with Kevin Klinger were shown and debated. The five talks by these researchers and practitioners were complemented by a workshop conducted by the Portuguese researcher José Pedro Sousa. In this workshop the participants were able to experiment with CAD/CAM technologies from concept creation to final production using Portuguese cork by Amorim and color medium-density fibreboard (MDF) by Valchromat on a 3-axis CNC router.

Unlike other conferences related to this theme, the Symposium Digital Fabrication was sponsored by Portuguese material manufacturing industries, who stressed their belief that digital fabrication and digital technologies are great tools for optimizing the materialization of architecture. By working together with these industries, architectural research can be done in close collaboration with the manufacturers and informs and is informed directly by the actual fabricators.

Keynote speakers presented widely representative works on Digital Fabrication. Kevin Klinger opened the symposium by providing an insight into how to see digital fabrication and the worldwide connectivity in the process of designing architecture. Klinger pointed out three major aspects associated to the new paradigm of architecture: the design-through-production system; the possibility of producing locally something that has been designed or informed by the global network; the new paradigm in which form follows performance. The need to form partnerships between academia and the manufacturers of building materials was one of the most discussed aspects among the speakers and this was stressed several times by Klinger. According to him, this partnership allows the testing of new products in real environments and increases the quality of industrial products. Klinger challenged academia to produce knowledge that may have real impact in society.

Bob Sheil addressed both the role of digital technologies in today's education and in architectural practice. In his talk, "Manufacturing Bespoke Architecture", Sheil noted that although digital technologies are emerging in architectural degree programs we have to work hard to integrate this new tools in the creative process of students. Sheil pointed out that architecture students still see CAD and CAM technologies solely as a tool to visualize and produce scale models. The possibility of using digital manufacturing technologies to test and optimize the digital models enables architects to design architectural solutions that can be proven to be adequate prior to their final production and assembly. Regarding this issue Sheil highlighted the need to "make" and to "build" during architectural degree courses using 1:1 scale models.

Tomas Diez, from Spain, talked about "Personal Fabrication: Fab Labs as a Platform for Change, From Microcontrollers to Cities". Diez showed several projects of the Insitute for Advanced Architecture of Catalonia in which he was involved, and particularly projects in urban areas which involve the interaction between man and machine.

The Brazilian experience was presented by Gabriela Celani from the University of Campinas, who focused on education. In her paper presented here, entitled 'Digital Fabrication Laboratories: Pedagogy and Impacts on Architectural Education" Celani reviewed the teaching of architecture throughout the ages to promote a reflection on the meaning of digital fabrication laboratories in schools of architecture today. She outlines three possible lines of action for a laboratory – research, applied development, and education – and concludes that most schools of architecture have sought to reconcile the three in order to explore all areas, thus resulting in higher productivity in comparison with cases of isolated approaches.

Celani concluded by saying that digital manufacturing is revolutionizing the process of designing and manufacturing in architecture, a revolution in which the paradigm of form as the driving force of the original architectural idea is being matched by the materiality and the structure.

The final lecture of the symposium was given by Tobias Bonwetsch from ETH Zurich, Switzerland, where he serves as Research Fellow in the field of Architecture and Digital Fabrication.

Bonwetsch's lecture was entitled "Tailoring fabrication processes" and focussed mainly on the application of robotics in the assembly of contruction components. He presented the work developed at ETH Zurich, which, employing much more powerful equipment such as industrial robots in adition to the milling machines, laser cutters and 3D printers, has gone one step further in the application of the technology of design and manufacturing of digital architecture. Bonwetsch showed how robotics can be incorporated into the design process and emphasized the various operations that a single robot can accomplish just by changing the tool with which it is equipped, such as cutting or adding material, making it much more versatile than a machine with only one function. In addition to the various possibilities of operation on the material, robots can also assemble components, something that no other digital equipment can do, and do it with high precision, resulting in complex assemblies that are very difficult, if not impossible to do by hand.

In his lecture Bonwetsch revealed a series of new possibilities in the field of digital manufacturing and was asked several times by the audience to expand on the capabilities of robots and human-machine interaction.

In the afternoons of both symposium days a workshop was given by José Pedro Sousa of FAUP / DARQ / OpoLab with the title "Digital Explorations > Material Realities". Sousa is an architect, researcher and teacher interested in exploring the conceptual and material possibilities that arise from the use of technologies for digital design and manufacturing. This researcher recently defended his doctoral thesis, entitled “From Digital to Material: Rethinking Architecture in Cork through the use of CAD/CAM Technologies” [2010], which explores the potential use of cork in architecture through digital technologies.

