ABSTRACT
In the last two decades, CAD/CAM technologies have opened new conceptual and material opportunities in architecture. By combining computational design and digital fabrication technologies, architects have embraced a higher level of geometric complexity and variability in their design solutions. Such non-standard possibilities were expanded with the recent introduction of robotic technologies in the discipline, which have allowed moving beyond the fabrication of building components to reach the construction of building parts. As a result of this digital condition, traditional materials have known innovative applications in architecture. In this context, this paper presents cork, which is a natural and recyclable material. By describing its unique set of properties and features, it argues about cork’s relevance for the building construction in the present times. With this underlying motivation, this paper defines the current state of the architectural research on the use of robotic fabrication with cork. It does so by describing and illustrating a set of different experiments conducted by the authors in their academic institutions. The results unveil a set of innovative applications of cork in building construction and, at the same time, contribute to show how robotic technologies can be used to rethink and update traditional and old materials in architecture.
1 INTRODUCTION

In the last two decades, the use of Computer-Aided Design (CAD) and Computer-Aided Manufacturing (CAM) technologies has "radically reconfigured the relationship between conception and production, creating a direct link between what can be conceived and what can be constructed" (Kolarevic 2003). The recent spread of digital technologies throughout the globe have supported a growing interest in exploring unique forms and constructive solutions in contemporary architecture that could hardly be conceived and materialized before (Sousa 2005). The differentiated facade panels in Frank Gehry’s EMP Project in Seattle, the irregular structure in Herzog & de Meuron’s Olympic Stadium in Beijing, the curvilinear form of Zaha Hadid’s Aliyev Center in Baku, or the variable wood components in Álvaro Siza and Eduardo Souto de Moura’s Serpentine Gallery in London, are just four examples that demonstrate the many levels and scales in the building construction industry that can be influenced by the use of digital technologies. After the Crafts and the Mass Production paradigms, architects are now facing the new (digital) technological condition that opens the possibility for non-standard modes of design and construction.

1.1 THE USE OF ROBOTS IN ARCHITECTURE

In practice, while CAD technologies allow architects to embrace geometric complexity and variability in the design, CAM technologies offer the response to the materialization of such unique creative intentions. Over the last years, the use of Computer Numerically-Controlled (CNC) fabrication machines became a familiar practice in architecture and building construction to produce building components with customized shapes, textures or forms.

However, regardless of those already innovative conditions, the recent exploration of industrial robots in architecture introduced by Gramazio & Kohler (2008) set an important step-forward in the field of design materialization. Initially developed for other disciplines based on mass-production logics, the industrial robot presents a series of major opportunities for a discipline like architecture, which is interested in non-standardization. By mounting in the right end-effector, the robot can be programmed to perform a wide range of additive, subtractive and formative fabrication processes, which are usually executed by different CNC machines. However, in doing so, its 6-axis (or more) movements in space introduce a higher degree of freedom in the production process. Besides this improvement, the exploration of other more specific processes, like material handling (e.g., with grippers or vacuum systems), can extend the impact of CAM in architecture from the fabrication of building components to the construction of building parts. The Gramazio and Kohler’s Gantenbein Winery in Flasch, Switzerland, is an example of a building where a series of robotically pre-assembled brick walls were employed in its construction.

In short, unlike other CNC fabrication processes, the relevance of using industrial robots in architecture is twofold. On the one hand, it is tied to its flexibility and capacity
to interfere at any stage of the building construction process (i.e., from fabrication to construction). On the other hand, its potential is also linked to its capacity for dealing with geometric complexity and embracing variable fabrication procedures, instead of automating repetitive routines, as it happens in other disciplines.

1.2 MATERIAL INNOVATION IN BUILDING CONSTRUCTION

Facing the context of non-standard architecture, the building construction industry cannot remain indifferent. Their success and competitiveness depends not only on their capacity to address the current architectural interests, but also on their talent in developing and presenting new solutions that can surprise and inspire designers. Overcoming the limitations of standardization, both routes for innovation have set two major trends in the materials industry (Addington and Schodek 2004; Kolarevic and Kingler 2008):

- The invention of new materials, artificially designed and customized (e.g., composite products);
- The rethinking of new applications for existing and traditional materials.

