Negotiated Materialization: Design Approaches Integrating Wood Heterogeneity Through Advanced Robotic Fabrication

Giulio Brugnaro, Angelo Figliola and Alexandre Dubor

Abstract Whilst robots are predictable, repetitive, predefined and constant, natural materials present unpredictable complexity. Over the past few centuries, materials have been standardized to fit industrial processes, in an attempt to defy this unpredictability. Thanks to new advances in sensing technologies and computational design, today we have the opportunity to reintegrate the intrinsic properties of natural materials in their full complexity. What is the potential of a synthesis between the particularity of each specific material element—specific properties and parameters—informing the fabrication process? Digital and Robotic Fabrication are based on the use of flexible machines that open the possibility to mass-customize the production process. Combined with sensors and computational analysis, they allow to work with "soft systems", both adaptable and continuously evolving, whose dynamism is constantly fed by a flow of information. How can the designer integrate this uncertainty and complexity in the design process? In this paper the authors specifically discuss the management of structural and material tolerance inherent to large scale construction and anisotropic materials, such as wood. A series of projects developed and built at the Institute for Advanced Architecture of Catalonia and the Bartlett School of Architecture are used as case studies to investigate tolerance management in Digital Fabrication with different kinds of wood.

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1 Introduction

Within the context of industrial production, robotic fabrication processes are devised as short, constant and repetitive tasks, however, when handling natural, heterogeneous, materials, this requires to continuously adapt to the specificity of the material's specific properties and behaviours. Recent advances in sensing technologies and computational processing allow to integrate such properties within our design tools through different layers of complexity. Once materials can actively inform the fabrication process, how can the synthesis of such information lead to novel design opportunities? In the selection of projects presented in this chapter, the flexibility of industrial robots provides the opportunity to explore the consequences of such new material understanding towards the customisation of production processes.

1.1 Dynamic Blueprints and Cyber Physical Making

The integration of sensors and computational analysis allow to devise manufacturing processes as "*soft systems*", adaptable and continuously evolving frameworks whose dynamism is supported by a constant flow of feedback information (Kwinter 1993). The ability to dynamically act and react, presenting a certain quotient of intelligence, make such systems sensitive to variations due to the interaction between the different actors and components involved in the overall process, such as the anisotropy of the materials used. This therefore progresses from a hard system of standard industrial processes, to a soft one governed by an intelligent responsiveness: combining the customization of tools, use of sensors and computational capabilities (Alemany and Portel 2014; Vasey et al. 2015; Brugnaro et al. 2016). Such adaptive relationships are defined by Achim Menges as "Cyber Physical Making" (2015) and described as follows: "*In behaviour-based making, data is continuously gathered and feedback to the system, which means that new information is gained on the run and new insights can be had; or in other words, design can evolve in the process of making*". According to this definition, the role of computational design in processing real time data and calibrating the digital model in accordance with the production sequence, is evident. Hence, it is possible to define adaptive systems in relation to the variable parameters of the manufacturing process, the material used and the interaction between the two components that inform the digital model in real time. The described methodology makes it possible to use the robot not as a simple *performer of programmed actions*, returning to the definition of servo supplied by Capek (Capek et al. 2004), but as a design agent able to materialize virtual and digital space through an adaptive and responsive process (Menges 2015a, b). By extending the receptivity of the robot through a series of sensors, it is possible to implement a system of feedback loop relations between man, machine and material. Engaging with feedback loops signifies building relationships and designing a dynamic, non-linear system that can guarantee adaptability to the local scale (Gramazio and Kohler 2014). *Mario Carpo,* in conversation with *Mathias Kohler* during the 2014 International Fabricate Conference, discusses the feedback loop process: *"The topic you were talking about, automatic feedback between the machine and the material it's working with or an intelligent machine that can interpret the resistance of the material, is the next step of digital craftsmanship"*. The machine becomes an extension of the artisan/designer, who has perceived and analyzed the physical properties of a material through his own hands (Carpo 2014). In this new context of production, design needs to negotiate traditional (top-down) decisions of form and function with this new (bottom-up) decision of materiality and making. A negotiation between digital design and digital craftsmanship that requires dynamic blueprints rather than static ones. "Dynamic Blueprints (Dubor and Diaz 2013)" offers a new tool for the designer to negotiate the materialisation of the project, where uncertainty, inaccuracy and unpredictability coming from the material and the fabrication process could be integrated in the design within predefined boundaries and logics, in accordance with the overall design goals.

1.2 Digital Negotiations in Wood Constructions

How can designers integrate this material feedback in the design and making of wood constructions? The technologies available today and the high level of integration between them allow to establish an intertwined logic among the various phases of the design and construction process. The unpredictability and the complexity that comes from the use of low-engineered materials such as wood and the fabrication set-up, needs to be managed establishing a virtual connection between digital and physical model. This connection can be materialized in the different phases of the design process using IoT protocol and various technologies such as 3D scanner, drones or VR devices that helps to create a feedback-loop logic among digital and physical models ensuring the materialization of the complex flow of information of the virtual space. Being able to control and manage the behaviour of the materials enhance the possibility to exploit the full potential of the computational design process without referring to industrialized material and codified tectonics. This means designing in accordance with the material and with machining tools defining a system of relations able to self-organize according to dynamic external inputs. The intertwined logic can have a relevance both in terms of the design process and shape generation and in the assembly and production of technological components. The use of this design methodology makes it possible to fabricate complex material systems for which it is difficult to predict the result through digital simulation due to the non-linear relationship between material, manufacturing tool and external parameters (e.g. ambient temperature and humidity) which makes it obsolete the use of digital manufacturing paths due to their lack of adaptability to changes in the production process (Dubor et al. 2016). Through the use of sensors, it is possible to adapt the parameters of the production process with respect to real values and to approximate the result obtained with respect to the digital model. The process experimented through the workshop highlights two fundamental aspects with respect to the interactive process: the possibility of transferring complex and non-linear material systems from the digital and virtual space to the physical one, and the result of which is not predictable through digital simulation and adaptability to the tolerances of the production process. Overcoming tolerances due to the relationship between material and production process turn out to be a fundamental aspect in the materialization of complex morphologies through robotic fabrication. The progressive accumulation of errors during production process can be eliminated by programming a computational system based on feedback loop logic, giving rise to adaptive assembly processes (Jeffers 2016; Dörfler et al. 2016; Wu and Kilian 2016; Schwartz et al. 2016).