The workshop held during this symposium was intended to provide the public, composed of students, architects, designers, plastic artists and other professionals with an opportunity to experiment and try new methods of approach to the themes discussed in the cycle of conferences. The two workshop sessions were held along with the two-day event, allowing, in the first session, the first contact with three-dimensional modeling techniques using the Rhinoceros software (fig. 1) and, in the second session, experimentation with digital subtractive manufacturing techniques (fig. 2). The workshop was attended by twenty-five people from several countries so the official language, as in the symposium, was English.

Fig. 1. First day of the workshop, work on 3D modeling with Rhino

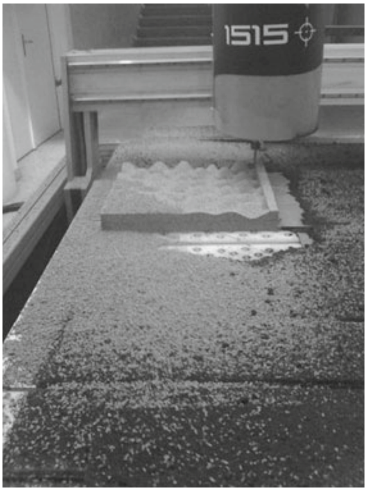

Fig. 2. Second day of the workshop, milling cork with a CNC router from Ouplan

Fig. 3. Some results of the workshop using cork from Amorim and color MDF from Valchromat

The works produced in the workshop allowed several issues to emerge. On one hand, complex geometries were explored as well as their transition from digital to material. On the other hand, digital manufacturing was explored as an aid to designing, in the sense that real-time production of the model allows a rapid evaluation, quick alterations and re-fabrication. Other aspects covered during the workshop were the possibilities of working with cork and MDF both in terms of the cutting and surface cutting texture development (fig. 3).

During the Symposium, the SUTURE installation by New York-based a|Um Studio – Carla Leitão and Ed Keller – was exhibited (figs. 4 and 5). SUTURE is an expanded cinema installation which "proposes a new architectural body created through event, gesture and temporality informed by a contemporary reconsideration of cinematic and architectural affect" [Leitão and Keller 2011]. The installation used digital video which, according to the authors, acts as a critical lens and interface to expose the relations between humans and their environment.

The SUTURE installation inhabited the ISCTE-IUL's large, double-height exhibition room and formed a mandatory path between the symposium's conference venue and the workshop room. The path started at a large scenic ramp which led the visitor down to the exhibition room, allowing a wide view into the entire space. As visitors encounter the installation at the ramp, their gestures mediated between abstract and real space cinematic and haptic events. Motion and presence sensors were placed in the columns along the ramp providing interaction points and encouraging visitors to create new signal paths and new cycles in the space. In addition, three networked computers, three video projections and a soundscape form the layers of event, which accumulate and mutate according to rules of self-organization in the network [Leitão and Keller 2011].

Figs. 4-5. SUTURE installation by a|Um Studio, Carla Leitão and Ed Keller, Programming by George Showman. Photos by João Morgado - Fotografia de Arquitectura

Digital fabrication at ISCTE-IUL

Digital fabrication is a recent area of expertise in ISCTE-University Institute of Lisbon. It was the result of a number of contributing aspects. First we will briefly explain the set up and the inherent development strategy of the laboratory. Second, an overview of ongoing or recent research projects is presented.

ISCTE-IUL Vitruvius FabLab set up

The creation of a digital fabrication laboratory at ISCTE-IUL was based on three main assumptions. The first starting point was the recognition of a great potential inside ISCTE-IUL in taking advantage of latent synergies. With regard to digital fabrication, our university has other strong scientific groups besides architecture that were interested in the laboratory, namely computer sciences, entrepreneurship and society and technology. One other assumption was the desire and the need to further develop a clear differentiation within Portuguese higher education in architecture. To follow this objective, specific high-level scientific competence was needed. Therefore, the third assumption was the fact that the Department of Architecture and Urbanism had, at the time, two teachers finishing Ph.D. research in this field of expertise. Moreover, other existing specific expertise included construction materials and structural engineering.