It is in the scope of the second tendency that this paper’s topic is inscribed. With the help of digital technologies, traditional materials like concrete, wood, metal, glass or stone have been produced with intricate and customized dimensions, shapes, forms and textures. As a result of this technological upgrade, architects have kept alive their interest in using such old materials independently of the complexity or uniqueness features of their designs.

By recognizing this fact, and the architectural tendency towards non-standardization described before, it is important to investigate the possibility to rethink the application of cork in architecture through the use of robotic fabrication. By presenting this material and its unique properties, and by mapping the current state of the research conducted with robotic fabrication, this paper wants to contribute to:

- Innovate the fabrication processes and architectural applications with cork;
- Inform the architectural field about the relevance and potential of this 100% natural material for the building construction industry;
- Approximate the world of robotic technologies to that of architecture and building construction.

2 THE RELEVANCE OF CORK

Cork is a natural and recyclable material, which is extracted from the cork oak tree (i.e. Quercus Suber) that finds its natural habitat in the West borders of the Mediterranean Sea (Figure 1). Unlike wood harvesting, the extraction of cork from the bark, which happens every 9 years, does not imply the death of the tree. Its singular capacity of
growth and regeneration opens "the possibility of using the cork oak tree as a sustainable producer of cork throughout its lifetime" (Pereira 2007).

The unique convergence of different properties in a single element makes cork a unique natural material. As older studies (Stecher 1914) and recent ones (Pereira 2007; Gil 1998; Gibson 1999; Fortes 2004) demonstrate, the cellular structure and chemical composition of cork is at the basis of its lightness, buoyancy, viscoelasticity, compressive resilience, and low conductivity of heat and sound properties. From the aesthetic and sensorial point of view, its texture, colour and temperature convey the idea of a warm and comforting material.

These singular features led man to use cork since the antiquity, ranging from the simplest applications (e.g., fishing nets, swimming aids, shoes) to the most advanced ones (e.g. in the automotive and aerospace industries). The global industry of cork is largely dominated by Portugal followed by Spain, with the first being responsible of more than 50% of the world production of cork.

Thus, both its local (i.e., economic) importance for Portugal, and its global (i.e., ecological) relevance for the sustainable challenges of our world constitute two major motivations for the authors to conduct research on this material.

2.1 APPLICATIONS IN ARCHITECTURE
Although its main focus has been in the production of cork stoppers, the industry of cork has been connected with the building construction industry through the production of cork agglomerates. Among them, the expanded cork agglomerate (i.e., internationally known as ICB or Insulation Cork Board) seems the most interesting product for architecture for two reasons. On the one hand, although it is processed, it remains as a 100% natural material. As described in detail by Sousa (2010), its agglomeration process consists in injecting superheated water vapour through an autoclave filled with cork granules. Under such temperature and controlled pressure, the cork granules expand against each other and release a chemical substance—suberine—that bonds them all together without requiring the addition of any other adhesive product. The resulting expanded cork agglomerate blocks are thus still 100% made of cork, and inherently possess cork’s performative and recycling possibilities (Figure 2). On the other hand, unlike other cork products, the expanded cork agglomerate is produced in a big size block format, which is suitable to address the large scale of building construction.

The traditional application of the expanded cork agglomerate has been as a hidden insulation material inside the walls. However, by perceiving its unique properties, the Portuguese architect Álvaro Siza proposed, for the first time, to use it in the facade of the Portuguese Pavilion for the Expo 2000 in Hannover (Figure 3). Since then, the Portuguese company Amorim Isolamentos started to promote the exterior application of the expanded cork agglomerate in building construction. A growing number of architects
began to employ it as a natural and recyclable material that alone can solve different building requirements at the same time (e.g., acoustic, thermal, aesthetic or formal interests).