2 Tolerance Management in Digital Fabrication: Case Studies

Following this thinking, the authors of this paper discuss specifically the management of tolerance as "an allowable amount of variation of a specified quantity, especially in the dimensions of a machine or part" inherent to large scale construction and anisotropic material such as wood. A series of project developed and constructed at IAAC are used as case studies of tolerance management in Digital Fabrication with different kind of wood. The first project "*Fusta Robotica*" (2015) overcome material and fabrication imprecision by integrating redundancy and tolerance in the design and by using "green" wood that would later on dry, twist and lock the overall shape into position. The Second project "*Digital Urban Orchard*" (2016) overcome the challenge of imprecision by dividing the construction in two separate phases: First production and construction of the raw wood structure; and in a second phase 3D scanning of the installed structure before manufacturing and assembly of the additional layers of construction (skin, pipes, furniture, etc.). The Third Projects "*Robotic Sawmill*" (2013) and "*Digital Woodcraft*" (2017) overcome the material unpredictability of wood logs by 3D scanning each piece before fabrication, integrating its very specific shape in the design and robotic fabrication process. Finally, the Fourth Project "*Adaptive Robotic Carving*" (2017), developed at the Bartlett School of Architecture in London, focuses on the adaptive training of a robotic fabrication system aimed toward the integration, within a design interface, of the instrumental knowledge necessary to deal with timber properties and behaviors, through a combination of sensor data and machine learning. The analysis of those four processes, in addition to the definition of the limits and potentialities of the design approach for each case, opens the debate on the role of technological experimentation in the post-digital era, characterized by the process information that includes digital computation, materials scanning and robotic fabrication. These case studies challenge the conventional link between drawing and construction, looking at new dynamic ways to design, towards "Dynamic Blue Print" capable to integrate the variety of property that a material such as wood could offer to digital construction.

2.1 "Fusta Robotica" and "Digital Urban Orchard"

Fusta Robòtica Pavilion[1] (Fig. 1) and Digital Urban Orchard[2] (Fig. 2) have been developed as part of the OTF 2015/2016, Open Thesis Fabrication, the Applied Research program whose objective is to design and fabricate a full-scale functional prototype to be implemented in urban public spaces. Material, functional, structural, and environmental criteria performance have been adopted to directly inform and materialize the computational design generation through robot-assisted fabrication and assembly processes. These two 1:1 scale wooden prototypes implement the methodological application of the mass-customization paradigm in architecture facing the issue of wood unpredictability in all the phases of the design process,

Fig. 1 IAAC, Fusta Ròbotica 2015. © Alexandre Dubor

[1] https://iaac.net/educational-programmes/postgraduate-open-thesis-fabrication/past-editions/fusta-robotica-otf-2015/.

[2] https://iaac.net/educational-programmes/postgraduate-open-thesis-fabrication/past-editions/digital-urban-orchard/.

Fig. 2 IAAC, Digital Urban Orchard 2016. © Andrea Quartara

from idea development to construction and assembly. They physically actualize two different agenda and they propose two different methodological approach to digital materiality in relation to wood properties.

2.2 Fusta Robotica: Design Against Material

At first, Fusta Robòtica Pavilion (Figliola and Dubor 2017), resulting from a collaboration between academic institution and industry, is a tectonic attempt to overcome the limits of building with Catalan wood, highly deformable hence unsuitable for construction. Fusta Robòtica has the virtue of being the first low-impact and zero-kilometre Spanish project that has applied robotic technology to Catalan wood. The Mediterranean pine timber solely used for palettes or biomass, due to its tendency to warp while drying, have been used here. The material provided by the industry, partner of the research project, is composed of wooden elements with a square cross-section and dimensions of 38 mm × 38 mm × 2000 mm. Parallel to a formal and tectonic exploration, the first phase of the project included an intense series of tests concerning the technological and material system. In this specific case, the analogical series of tests have been fundamentals to understand the behaviour of the material,

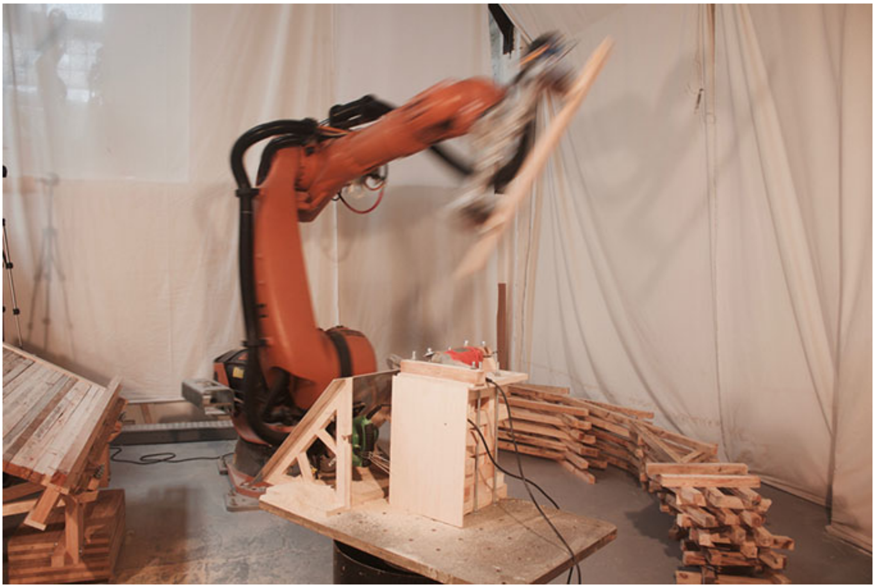

Fig. 3 Fusta Ròbotica: robotic fabrication process. © Andrea Quartara

exploring its mechanical and physical properties, and correctly inform the computational design process to ensure the feasibility of the project. Specifically, two areas of investigation were outlined: the first concerned the possibility of combining different digital fabrication strategies to design and materialize technological systems, the second one concerned the study of connection joints between the various technological units taking in consideration assembly logics. Through the experiments carried out on the material in accordance with the digital manufacturing method and the tools available (Fig. 3) (industrial robot KUKA KR 150-2 L110, circular saw and drill) it was possible to define some criticalities with respect to which to make informed design choices. Among these we can mention: the variation of the curvature following the drying process; the need to preserve the resistant section of the material so as not to damage the structural properties; the need to optimize the use of the material to reduce the structural weight; the min and max dimension of the work space in the robot room (1800 mm × 3600 mm). In relation to this, the design process has been optimized through a series of informed choices:

- Fabrication with straight green wood, knowing the wood will deform after assembly while drying;
- Redundant structure, composed of a multitude of small elements attached at least in three point, as to force element to stay straight while drying and as to "lock" the pieces in position- Nailed joints instead of milled joints to preserve the structural section of the components;

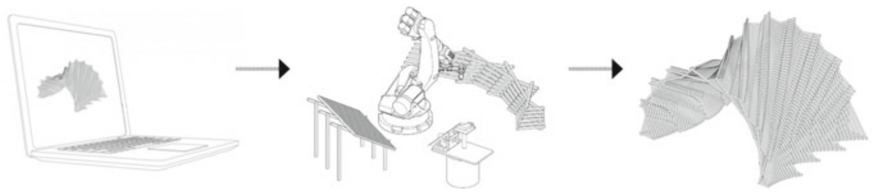

Fig. 4 Fusta Ròbotica: computational workflow from design to construction. © Ji Won Jun

– Discretization of the surface through the production of sections with a constant thickness whose dimensions can be traced back to 1800 mm × 3600 mm to be assembled manually.

Through this methodological approach (Fig. 4), the design is informed about the mechanical and structural properties of the material used as well as the tools involved in all the phases. The bottom-up method adopted allows to guarantee the feasibility and construction of the prototype and considers the material as an active agent and not as an imposed element to be considered in the final phase of the design process. Redundancy and tolerance are essential parameters both at (structural) design and fabrication stages. Fusta Ròbotica has demonstrated how the tectonic configuration can be the "tool" that helps to manage the tolerances of the low-engineered material used for the construction. In this case, the overall shape overcame the material properties in the design hierarchy.

2.3 "Digital Urban Orchard": Design with Tolerances

Moving forward, Digital Urban Orchard expresses a more detailed functional program: the interrelation of context, function, geometry and fabrication have been directly embedded within the computational design (Figliola 2017). The soilless cultivation system together with the setting of a new relational space can colonize Barcelona's rooftops, under the light of reducing the footprint of new built environments. The final shape has been selected out of a catalogue of options. The design of the pavilion has highlighted a further aspect regarding the applicability of structural wood systems in architectural practice: the control of formal generation through the parametric process and the possibility of customization offered by the robotic fabrication (Fig. 5), allows to overcome and expand, the concept of structure to that of an integrated system that manages to aggregate primary and secondary structure, systems and furnishings through specific morphological configurations. They result from an optimization process informed by maximum stick-length, range of possible angles to cut the stick edges as well as by different environmental analysis that made able the designers to correctly mediate between design and digital pro-

Fig. 5 Digital Urban Orchard 2016: robotic fabrication process. © Andrea Quartara

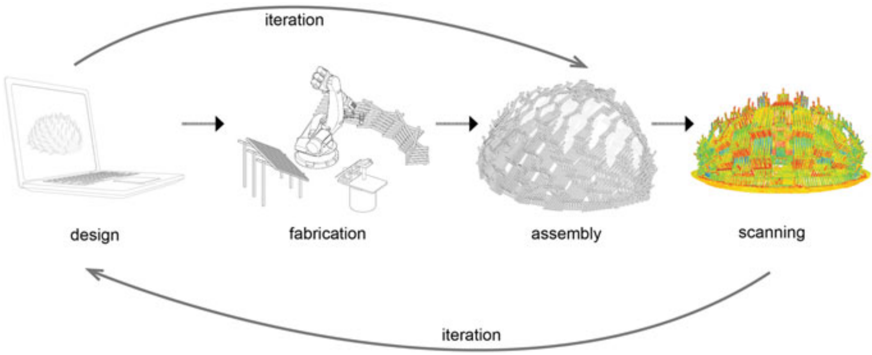

Fig. 6 Digital Urban Orchard 2016: design with tolerances. Computational workflow and 3D scanning process. © Angelo Figliola

cesses. Both constructions adopt the same structural principle: small size and square section wooden elements have been cut, placed and nailed in position one-by-one to create redundant structures. In particular, Digital Urban Orchard enriches the seamless design-to-fabrication process taking in account of manifold parameters, apart from the solely geometry. Hence, the previous structural pattern, generated by the sequence of main truss and structural stiffener, has been improved with hydroponic system supports, skin supports, and furniture. This was made possible thanks to gripper technology applied for multitasking process based on external tailored effectors.

