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Modelling A Complex Fabrication System

New design tools for doubly curved metal surfaces fabricated using the English Wheel

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Standard industrialization and numeration models fail to translate the richness and complexity of traditional crafts into the making of the architectural elements, which excludes them from the industry. This paper introduces a new way of modelling a complex craft fabrication method, namely the English Wheel, that is based on the creation of a cyber-physical system. The cyber-physical system connects a robotic arm and an artificial neural network. The robot arm controls the movement of a metal sheet through the English wheel to achieve desired geometries according to toolpaths and predicted deformations specified by the neural network. The method is demonstrated through the making of 1:1 design probes of doubly curved metal surfaces.

Keywords: Digital craft, metal forming, doubly curved surfaces, robotic fabrication, neural networks, cyber-physical system

INTRODUCTION

The building industry, since the Renaissance, has been based on the notion of control through drawing. Architectural design is seen as a strictly intellectual activity, detached from the manual aspects of making and building (Hill 2005). Design concepts are expressed through drawings, from initial sketches to standardized blueprints. The nature of information carried by these drawings has drastically changed in the last decades with the democratization of CAD/CAM, expanding drawing notations into holistic BIM models, or even near-zero-tolerance models. This revolution in the digital fabrication by the advent of Industry 4.0 has been essential in making manufacturing more efficient, however it has not questioned the act of design; it has not reconciled the architect back with making. In fact, the current design paradigm is a 2-step linear process: Design through drawing, then pushing of numerical data into manufacturing. This design workflow is segmented across the industry between architects and fabrication specialists (Callicott 2005). More often than not, the design space is dictated by the machine dexterity and morpho space of the manufacturing technique, and geometries that are hard to discretize are swapped for simpler ones. In short, we cannot build what cannot be previously specifically drawn (Carpo 2011).

This paper suggests that this linear design-to-production file-to-factory organization of the contemporary architectural process represents a missed opportunity in terms of design possibilities: we are leaving behind ‘crafty’ fabrication processes that are
resisting numeration because of their complex nature, and in doing so also leave behind productive methods of creating certain shapes and forms. The design workflow described in this paper exploits both artificial intelligence and robotic fabrication. The fabrication model is continuously evolving, and is able to account for, and learn from emergences during the manufacturing process (Sharif and Gentry 2015). It aims at exploiting the advantages of both crafts and robotic processes by implementing a cyber physical system, in an aim to bring back the millennial act of design-through-making, from Homo Faber to Robot Faber (Figure 1).

THE ENGLISH WHEEL
This research focuses on the English Wheel as an example of a traditional craft that is particularly relevant to the production of architectural elements. Known as a tool mastered by skilled panel beaters to make doubly curved car fenders out of metal sheets, it is composed of two wheels, an upper flat wheel, and a crowned bottom wheel that sits on top of a threaded rod used to control the distance between the two wheel, and thus the pressure of the forming. By rolling a sheet of metal between the two wheels, back and forth in a zig-zag fashion (we will refer to this as tracking pattern), the material is stretched and thus forced out of plane, producing a doubly curved surface. Multiple passes, and denser tracking patterns, increase the amplitude of the curvatures produced. Cross wheeling produces a more even curvature in both directions, and it is also possible to flip the piece to produce hyperbolic surfaces. The wheel also comes with a set of 5 crowned wheels with different curvatures, and thus different contact areas that work the sheet. The limit with the English Wheel as we know it is that its mastering requires years of skill honing, and even then, a craftsman always needs to have a pre-defined mould against which to test the piece while making it: not two pieces made on the English Wheel will ever be identical, and they do take an extensive amount of labour and skill to be made.

This is where envisioning a Robotic English Wheel process might be of use: A robot is capable of repetitive execution of the same piece, but is also able to produce a large number of bespoke pieces with no additional overhead. It is capable of applying more pressure than a human thus producing the piece in less passes, and time. This increased pressure of forming leaves behind a tracking pattern trail unique to Robotic English Wheeling, and that has the potential of becoming an additional aesthetic element of design and surface expression of the doubly curved sheet, alongside its geometry (figure 2).

By discovering and modelling the relationship between tracking pattern and curvature, the Robotic
English Wheel can unlock new possibilities for doubly curved surfaces in architecture, in a flexible and sustainable way. In general, doubly curved surfaces are the least desired in architectural façade construction, because of the difficulty and cost involved in the making of large number of custom panels. They are either approximated to flat tassels, or discretized into developable singly curved panels. In very few cases are few panels left doubly curved. They can be custom produced, without mould, either by techniques like on-site cold bending such as Gehry Partners’ Experience Music Project in Seattle, which is less costly but yields poor precision (tolerances estimated to be larger than 2mm), or prefabricated using multi-point stretch forming such as Zaha Hadid Architects’ Dongdaemun Design Plaza, a method that requires expensive and custom machinery (an adaptable die forming mould), the average cost of a panel in that project being 260$, claimed lower than the 3000-7000$ range per square meter that other forming methods would cost (Lee and Kim 2012). The usage of the Robotic English Wheel immediately expands the design possibilities of freeform doubly curved surfaces in architecture, without mould or extravagant machinery.