### 2.2 DIGITAL RESEARCH ON CORK

Despite this innovative application, the expanded cork agglomerate product remained commercialized in standard flat and rectangular formats, available within a set of pre-defined thickness and densities. Resulting from the mechanical production process described before, this condition prevented the material to be employed in architectural designs requiring customized material geometries and effects.

To investigate the possibility to overcome this condition, the author José Pedro Sousa developed his Ph.D. research in a close collaboration with the company Amorim Isolamentos (Sousa 2010). In his research, Sousa tested and evaluated different CNC fabrication processes in the production of customized shapes, textures, and forms. The results led to propose the integration of a specific set of CAM technologies in the end of the production chain. As a consequence, the company decided to implement CNC fabrication technologies in the factory (i.e., 3-axis milling machine) to embrace the commercial opportunities of the non-standard architecture.

Since then, the use of cork in architecture has known some innovative applications in practice, which have demonstrated that cork can be used to fulfil some current design interests discussed earlier in this paper. Commissioned by the Amorim Isolamentos, the Cork Vault Pavilion (Figure 4)—designed by a group of professors and students of the CEAAD program (Note 1) (Varela P et al. 2014)—and the Wave Cork Panel (Figure 5)—conceived at the DFL (Note 2) (Figure 5)—are just two examples that show the emergent opportunities for the application of cork in architecture opened by the use of CNC fabrication technologies. Going beyond traditional thermal insulation applications, these works rethink the material pointing towards new structural, acoustic, and aesthetic uses.

### 3. ROBOTIC FABRICATION WITH CORK

Aside with the investigation on CNC fabrication, the exploration of robotic fabrication with the expanded cork agglomerate emerged as the next logical research step. Thus, the authors initiated this avenue of inquiry three years ago by joining their research institutions (Note 3). During this period, this interdisciplinary collaboration set three fabrication directions to explore the use of industrial robots with cork: (1) Cutting; (2) Milling; and (3) Assembly.

Next, this paper presents a brief description and illustration of the work produced in the scope of each topic. As a note, since the expanded cork agglomerate is the only cork product discussed in the rest of the paper, it is going to be, from now on, simply referred as cork, to simplify the text.
3.1 ROBOTIC CUTTING

From earlier research work (Sousa 2010), the use of CNC water-jet technology revealed to be the most efficient one to cut cork. Due to cork’s soft composition, this process can cut very thick boards in a single pass with a very little amount of abrasive. Furthermore, CNC water-jet cutting leaves an excellent surface finishing quality and can benefit from the freedom of movements of a robotic arm.

This possibility was tested and demonstrated by conceiving a cork panel with a set of perforations that challenged the 6-axis movements of the robot. The design of each opening is defined by connecting a circle in one side of the panel to a clover-type contour in the opposite. The resulting ruled surface geometry cannot be produced using conventional 3-axis CNC water-jet cutting processes; instead the 1000x500x100mm cork panels were cut by the water-jet system mounted in a MOTOMAN robotic arm. Although the technology allowed for a single cutting operation, the geometric intricacy of the openings required two cutting passes and manual removal of the waste material. The process was very precise, but, due to the design features, it was also slow. It took almost three hours to produce a complete panel. This experiment resulted in the production of eight panels for the assembly of the Clover Wall, a 1:1 scale prototype for an architectural partition wall built in cork, which through its openings, could also filter the light in space (Figure 6).

In this prototype, the openings are all identical. Nonetheless, its geometry is sufficient to demonstrate the ability of water-jet technologies mounted in robots to cut cork. In future, the exploration of parametric variation in the definition of the openings can conduct to more spectacular results, opening the door to the controlled filtering of light. However, the time consumption in water-jet cutting can prevent the resulting product from being commercially affordable. A more optimized balance between geometric intention and the fabrication process would be required to yield cost benefits of this process and exploration in architectural construction.