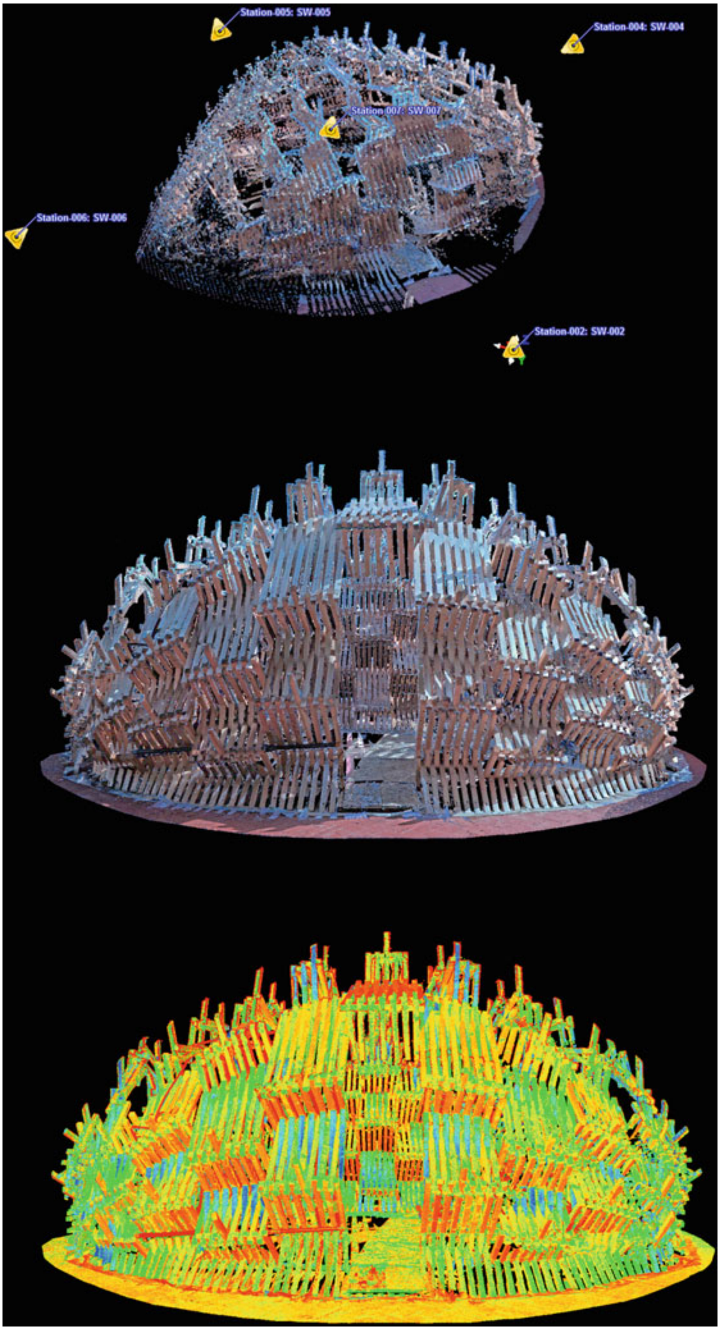

Fig. 7 Digital Urban Orchard 2016: scan of the overall wood structure allows to define the spatial coordinates of the anchor points of the skin overcoming the mismatch between digital (x, y, z) and physical (x1, y1, z1). © Angelo Figliola

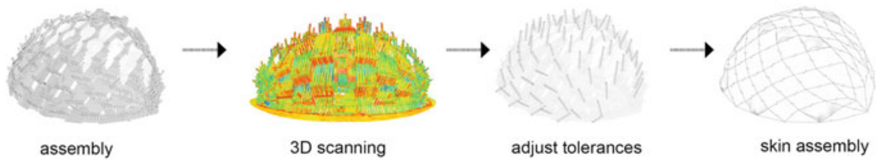

Fig. 8 Digital Urban Orchard 2016: design with tolerances. From assembly to scanning and skin assembly. © Angelo Figliola

The size of the robot-cell together with the custom-developed tools limits define some design constraints but, at the same time, they trigger the implementation of a cost and time-effective fabrication system. However, the pavilion present imprecisions coming from two phases of the production process: the robotic assembly (including a nailing process of the structural sections) and the in situ manual assembly where the tolerance is constantly increasing. Due to the difference between the digital model and the physical one, the major difficulties are in the integration between the main structural system and subsystems such as technological devices and the silicone skin. To overcome this problem and ensure the installation of the skin, a digital scanning process was used after the completion of the pavilion (Fig. 6). The scan of the overall wood structure allows to define the spatial coordinates of the anchor points of the skin overcoming the mismatch between digital (x, y, z) and physical (x1, y1, z1) (Fig. 7). The new model obtained by the scanning process allows to update the digital model and to inform the fabrication of the diagrid skin ensuring the correct installation (Fig. 8). These working prototypes lay the groundwork to further developments scaling up the construction process, allowing a high-level of mass-customization and cutting down the manufacture costs. Digital Urban Orchard introduces the theme of communication between the different design phases to overcome the problems deriving from the large tolerances. The tolerances that accumulate during the various phases of the project, from manufacturing to assembly of components, are managed through a feedback loop process between the in situ assembly phase and the installation of the technological subsystems thanks to the 3D scanning of the overall shape. The material properties overcame the overall design in the design hierarchy. Other strategies can be applied to overcome this problem: interlocking connection systems can be carved between adjacent sticks ensuring the overall structure alignment at every stage of production; AR technologies to verify the correspondence between digital and physical model during the robotic and the manual assembly process.

2.4 "Digital Woodcraft" and "Robotic Sawmill": Design and Fabrication Strategies Based on Natural Wood Characteristics

One of the research lines explored at IAAC, concerns the use of natural and low engineered material as an active agent in the design processes, thanks to the innovative technologies of computation and digital fabrication that allow managing the morphological and constructive complexity. The first experimentation in this regard took place during the 2013 seminar, *Robotic Sawmill*, exploring the potential offered by the robotic manufacture in the processing of wooden logs for the realization of a prototype 1:1 scale of coverage for a shelter to be built near the Campus of Valldaura. One of the peculiarities of the seminar is the use of a chainsaw, an end-effector that recalls the analog fabrication/production processes of the trunks and of the structural connections. Equipping the robotic arm with an analog tool means implementing the potential offered by traditional techniques making it possible to materialize the complexity of digital space derived from the lack of homogeneity of the material and its tolerances (Fig. 9). The construction of the joints was preceded by the scanning of the trunks and the development of a digital workflow to facilitate the digital reconstruction of the physical component (Fig. 10). Parametric design is the instrument by which the digital chain is synthesized, which includes data acquisition, the design of joints and connections as well as the definition of the parameters necessary for the manufacture and processing of components that integrate the specificities of the scanned material (Fig. 11). The Digital WoodCraft project,[3] a thesis developed within the Master in Advanced Architecture of IAAC, MAA 2016/2017, represents an evolution of the research line described above. Specifically, the thesis wants to explores the tectonic and performative potentials deriving from the use of natural and non-engineered material, such as tree trunks, in the design processes. Experimentation is inspired by the observation of the natural world as opposed to the artificial/industrial one: the morphological complexity that can be found in the natural forms of trees able to guarantee excellent structural performance is standardized through an industrialized production process aimed at eliminating imperfections and the inhomogeneities that characterize the material for the production of the final product.