From these premises, a fundamental question arose. What should the scope of the laboratory be? This issue has been addressed over the past few years by scholars and practitioners. At the "Symposium Digital Fabrication: a State of the Art", Gabriela Celani presented a very interesting view about how digital fabrication laboratories in academic environment serve three main goals: research, development and education. Celani argues that there is a challenge in fulfilling these objectives keeping track of the need to incorporate in architecture curricula the ever new possibilities brought by digital fabrication.

Research is a fundamental activity of the academic environment, which means that a university laboratory has to comply with the respective requirements. On the other hand, research in architecture has to focus, at some point, on solving specific practical problems. Accordingly, an academic laboratory in a school of architecture should also allow for practical problem solving. In a digital fabrication facility, this means, among other things, the development of construction materials and systems. This task is better undertaken in partnership with the industry corresponding to the development facet. The association with industry may also allow for a financial turnover, which is quite relevant in ISCTE-IUL's strategy to face the actual economic environment by promoting entrepreneurship.

With regard to education, there is indeed a huge challenge, at least when considering the overall main objective of giving students effective competencies in digital fabrication related to architectural design. First of all, it should be noted that it is not difficult to capture students' interest in these technologies, since the outputs from digital simulation and fabrication are usually visually impressive. There is a sense of the new and avant-garde that stimulates young people's restless minds. Work done with students exclusively within digital fabrication matters is often very interesting. These kinds of results are obtained in specific courses intended as an introduction to the concepts, software tools and the machinery. However, things become more complex when there is an attempt to go further in the use of these tools.

Incorporating digital fabrication methods and potential in the process of architectural design requires more than just knowing how to use its tools. It is above all a matter of attitude. The main courses in architectural design are usually coordinated by practitioners that do not have a specific experience in using digital fabrication as a tool that informs the design process. The consequence is that students find it difficult to dialog with their design teachers when these technologies are an important part of their architectural proposal and not just a representation tool.

This same problem has been noted with other types of knowledge and expertise. For instance, the use of life-cycle or energy-related issues as a justification for a given design result was (and to some extent still is) often disregarded by some architectural design teachers. This may be in part explained via the *beaux-arts* approach to architecture which has traditionally informed architectural curricula in some countries, namely Portugal. Functional requirements, technological issues, building physics (just to mention a few examples) are often considered questions to be solved with the support of engineers at some point, late in the design process. This means, within the *beaux-arts* approach, that those are not issues that inform architecture but rather problems that complicate the production of architecture.

The integration of digital fabrication and related technologies in architectural education is reliant on another challenge. Unlike the above mentioned issues, to use digital fabrication to its fullest potential means to complement the architectural design process. For example, thermal comfort should inform the idealization of a building from its very beginning because it has consequences on the form, volume, glazing, materials, etc., but thermal comfort is not a design tool. Digital fabrication may inform the generation itself of the building, being a significant part of the design process. This assumption implies that the teaching of architecture, if willing to use these tools, needs to assume new methods.

How to drive this shift is then a major question. The answer is not unique and depends on several conditions. In ISCTE-IUL a two-way strategy has been defined and is now in its implementation phase. Two main criteria form this strategy: encourage and involve graduate students and produce high-level research. The rational is that high-level outcomes will support the explanation of the potential of digital fabrication in architecture and basic competencies among lower-level students are essential for future exploration of that potential.

The first criteria – teaching of basic competencies – has been achieved up to now through optional courses where students learn the basics of shape grammars, auto-LISP programming and digital fabrication. The second criteria – high-level research – is being implemented with ongoing multidisciplinary research projects and through a one-year post-graduate learning programme called Digital Architecture (in partnership with the Faculty of Architecture, Oporto University).

The implementation of this strategy is also based on the establishment of several internal and external partnerships. Internally, ISCTE-IUL specialists in computer sciences are working with architects to form the core team of ongoing research. The main subjects addressed by these colleagues are programming, shape grammars, multi-agent expert system shells and augmented reality. ISCTE-IUL is also one of the partners of the science centre *Ciência Viva do Lousal* where a CAVE Hollowspace is installed. This facility is used within the Digital Architecture programme to produce 3D simulation outputs by students and teachers.

External partnerships include Portuguese manufacturers of building materials, an authorized Rhino Centre, other Fab Labs and the Centre for Research and Studies Art and Multimedia (University of Lisbon).