**CYBER-PHYSICAL CONCEPTUAL FRAME**

In the status quo, architects are concerned with structure and behaviour models of their artefacts after fabrication and assembly, leaving the industrialized production process to other experts. A design-through-making approach promotes the understanding of the relationship between the material and its behaviour during the fabrication process as a design possibility (Nicholas and Tamke 2012). This is the key to establishing design control over geometries made with the English Wheel. Early experiments with Robotic English Wheeling at Zahner created tracking patterns for the robot to follow based on the Gaussian curvature analysis of a given shape, however modelling shapes attainable with the English wheel using particle spring system proved to be of insufficient precision [1].

Using empirical measurements of our first in-house forming experiments, it was discovered that the forming entails both an elastic and a plastic deformation, and that the accumulation of passes on different directions is non-linear. Thus the relationship between the tracking pattern and resulting geometry heavily relied on the metal sheet material properties. This information is hard to calibrate on Kang-
roo for Grasshopper, and using a specialized FEA software represented a discontinuity in the design process, since it would require to leave the Rhino environment. Therefore, in order to model this complex fabrication method, a new approach that would account for, and learn from, the complexities and emergences that happen during the fabrication process needed to be developed. By re-creating the craftsman’s cognitive system of design-through-making and constant dialogue between brain, body, tool and artefact, this research builds a continuously evolving fabrication model through teaching the Robot the craft of the English Wheel using Artificial Intelligence.

The method borrows from the principles of Cybernetics established by Weiner (1948): A network linking the analogue to the digital, where physical processes affect computations, allowing for control through feedback, and continuous information exchange. We call this a Cyber-physical Robot Faber. The robot is seen not only as a manufacturing tool, but as a first-person design agent aware of the material impacts and causal effects of fabrication actions, in the same way as a craftsman would be; through interaction, constructive memory and situatedness (Gero 2017). Differently from Brugnaro et. Al. (2016), the suggested approach goes beyond designing a closed mathematical system able to solve the physical problem at every iterations. It proposes designing an ever growing brain that acquires knowledge at every iteration, and that could develop a digital intuition as to Robotic English Wheeling.

**METHOD**

The Cyber-physical setup in place, as shown in Figure 3, is composed of a Dinosaurier English Wheel placed in front of an ABB IRB1600 robot arm, with a Kinect scanner ensuring the link between analogue and digital. It has been developed over multiple stages elaborated below.

**Fabrication physical setup**

The first stage consisted of tuning the fabrication parameters of the robotic system. A custom-made end effector composed of a 10cm x 5cm L-profile metal plate with a clamp was attached to the 6-axis Robot arm to enable it to hold the sheets. The robot pushes the sheet on the English Wheel placed before it. Understanding machine dexterity parameters was crucial to the developing of a successful motion framework. Initial experiments consisted of applying a planar tracking pattern to a 25x25cm sheet of 1.5mm thick aluminium. The English Wheel was placed fac-
ing 0° of axis 1, so to limit motion to the shoulder (axis 2) and elbow (axis 3) for providing the main push, and a rotation of the forearm (axis 4) while keeping a steady wrist. At a very small pressure, axis 4 reached limits of torque. The solution was to introduce a minimal slope into the pattern. This created space for the joint to dissipate the torque as it turns to start the next segment of the pattern. The forming of the sheets then became successful.

**Feedback loop setup**

The second stage consisted of implementing a feedback loop between the physical prototypes and their digital representation. This is necessary to enable the robot to do multiple passes over the same piece, since after the first pass is done at high pressure, the sheet is no longer flat and the motion toolpath has to be adapted in order to avoid physical damage. After forming the robot moves the sheet into scanning position, where the Kinect transfers the point cloud to the computer. The sheet geometry is thus iteratively updated in the design environment and the toolpath for the next pass is precisely generated, allowing the robot motion to follow the new geometry of the sheet (Figure 4). The usage of infrared scanning capacity of the Kinect is crucial to the success of the feedback loop, since it avoids the creation of occlusions and noise due to light reflections over the aluminium surface.