Some of the physical and mechanical properties that characterize the wood are eliminated through the discretization and homogenization of the component with consequent waste of energy and waste of material. In this regard, the research aims to introduce and test a computational workflow that involves the use of innovative technologies such as 3D photogrammetric scanning, parametric modeling and robotic fabrication in order to collect, analyze and produce complex and customized models and prototypes. The design process is based on the analysis and cataloging of wooden logs in order to identify the physical and mechanical characteristics of the components to be used as parameters of the design process (Fig. 12). Thanks to the computational workflow, the geometric characteristics and the mechanical properties

[3] http://www.iaacblog.com/programs/digital-woodcraft/.

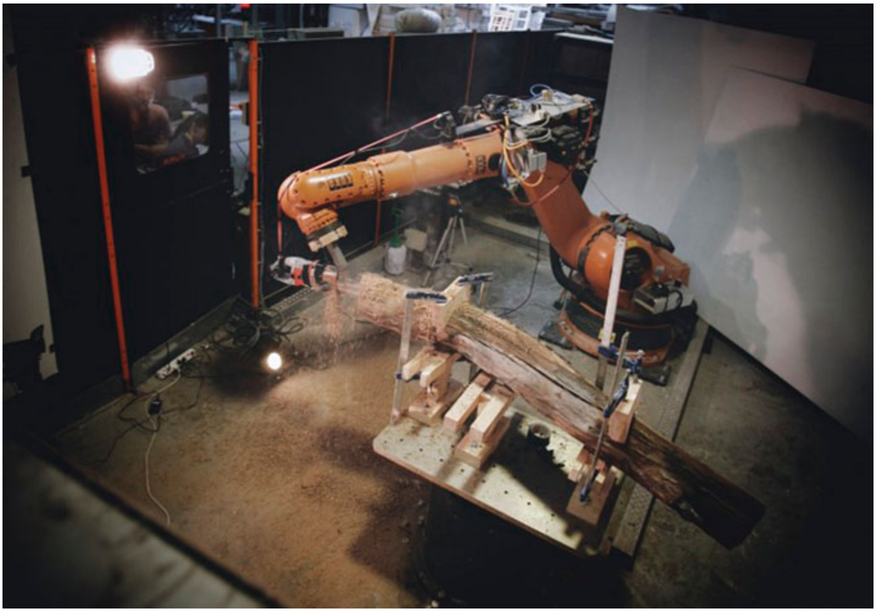

Fig. 9 How to teach a robot to use a chainsaw?|Robotic Fabrication Workshop @ IaaC|2013. © Vicente Gasco

of the material become design parameters that contribute to the formation of the final morphological solution. The direct connection between the log scan, the digital mesh and the robotic manufacturing process made it possible to realize complex structural joints and joints by controlling the tolerances derived from the use of natural and non-engineered material. Node manufacturing was carried out using a subtractive cnc milling process exploiting the potential offered by 3D photogrammetric scanning in the positioning of the component within the work area and the calibration of the tools used for the production process (Fig. 13). With the implementation of traditional workflows, industrialized components and standard prefabrication can be replaced and implemented by unique technological systems that cannot be reproduced in series, allowing a more efficient use of materials and exploiting the unique structural and morphological characteristics of the trees and natural materials. With the projects Digital Woodcraft and Robotic Sawmill another variable is introduced. Instead of using industrialized and engineered material, the experimentation keeps in consideration the natural material as the driver of the design choices.

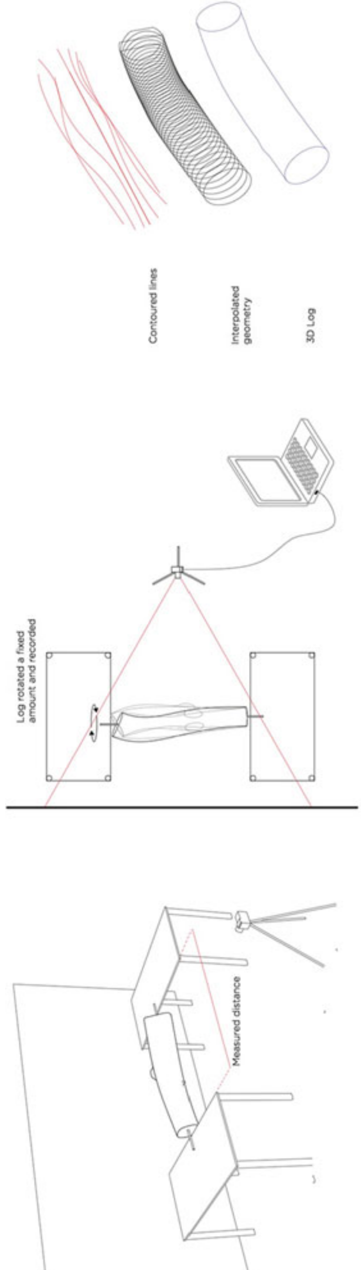

Fig. 10 Scanning Log Geometry|Robotic Fabrication Workshop @ IaaC|2013. © Vicente Gasco

Fig. 11 Fabrication of 1:1 scale prototypes of timber joints with a chainsaw-equipped robot|Robotic Fabrication Workshop @ IaaC|2013. © Vicente Gasco

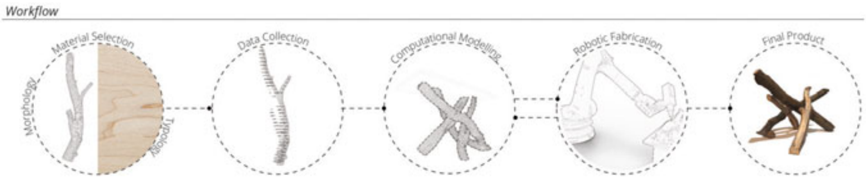

Fig. 12 Digital WoodCraft|Design and fabrication strategies based on natural wood characteristics. © Nikos Argyros