The described setup of the Vitruvius Digital Fabrication Laboratory (Vitruvius FabLab–IUL) is intended to promote and develop the use of digital fabrication and related technologies in architecture. We foster innovation through the implementation of the practical theorizing concept [Hagger and McIntyre 2006: 58-59] where new knowledge is informed by the experiment of its formalization. Designing architecture for the future will require ever more reliable and accountable procedures so that the construction and the operation phases are well planned. The optimization underlying this goal may pose a problem for innovation unless there is a means to experiment as much as possible before construction. This experimentation, which validates the knowledge produced, is made possible to a significant extent by digital fabrication.

Research projects

Vitruvius FabLab research is focused on architecture and addresses issues such as design logic form, electronic technology, artificial life, robotics and human computer interaction. Supported by these guidelines two main complementary projects are being developed: Emerg.cities4all and bio-construction through natural matter with computational form generation. We will also dicuss a recent workshop entitled "Discursive Wall – a Living System".

Emerg.cities4all. Emerg.cities4all is an ongoing research project focused on the development of a generative computer-aided planning support system for cities and housing for low-income populations. The system uses a descriptive method – shape grammars – and is based on a direct input strategy targeted to the common user with no digital expertise.

The Emerg.cities4all project arose with the goal of contributing new solutions to the housing problems of the economically underdeveloped countries, which are facing a rapid, uncontrolled urbanization. However, mass homelessness is still a consequence of the rural migration to urban peripheries. The consequence is the increase of informal mass construction settlements. Recent attempts to address these problems seem to have solved just a part of it and have created new issues as a result of the generalized and uncritical approach [Paio, et al. 2011].

The project assumes that it is possible to generate mass housing (creating an urban environment, houses and building solutions) based on the concept of mass personalization. This goal is achieved by creating a generative computer-aided system that develops a set of possible solutions to suit specific parameters related to local conditions. These conditions include climate, material resources, type of family, social characteristics and economic constraints.

Solution generation is based on a descriptive method such as shape grammars [Stiny 1980] as a generational urban settlement and multiplicity housing method, guaranteeing adaptability and evolutionary capabilities. The research is using this tool not only to generate new forms but also to better understand existing settlements through analytical grammars. Within this scope, the proposed shape grammar seeks to analyse how existing slums, *favelas* and *musseques* are generated and what social, cultural and spatial dynamics are involved in their growth [Paio, et al. 2011]. Despite the terrible living conditions, there are reasons to believe that the adaptability and evolutionary characteristics of their houses, as well as their social and spatial relations, have some inherent good qualities. Not having the intention to recreate existing settlements exactly as they stand, the new original grammars will also denote a human approach because they are informed by local humanized logics and specific ways of self spatial organization [Linhares, et al. 2011].

Regarding the feasibility of the generated design, the project will develop a serial construction system whose degree of detailing is dependent on specific partnerships with the construction industry.

The process is conceived on a basis of a multi-agent system, which enables interaction at three different levels: system specialist (builds and expands the shell); shape grammar specialist (builds a system applied to a specific area using the shell); common user (applies the system to create solutions in the specific area). To facilitate interaction with users, the system interface is based on a graphical and symbolic definition of shapes.

Bio-construction through natural matter with computational form generation is a research work based on a Ph.D. thesis being developed at Vitruvius FabLab.

The fundamental question that underlies this project is how to develop an external wall building system that has the ability of self adaptation in response to solar radiation in order to optimize thermal comfort conditions in the building. The project seeks the answer to the above question through biomimicry processes inspired on the evolution of biological self organization.

The ability to mutate requires living system capacities which will depend on specific sensors that will measure solar radiation properties, internal and external air temperature, relative humidity and wind pressure. The combination of this data will trigger the adaptation of the wall surface to change the way solar energy is absorbed and reflected. The goal is the optimization of solar heat gain through the wall considering the adequate thermal comfort strategy in face of the external conditions.

To adapt the wall's external surface requires a construction solution made of small elements combined through complex geometric patterns. This is being conceived by deliberated design criteria using already existing resources such *Variable Property Design* [Oxman 2010] and the *autopoiesis theory* [Maturana and Varela 1971].

Another crucial aspect is the definition of how materials may be used in the construction system. Several possibilities will be explored by analysing material properties such as mechanical strength, dimensional stability, water absorption, thermal conductivity and diffusivity, specific heat capacity, durability, cost and environmental impact. These properties will be integrated to define the most adequate materials to be incorporated in the prototyping phase. Following the definition of the most adequate materials, the assembly system will be addressed. The goal is to obtain a simple construction method that easily incorporates the installation of the sensors and of the movable parts. Prototypes will be fabricated at different scales to evaluate the possible combinations of materials / assembly systems. The ones found most suitable will then be fabricated at scale 1:1 for final validation.