3.2 ROBOTIC MILLING

Sousa’s 2010 research into the use of CNC milling technologies revealed the most effective process to be 3D subtractive fabrication operations. Furthermore, the capacity to combine cutting with milling operations makes 3D subtractive fabrication a flexible technology for the production of customized building components in cork.

As a preamble, it should be said that subtractive fabrication is not a very sustainable process as it implies wasting material through the removal operation. However, given that cork is a 100% natural and recyclable material, the released granules can be collected to generate other applications (e.g., as an aggregate for concrete mixtures, as a combustible material for heating systems in factories).
Thus, robotic milling was tested starting with the design of a cork panel with an undulating texture. Using Rhinoceros, the material effect was specified by designing the milling tool paths not by modelling a surface. In the fabrication, a customized end-ball milling tool, with a 100mm diameter, was attached to the spindle mounted in the KUKA KR120 r2700 HA robot of the DFL. This setup allowed the quick fabrication of highly expressive surfaces in 1000x500x70mm cork panels. With a single milling passage, each panel took only 6 minutes to be produced without compromising the surface finishing quality. This performance is invaluable from the economic point of view of the process. The experiment resulted in the production of 1:1 scale prototypes of two kinds for an architectural facade. One solution consisted in the serial production of a standard pattern, which always assures a geometric continuity between panels, independently of its position in space. The other solution was geared towards mass-customization, involving a series of differentiated panels to create a unique global effect (Figure 7).

The feasibility of this process was demonstrated in a recent application of the first solution in the facade of the ITeCons Laboratory in Coimbra (Figure 8). Nonetheless, from the geometric point of view, the exploration of the 6-axis movements of the robot is going to be further explored in future works.

### 3.3 ROBOTIC ASSEMBLY

Unlike the two previous fabrication processes, the robotic assembly of cork components can be considered as a novel possibility when compared with those supported by traditional CNC machines. Moving from the manufacturing of building components to the assembly of building parts is one of the innovations brought by robots into the building construction industry.

Inspired by Gramazio and Kohler’s pioneering work (Kolarevic 2003), the authors joined efforts to start this research avenue in 2012, in the scope of the IJUP research project (Note 4). Our work proposed the construction of non-standard walls made out of robotically assembled cork bricks with identical dimensions. This is an interesting approach for the industry, as it does not require any changes in their current industrial processes, which are based on standardization. By developing computational design techniques with Rhinoceros and Grasshopper, curved surfaces were converted into a series of discrete blocks, and their specific coordinates and spatial orientation were automatically listed in an Microsoft Excel file. This data was used to program a small-size ABB robotic arm to pick and place a series of 120x60x30mm size cork bricks. To overcome the reaching size limitations of the robot, the team conceived a bigger wall built out of the assembly of small robotically pre-fabricated parts (Figure 9).

This line of inquiry was continued in a currently undergoing research project on Robotic Technologies. With the support of the FCT (Foundation for the Science and Technology), the DFL/CEAU acquired the large size industrial robot from KUKA (KR 120 r2700 HA) to perform fabrication operations with heavier and bigger materials. By programming this
robot with the Grasshopper plugin KUKA/Prc (Association for Robots in Architecture n.d.), the authors designed and built a series of mock-ups with bigger 250x150x70mm cork bricks, like the Pixelated wall (Figure 10).

At this stage, the blocks were manually fixed with glue, and the study for the automation of this process is currently going on. Without this last achievement it would be difficult to assess the real time consumption of the robotic assembly processes, and the actual precision and flexibility of the process is evident. The geometries of the wall could hardly be built with precision by manually laying processes. In parallel, with the robotic arm approach, the team is currently developing at the INESC TEC an alternative technology for robotic fabrication based on a cable-robot system (Moreira et al. 2014). This approach aims at dramatically increasing the size of the robotically fabricated parts in the construction site by taking advantage of the fact that cork is a very light material. In any case, since what is being fabricated is a building part, the integration of structural analysis in the design process is also a future important avenue of research.