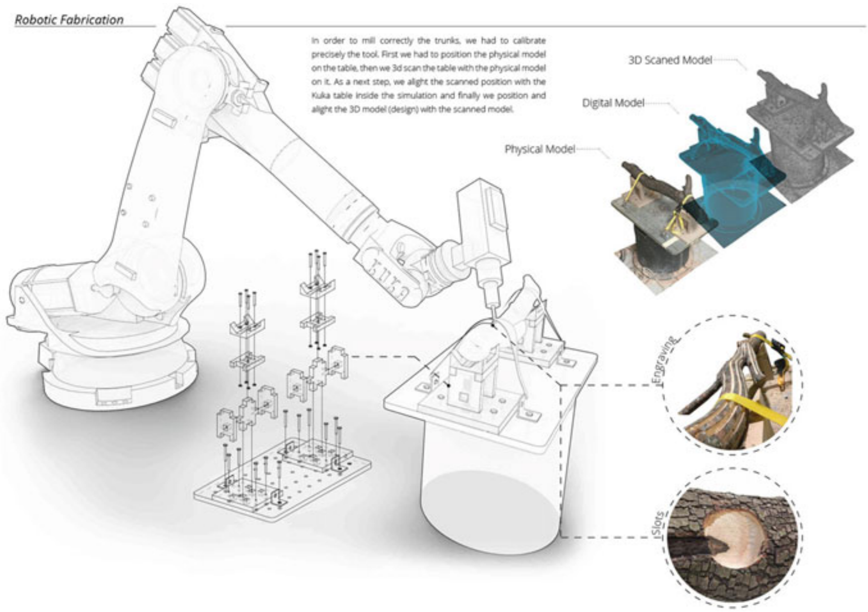

Fig. 13 Digital WoodCraft|Robotic fabrication process. © Nikos Argyros

3 Digital Craftsmanship

Within current design practices, the separation between the act of design and making requires the standardization of fabrication tools and materials, significantly limiting the range of design solutions available. Can we explore novel design opportunities extending the range of manufacturing processes available to designers through the integration of material and tool affordances as process drivers? If the fabrication process is not completely predetermined in front of the computer screen, leaving room for interpretation and exploration, the quality of the final outcome, because only partially anticipated, is continuously at risk and significantly depends on the capability of the fabrication framework to accommodate changes in terms of design, tools and materials. The definition of "*craftsmanship*" provided by D. Pye in his book "*The Nature and Art of Workmanship*" (Pye 1978), is particularly suited to this novel fabrication paradigm (Kolarevic and Klinger 2008): *"Craftsmanship…means simply workmanship using any kind of technique or apparatus, in which the quality of the result is not predetermined, but depends on the judgement, dexterity and care which the maker exercises as he works. The essential idea is that the quality of the result is continually at risk during the process of making."*. While the construction industry is one of most adverse to changes and risks, within this notion of craftsmanship, "*risk*" becomes a positive force that drives the making of an artefact. Digital fabrication tools could allow to embed this "*risk*" component through carefully articulated design explorations and lead to the discovery of unanticipated formal configurations or performance behaviours. For each task approached by a craftsman, there are different evaluation criteria, for instance, aesthetic quality or cost efficiency, technical procedures and material consideration involved that *"operate as positive forces for action not determinants of outcome*" (Keller and Keller 1993). The experience knowledge of the craftsman, accumulated through years of practice, allow to address these "*dimensions*" in order to create a new original plan of action. However, as discussed by Sharif and Gentry (2015), this preconception only initiates the task, while the "*the design concept evolves concurrent with the craftsman's act of production and the received feedback from the evaluation of material and objective conditions of the work*".

3.1 "Adaptive Robotic Carving": Digital Craftsmanship and Machine Learning

The project "*Adaptive Robotic Carving*", developed at the Bartlett School of Architecture as part of the InnoChain research network, focuses on the integration of materials performance within design to manufacturing workflows combining sensor data, machine learning and robotic manufacturing (Brugnaro and Hanna 2017). The project examines manufacturing processes as moments of discovery, where the digital model is constantly tuned as the fabrication progresses and designers are able to curate

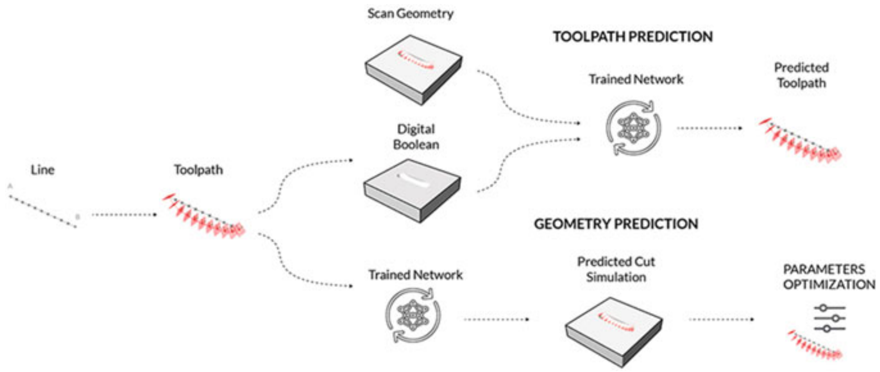

Fig. 14 The encapsulation of instrumental knowledge through the training process is aimed towards its integration within a design interface that allows to move back and forth between the prediction of carved geometries and generation of robotic toolpaths. © Giulio Brugnaro

