Foldable Responsive Surfaces

Two Design Studios with a Comprehensive Workflow

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The adopted methodology was defined by a multidisciplinary team with a strong believe in the efficiency of learning-by-doing design studios which resulted in an experimental digital workflow to create responsive surfaces based on the geometry of Rigid Origami. The workflow comprehends all the matters related to the creation of such surfaces, from the conception and definition of the surface's design using Rigid Origami’s geometry, passing through the virtual simulation of the movement, digital fabrication and material's choice, then the mechanics behind the movement, interaction programming, and the assembly of it all in real scale prototypes.

**Keywords:** Design Studio, Learning-by-doing, Rigid Origami Geometry, Responsive Surfaces, Parametric Design, Digital Fabrication

**INTRODUCTION**

Traditional architecture design process starts from principles that architectural structures are singular and fixed, statically integrated on their environment or context and unable to adjust as time passes and needs change. The emergent design processes and technologies require more than this, interactive structures as part of an environment or context with the ability to transform themselves as necessity comes. Consequently, architecture has witnessed a remarkable amount of experimentation with ways of using digitally managed information - be it geometric, structural, kinetic, mechanical - to rethink how buildings are designed (Marbel, 2012). The digital workflows are empowering the opportunity to increase computing capacity. This paradigm shift opened up opportunities for making objects and spaces more responsive, sensitive, and smarter.

In this sense we advocate that architecture should be able to evolve and adapt to user’s needs through the use of architectural elements that can change their geometry in order to change space, interact and communicate with its inhabitants.

Consequently the role of the architect gets a broader range. When designing an interactive structure, it is necessary to anticipate several issues related to the structure's response to the interaction with the users, the mechanisms that will put the structures in
The outcome of kinetic design is not a singular form, but a process from which a range of forms manifest over time. This requires designers to consider the design of control system and data input, as well as the design of the physical components” (Moloney, 2011).

In this sense teams from La Sapienza, Rome, and ISCTE-IUL, Lisbon, got together to create a Summer School where this paradigm could be tested through a comprehensive workflow that would ultimately lead to the creation of foldable responsive surfaces prototypes.

Both teams, Rome and Lisbon, have ongoing researches on Origami Surfaces and their kinetic capabilities so the main subject was easily decided, in fact it was the main reason for both Universities to get together in the first place.

The primary objective of the Design studios was to experiment on the kinetic potential of Origami Surfaces testing different geometries and their inherent movements, rigid materials and digital fabrication techniques, origami geometry parametric simulation, ways to actuate movement and interactions and at the same time teach all this to the participants in only two weeks.

In order to do so a multidisciplinary team composed by architects, computer scientists and electronic engineers got together to define the process for the design studios and the necessary lectures and masterclasses in order to provide participants with the theoretical and instrumental skills necessary to deal with the design and construction of responsive surfaces.

The first design studio was called Responsive Surfaces and was held in Rome at La Sapienza in September 2015 with students from Italy, Belgium, Iran, India and Romania, most of them were architects and PhD students. The 13 students were divided in four groups of 3 or 4 people by the tutors that had in consideration each person’s knowledge on parametric design and digital fabrication.

The second summer school was called Surfaces In-Play and was held in Lisbon at ISCTE-IUL in July 2016. At this Summer School there were 10 students from Portugal, Italy, Greece, Belgium, Bulgaria, Canada and Brazil. The students were architects, architecture and sculpture university teachers, PhD and architecture students and were divided in five groups.

On both Summer Schools there was a real concern about giving the participants insight about all the subjects at stake. The designer does not have to be an expert on all the fields involved but has to be in possession of some knowledge about those fields in order to be able to create transformable objects that respond to the intended purpose and integrate on them all the mechanical and computational features. The designer is the central point, the pivot, through which the involved areas get to be an integral part of the architectural object.

“Digital age is forging a very different kind of architecture and, at the same time, providing unprecedented opportunities for the significant redefinition of the architect’s role in the production of buildings” (Kolarevic, 2003).

In this sense the Design Studios’ goal was to test the workflow, by using it in a real context at the same time that it allowed to test Origami geometries, ways to actuate the movement, materials and digital fabrication techniques.

DESIGN STUDIO’S STRUCTURE

The design studios started with two days of open lectures on more general subjects like kinetic and responsive architecture, physical computation and parametric design. On the first year there were lectures on Responsive Architecture and Environmental Design by Alessandra Battisti, Physical Computation by Lorenzo Imbesi, Responsive Surfaces and parametric softwares by Anna del Monaco and Applied Parameterization by Alfonso Oliva from LERA+.

At Lisbon it was additionally made a call for papers that were presented during the two conference days, grouped by the subject of each keynote speaker. Parametric Design with Arturo Tedeschi,
Origami Geometry with Paul Jackson, Kinetic Architecture with Michael Fox and Interactive and Responsive Architecture with Ruairi Glynn.

The first two days of lectures had the purpose of making the students familiar with the concepts presented by the speakers with a special focus on built examples and correspondent explanations. This way a sort of "built state-of-the-art" legitimized these kinds of practices and allowed the students to reflect on the positive achievements of these architectures and on ways to resolve the negative ones.

On both years the next two to three days were spent with masterclasses where Rigid Origami was the main topic, like a passage from global (the two days of conferences) to particular. The masterclasses focused on geometry and mathematics of rigid origami surfaces, interaction with objects, digital fabrication, arduino programming, and finally the folding simulations of rigid origami surfaces using Rhinoceros with Grasshopper, Kangaroo and Weaverbird and the communication with arduino using Firefly.