**Neural network computational setup**

The third stage consisted of building an Artificial Neural Network that specifies the forming instructions necessary to create a physical curved panel geometry. Using a selection of the produced pieces, a workflow was implemented to translate the geometries into false colour images representing the extents of variation of the panel in x, y, and z. That was fed as input to the network. The training output was a series of binary images representing the tracking pattern of every piece. Since the dataset was composed of relatively few pieces, it was augmented to 320 tensors by rotating every piece 90, 180, and 270 degrees, as well as dividing the panels into smaller pieces. A Fully Convolutional Network architecture, that is usually used in semantic image segmentation (Long et al. 2015), was used to give a dense pixel per pixel prediction of the tracking pattern given a certain geometry. The network has a convolutional autoencoder hourglass architecture: 3 downsampling convolutional layers, followed by 3 upsampling convolutional layers, and a final layer encoding the output images. The training was done on PyCharm using Keras with Tensorflow backend.

**RESULTS**

**Design probes**

The first set of design probes (Figure 5 left) consisted of 25x25cm squares. Their main goal was to isolate the fabrication parameters of the English Wheel in order to gain an initial understanding of the process. The results show that varying the frequency of the tracking pattern zigzag (from 5mm to 35mm spacing) is indirectly proportional to the curvature produced. Additionally, also the location and orientation of the tracking pattern affects the curvature. Leaving a gap away from the border is key to obtaining a positive gaussian curvature, while a non machined area surrounded by machined areas creates a hyperbolic surface. The curvature is produced in an orientation perpendicular to the machining polyline.

The second set of design probes (Figure 5 center) consisted of 25x25cm squares as well as . Their goal
was to prove the success of the feedback loop and to explore multiple pass forming. The results show that multiple passes of the same tracking pattern amplified the curvature. Cross wheeling a second pattern in the same orientation creates a more regular synclastic curvature. Flipping the orientation of the piece in the second pass and wheeling a second pattern yielded the most interesting hyperbolic results.

The third set of design probes (Figure 5 right) broke free from the regular square onto larger less regular polygons. Their goal was to explore different combinations and overlaying of patterns in different orientations and exploring the design space of geometric compositions that the English Wheel could produce.

**Computational Workflow**

The network was successful in translating geometry to tracking pattern. The predictions over the training dataset output had a precision rate of 94% and a precision rate of 75% over the test dataset (Figure 6). This slight decrease in performance between the two is a mark of slight overfitting due to the limited diversity of training samples. However, considering that the toolpath has to be post-processed in Grasshopper in order to ensure fabrication feasibility and collision avoidance of the robot using the wheel, this is acceptable in our case. Moreover, this problem will be avoided in the future by using a more diverse learning dataset, as more panels are produced using this method.

**1:1 Assembly demonstrator**

A noteworthy aspect of the design probes is their immediate geometric rigidization due to their shape. Pieces formed with double curvature had a significantly higher resistance to deflection, and therefore a higher bending stiffness, than their flat counterparts, when submitted to a load applied perpendicular to the surface (Figure 7). To demonstrate the associated structural opportunities, an assembly of 11 panels was made (130x40x90cm approx). Panels on the same side of the skin were connected at points using lasercut polyester joints in order to transfer loads between panels. The two sides of the skin were connected with 23 custom made aluminium threaded...
Figure 6
Neural Network predictions (bottom) compared to true values (top)

rods, that allowed for a varied structural depth in the composition. The assembly (Figures 8,9) is successfully self-standing despite its slanting geometry and very light weight (approx. 10kg).

Figure 7
Deflection under 10kg load of an aluminum sheet flat (top) and doubly curved after forming (bottom)

CONCLUSIONS
The cyber-physical setup developed in this research has demonstrated, through the production of design probes, the potentials of the English Wheel coupled with advanced interdisciplinary computational methods, as an easy, fast and cheap method of fabricating bespoke doubly curved metal surfaces. The method expands the repertoire of surfaces achievable via efficient manufacturing, and without complex discretization pre-processing. The fabricated pieces also illustrate an aesthetic quality that is unique to Robotic English Wheeling, that has the potential to become an element of design and composition, rather than just a fabrication mark only achievable through handcraft.

Further refinement of the neural network is needed for a better control of the relationship between designed geometry and machining toolpath. For instance, a larger training dataset would contribute to a better neural network training process,
Figure 8
11 panel assembly demonstrator, front and top view
Figure 9
11 panel assembly demonstrator, close-up details
and thus better results. Further potential also lies in integrating the structural performance of certain geometries at the neural network stage in order to achieve better performance-based design. This introduces a novel way of thinking of sheet metal in architecture not just as a mere cladding, but as lightweight, and thin self-supported structures, that consider both structural and programmatic performances.

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**Image Credits**

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