their own custom design to manufacturing workflow, integrating real-world material behaviors to take better-informed design decisions, rather than working within a standard CAM framework, which usually describes the workpiece as a block of a generic non-material (Fure 2011). Focusing on subtractive manufacturing with timber, the technical core of the research questions whether is possible to use real-world fabrication data, collected both by human experts and autonomous robotic sessions, to achieve a more accurate geometrical prediction of non-standard tools operations on a specific wood species, and, conversely, if it's possible to reconstruct backwards the robotic toolpath that generated a given carved geometry (Fig. 14). To achieve this, the developed methods present a series of training procedures for a robotic fabrication system where the instrumental and material knowledge of skilled human craftsman is captured, transferred, robotically augmented and finally integrated into an interface that make this knowledge available to the designer. The sensor data, collected in datasets, are used to feed a machine learning procedure to extract correlations between the fabrication parameters and their material outcomes and use such knowledge to inform future robotic fabrication tasks with a similar set of wood species and carving tools (Fig. 15). In the specific, the robotic training methods are structured around three main stages: (1) Recording, (2) Learning (3) Fabrication. The goal of the recording stage is to collect sensor data and create a library of fabrication datasets. During each recording session, a system of motion capture cameras is used to track with high degree of precision the position and orientation of clusters of reflective markers applied on the carving tool, reconstructing it in real-time in the digital design environment. The combination of such methods with a force feedback sensor allows to record fabrication datasets simultaneously with the performing of the carving operation. In addition, after the recording session, a digital scan of each training board is generated through photogrammetric reconstruction. Each cut is analysed through different parameters such as tool/workpiece angle, tool/grain direction angle, force feedback, feed rate, target cut depth, target cut length and the

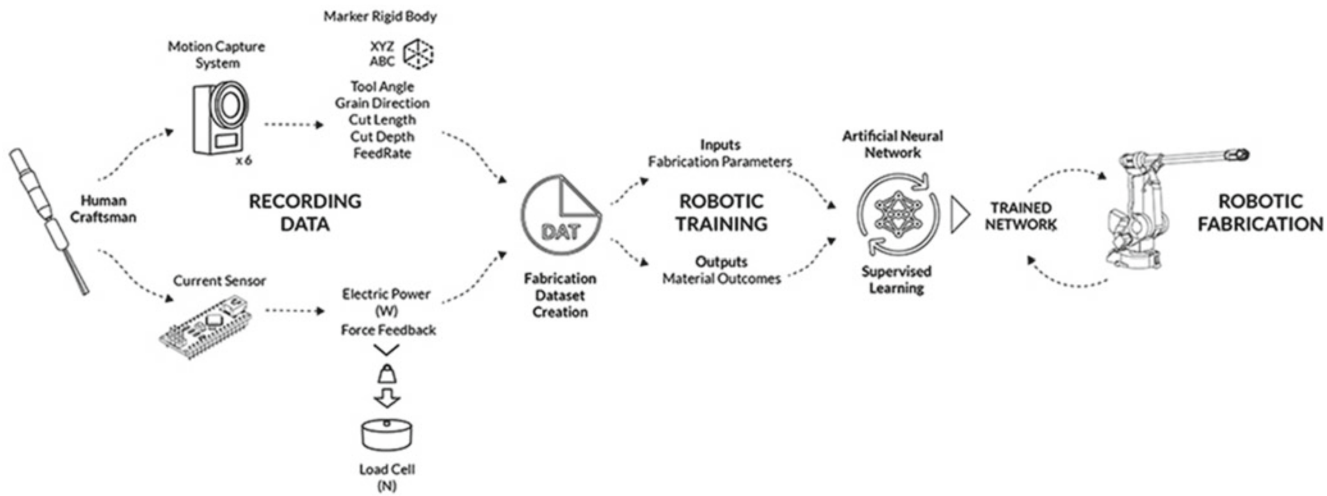

Fig. 15 The overall training process is articulated in three sequential stages (recording, learning, fabrication) focused around the transfer of instrumental knowledge from the domain of human craftsmanship to robotic manufacturing. © Giulio Brugnaro

Fig. 16 During the fabrication stage, the robotic toolpath is optimized to match the original design intention with tool affordances and material properties, such as the wood grain directionality. © Giulio Brugnaro

Fig. 17 The trained system could be used to predict combinations of multiple cuts to generate specific patterns on the carved surfaces. © Giulio Brugnaro

material outcome that these generate measured in the length, width and depth of the cut. Following the human demonstration, the carving dataset is consolidated through autonomous robotic fabrication sessions aimed to collect more data to improve the training performances through a finely interpolated collection of cuts generated by sets of fabrication parameters within the operational range defined by the skilled craftsman. In the next step, the aim of the learning stage is to extract meaningful correlations in the recorded data, namely between the fabrication parameters and their material outcomes, and use these to inform, in a new "unseen" configuration, the robotic fabrication process. This implies the extraction of the instrumental knowledge present in the dataset into a transferable and usable design tool through a supervised machine learning process. The selected computational approach is an Artificial Neural Network (ANN), which, loosely inspired by its biological equivalent, could be described as a layered and interconnected network of "neurons" able to "*process information by their dynamic state response to external inputs*" (Hecht-Nielsen 1990). The network topology not only determines the performance of the system but also needs to be configured in terms of inputs and outputs considering the intended use of the trained network in a practical application during the fabrication stage (Fig. 16). For instance, the learning objective could be structured to predict the simulation of a subtractive operation from a user-defined toolpath and a series of fabrication parameters, or conversely, generate a robotic toolpath out of a carved geometry obtained from a 3D scanned element. While conventional digital Boolean operations results insufficient in calculating the result of subtractive operations with non-standard tools and heterogeneous materials, the trained network provides the opportunity to explore design solutions through a more accurate simulation that takes into consideration specific tool affordances and material properties such as the wood grain direction (Fig. 17). Furthermore, the network prediction allows to optimize individual fabrication parameters to increase the efficiency of the process measured through the material removal volume or fabrication speed. For such reasons, the project suggests the potential of machine learning strategies for the customization of design to manufacturing workflows which can be flexibly trained according to different design intentions and material performances, through the extraction of human tacit knowledge and its integration within a simulation framework.