Data collection and interaction criteria will be controlled by open-source platforms. Fabbers and C/C++ programming will be integrated to provide the necessary information to the wall thus creating an autonomous input/output organism.

Apart from the ability to respond to thermal comfort requirements, the wall will also have an interesting architectural feature: it will regenerate itself by changing the appearance of its external surface.

Discursive Wall – a Living System. Discursive Wall – a Living System was an extended workshop that took place at de Vitruvius FabLab–IUL facilities in March 2012. The objective of the workshop was to develop and fabricate an interactive living system wall prototype. The wall is intended to respond physically to sound interacting with the surrounding environment and establishing a direct dialog with the inhabitants [Oliveira et al. 2012].

The fundamental issue that supports this system is the creation of an architectural living system constantly being designed and re-designed by its inhabitants, minimizing acoustical problems of the space.

The methodology employed to develop the discursive wall includes four steps. The first is to design and fabricate the interaction unit that will define the living system through CAD/CAM/open source process. The second step consists of informing the metabolism and organizing the units of interaction in a closed circular process. This is achieved through a mathematical description method enabling the definition and redefinition of the rules by the computer modelled parametric process. Interactive simulations are produced through the open source platform and C/C^{++}. The third stage is to assure that the circular organization will be respected. To establish this circular organization an open source code based in C/C^{++} is used. Finally, the fourth step is the creation of a response mechanism through the use of sound sensors. These enable the production of different reactions and situations on the uninterrupted living system. Therefore, the discursive wall maintains the capacity of "speaking" to the inhabitants of the room.

Conclusions and future work

The "Symposium Digital Fabrication - A State of Art" provided an opportunity to reflect on digital tools and the gap between the digital fabrication, academia, research and practice. If on the one hand we are aware of paradigms such as design-through-production, the possibility to create and produce *in loco* and the recent "form follows performance", on the other hand students still tend to see CAD/CAM resources as simple tools to produce scale models. Therefore the greatest challenge faced by academia is to produce knowledge through the possibility of using manufacturing technologies, testing it and optimizing their products, establishing the bridge between creators, researchers, the industry and material manufacturers. The incorporation of robotics in the design and manufacturing process, operation material and its use in the assemble components gives us new possibilities for producing architecture.

The digital fabrication technologies methods are now pointing to a new way of conceiving contemporary architecture. Implementing in academia these resources common to the industry, with a strong theoretical and historical basis and providing a straight relationship with cultural identity, will redirect architecture to the basic principles of construction thinking, increasing the potential of research and practice. As in many other areas of knowledge, architectural academia could also be the pioneer in the experimental field, making an intelligent use of digital fabrication tools and their potential. Academy can become the provider of new research, experiments and new tested models that will improve everyday practice with new tools and solutions for future projects. The combination of the right resources, technology, creative minds and a fundamental multidisciplinary knowledge, makes academia's contribution essential to the enrichment of contemporary and future architecture. Robotics, open source and scripting resources are the means that bring us new ways of conceiving the architectural processes. These tools enable us to rethink the traditional design and construction process, by giving us the necessary inputs to test, built and construct anywhere at any moment.

Vitruvius FabLab-IUL is directing its research to the community, trying to solve local problems, looking at the human-machine interaction.

Future work includes an open online platform to follow the concept of sharing within the community. Ongoing projects will be detailed and explained in this online platform, providing all the tools and the experienced knowledge so that anyone, anywhere, may build their own solutions.

One relevant project that we have recently embraced is the "Guardian", an interior façade of a public library that reacts to the excess of noise. The Guardian produces intensive light signs when the library inhabitants produce excessive noise, keeping colors soft when the sound scale is adequate to the space.

At the present moment, three human issues from the past are being addressed again: the 1980s cliché of the human-machine interaction, the 1990s condition of the Skin, and the ancient human necessity to imitate the forms of nature. Recent achievements in these research areas are essentially based in new digital tools. Thus, rethinking these issues, crossing them with our current society needs, with all these emergent conditions of technologies and with its fundamental academic condition is leading us to new projects. To provide a solution for a south facade, we will develop a wall responsive to its own environment. This project aims at solving problems related to sun and natural ventilation through the creation of mutable shadows and mechanisms. In these future works we envision adding higher levels of functionality to the purposes of architecture.

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