4 CONCLUSION

Motivated by the unique properties and features of cork, the authors wanted to map the current state of the architectural research on robotic fabrication with cork. The experiments presented in this paper contribute to unveil the emergent possibilities to use this natural material in building construction and to rethink its traditional applications. Confirming the validity of robotic fabrication, future research directions should follow two complementary paths: they should highlight and explore the specific material qualities of cork to embed them in the design and fabrication logics; and they should investigate more the singular features of robotic fabrication processes when compared with other technologies. The 6- (or more) axis movements, the possibility to combine different fabrication operations, and the ability to integrate other devices (e.g., sensors, vision systems, scanners) are some of the features that can enhance the potential of future cork constructions in architecture.

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NOTES

1. The CEAAD is the Advanced Studies Program in Digital Architecture promoted by the FAUP (Faculty of Architecture of the University of Porto) and the ISCTE/IUL (University Institute of Lisbon). The Cork Vault Pavilion was designed by CEAAD’s students Maria João Oliveira, Emmanuel Nove and Pedro Varela, under the supervision of Professors Alexandra Paio (ISCTE/IUL) and José Pedro Sousa (FAUP).

2. The DFL (Digital Fabrication Laboratory) is the research group of the CEAU (Center for Studies in Architecture in Urbanism) of the FAUP. Founded and directed by Prof. José Pedro Sousa, the DFL investigates the impact of Computational Design and Digital Fabrication technologies in Architecture and Building Construction.

3. The DFL/CEAU at the FAUP (Faculty of Architecture, University of Porto), the FEUP (Faculty of Engineering, University of Porto) and the INESC TEC.

4. The IJUP is a funding program promoted by the University of Porto to support small research projects developed by young researchers and students.

REFERENCES


JOSE PEDRO SOUSA

José Pedro Sousa is Assistant Professor at FAUP (Faculty of Architecture, University of Porto) where he founded and directs the DFL - Digital Fabrication Lab, and co-directs the Post-Graduate Program in Digital Architecture. He has a PhD in Architecture from the TU Lisbon (2010), a Master in Genetic Architecture from the ESARQ-UIC (Barcelona, 2002) and a Graduation in Architecture from FAUP (1999). He was also a Special student on Design and Computation at MIT (2003) and a Visiting Scholar in Architecture at the University of Pennsylvania (2005). His research interests range from computational design, digital fabrication, architectural geometry, material innovation and cork design in architecture. He was awarded with the 2005 FEIDAD Outstanding Award (1st), the 2009 Young Research Award of the TU Lisbon, and currently coordinates funded research projects on robotic fabrication technologies.

GERMANO VEIGA

Germaino Veiga is a mechanical engineer with a PhD in Robotics and Automation (2009) by the University of Coimbra. In 2005 he was an invited researcher at the University of Lund, Sweden, and was a researcher (2002-2011) and Invited Professor (2007-2011) at the University of Coimbra. He is now Senior Researcher at INESC TEC, in Porto, and his research interests are on future industrial robotics including, plug-and-produce technologies, robot programming, mobile manipulators, HRI. He has been involved in the FP6 SMERobot working on the WP5 dealing with plug-produce and was member of the Exec. Committee of the FP7 ECHORD project. Currently is the coordinator of the INESC team that is participating in the FP7 projects CARLoS, and STAMINA, both addressing mobile manipulators for industrial applications.

A. PAULO MOREIRA

A. Paulo Moreira graduated with a degree in electrical engineering at the University of Oporto, in 1986. Then, he pursued graduate studies at University of Porto, obtaining a M.Sc. degree in electrical engineering systems in 1991 and a Ph.D. degree in electrical engineering in 1998. Presently, he is Associate Professor at the Faculty of Engineering of the University of Porto and researcher and manager of the Robotics and Intelligent Systems Centre of INESC TEC. His main research interests are process control and robotics.