4 Conclusions

The series of design strategies presented in this chapter address the issue of tolerance control derived from the use of non-homogeneous material, such as timber, and how its latent material agency can be exploited as an active driver for design processes, instead of being conceived as a passive receiver of previously defined design choices. The different approaches could be summarized as follows:

- **Fusta Robòtica**: Design in contraposition the material through specific morphological configurations that overcomes the material's unpredictability. Analogue testing is propaedeutic to understanding the material properties, and consequently to extract rules with which to construct the digital model and overcome materials imperfection.
- **Digital Urban Orchard**: Design negotiation connecting different phases of the design process, utilizing communication protocols based on feedback loops between design and construction. Through a scanning process and a digital reconstruction of the physical prototype, it's possible to overcome tolerances derived from the material used and the robotic fabrication process. Based on the method-

ology described above, a perfect integration between technological systems is ensured, taking into account the inhomogeneity of wood, and without forcing the final shape in contraposition to the material properties.

Robotic Sawmill: Design in accordance with material's heterogeneity, the material becomes an active agent of the design process. The methodology is based on the precise digital reconstruction of the physical component and its physical and mechanical properties that allows to design taking into account the tolerances that derive from the non-homogeneity of the material. Material properties as active agent in the design process.

- **Adaptive Robotic Carving**: Integration of material and tool affordances as process drivers through the training of a robotic fabrication system specifically tuned to operate within a selected fabrication and material domain. The trained system, based on sensor data collected during a series of recording sessions, has been used to provide an accurate prediction/simulation of the carving operations and explore multiple material solutions in terms of carved geometries and textures marks, before moving to the actual fabrication stage. Such encapsulation of instrumental and material knowledge into a design interface allowed, not only an effective geometric evaluation, but also provided the designer with an understanding of the outcome generated by specific fabrication parameters and material properties, such as the influence of the grain directionality in the actual carved shape.

In the light of the presented projects, the integration of material information within advanced robotic fabrication opens new opportunities in the design and making of wood construction. The need for tolerance and adaptation to the wood's unpredictability has led the design to fabrication to integrate more sensors and be more flexible towards streams of feedback information. As shown in the presented examples, the digitized flow of information from the material and fabrication process can inform the design before, during or after the construction process, leading to a series of novel design approaches integrating tolerance and unpredictability at various degrees.

In this Cyber Physical Making context, Dynamic Blueprints offers a new tool for designer to negotiate the materialisation of the project, while the implementation of machine learning strategies offers the possibility for robots to play a stronger, active, role in the design and making process. With such technological advances, the concept of craftsmanship has the opportunity to be re-integrated within the industrial fabrication process, such as robotic and digital ones, towards a Digital Craftsmanship capable of integrating wood properties in their full complexity (Fig. 18).

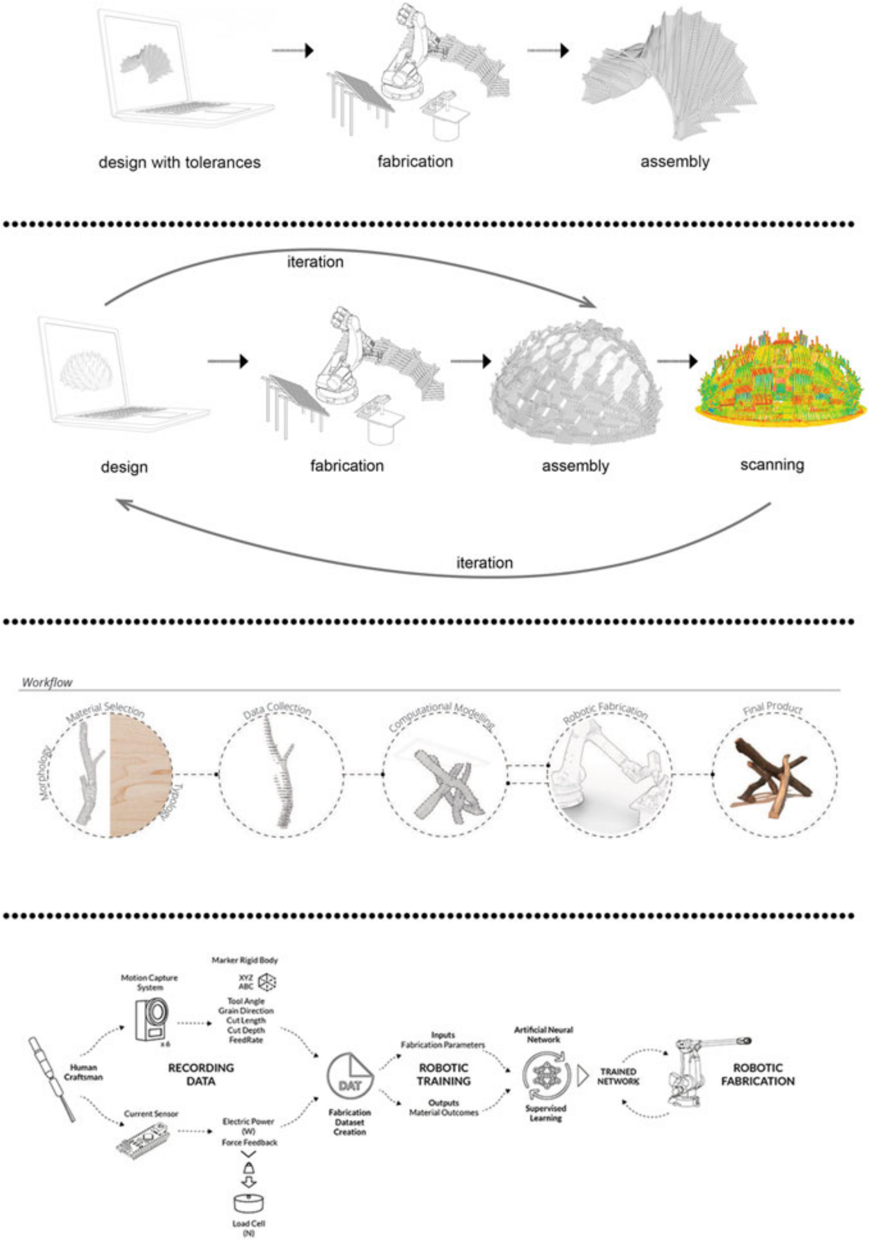

Fig. 18 Summary of design strategies proposed through the narrative of case studies. © Angelo Figliola

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