The masterclasses reflected the defined workflow to be used as the methodology of the design studios. The workflow could not be linear because the steps cannot fit in a hermetic case, it is often necessary to reassess previous steps when problems are founded further, especially when the students are new to the subjects. So the proposed workflow comprehends several stages but works as an algorithm where critical judgment is essential.

The first step consists on the analysis of the available space for implementation of the surfaces, the existing constraints, either dimensional or locational, and also the formal objectives for the surface. The next step entails the design of a surface that can correspond to the formal constraints and demands through design and paper models. After that the chosen pattern is submitted to the digital simulation of its folding through an algorithm developed on Rhinoceros with Grasshopper, Kangaroo and Weaverbird and the communication with arduino using Firefly.

The fourth step is a point for critique where it must be evaluated if the developed surface is applicable to the initially defined objectives and existing constraints. If the answer is "Yes" then it is possible to proceed to the next step, if it is "No" then the student must retreat to the second step and change the pattern or create a new one and follow the subsequent steps again.

When a positive answer is reached on the fourth step it is possible to start defining the mechanic system that will make the movement happen. This system must respect the chosen fixed points and drive the moving points as defined on the paper models and digital simulation. The fifth step is where is de-

![Workflow algorithm](image)

**Figure 1**
Workflow algorithm

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decided the kind of “life” the structure will have, if it will react to atmospheric, lighting or thermic conditions or if it will have a more close relation with the users like moving when they get near it. The penultimate step consists on the choice of the material to formalize the surface. The material choice depends on several factors, if the structure will be used outdoors or indoors, if its dimensions allow it to be fabricated from a single sheet of material and if the material’s thickness allows it to be folded or if every face must be made separately either because of the faces dimensions or material’s thickness, and most importantly if the material has the qualities to be used for Rigid Origami surfaces, i.e. if it is rigid and isotropic.

The final step is the construction of the surface. The digital simulation allows to create the drawings of the crease pattern that will be used with the digital fabrication tools, after that remains only the assembly of the surface and its connection with the kinetic system, the sensors and the actuators. (see Figure 1) (Casale and Valenti, 2012) (Demaine et al., 2011).

During the Rigid Origami masterclass the students learned all the basic geometric rules and tested on paper models some of the most known crease patterns, such as the Miura and Yoshimura patterns and a variety of the patterns included on Paul Jackson's (2011) book “Folding Techniques for Designers: From Sheet to Form”.

The masterclass, along with the folding exercises, allowed the students to understand, in the most tangible manner, the implications of the crease pattern's geometry on the forms assumed by the surfaces after completing the folding process. It also allowed them to understand the kinematics of each model, the possible ways of movement and the structural ability gained by the paper due to its folding.

The conclusions taken from this masterclass guided the design of the crease pattern of each group and the decisions on which movements were envisioned and how to make them happen, which should be the fixed points and the moving ones.

MASTER CLASSES

Rigid Origami

Rigid Origami Surfaces have a tangible geometry, it is possible to experiment directly and quickly with a simple sheet of paper the transformations that happen during the folding and unfolding of such surfaces.

In Rigid Origami the final model must be the result of the folding of a single sheet, it must be possible to flatten the model without creating new creases and it is required that the faces are plan and have the same area at all times. This means that the material cannot bend neither stretch on the face’s area. From here is possible to infer that the creases have to be straight and cannot change their length during the folding process. The creases work as hinges between the flat faces. By creasing a flat material it acquires structural and elastic abilities. Surfaces folded according to the rules of Rigid Origami can acquire different configurations by the application of forces at strategic points. Such surfaces have the power to grow, shrink and adapt to many configurations (Casale and Valenti, 2012) (Demaine et al., 2011).

Digital Simulation

Generating the surface’s folding process in space is possible by geometrically controlling the basic constituent entities of the ‘articulated surfaces’: the surface pattern, the line/hinge between the faces, and the point/vertex where the hinges meet. By applying the basic rules of descriptive geometry, an algorithm that can control the entire surface was constructed through nodal programming tools (Rhinoceros + Grasshopper + Kangaroo).

The developed method was based on the specification of the geometric algorithms that connect the basic entities of the folded surfaces, guaranteeing topological invariance of the moving form. By acting on the variables in the algorithm, it was possible to control the movement of the form from one configuration to another, thus designing the movement.

The first step of the algorithm is the configuration of the geometry, the definition of the entire surface area as a mesh and the assignment of mountain or valley folds to the edges.
The second step is the establishment of the kinematic scheme for the physical impulses that comprises the definitions of the anchor points, edge hinges and rails for movement. Finally when subject to the proper impulses, the surface reacts by moving the faces, which maintain the geometries established during the configuration step. General rules govern the movement and overall form of the surface without discontinuities during the transformation that is synchronous to all faces, simulating in digital space the actions that will be made on the physical prototype.

\[ \text{Figure 2} \]

Step motor and cables attached to the wood frame

**Interaction and Arduino Programming**

In the interaction and Arduino programming master class several examples of interaction with foldable surfaces were demonstrated with the purpose of explaining basic interaction processes and how it was possible to control the shape of a structure.

Participants learned how sensors can sense user’s information/intentions and were introduced to light, sound and distance sensors and also to potentiometers so they could mimic other kinds of interactions. Several actuators were tested, mainly servo motors and linear actuators and students learned on how actuators could be used to act on structures by changing their shape through cables and pulleys, sprockets and discs and also ways on turning linear actuators movement on circular movement.

In the second part of the masterclass participants were introduced to microcontrollers and particularly to the Arduino. Some basic circuits with sensors and actuators were showed. Using these circuits participants were introduced to what is a program, how does the controller respond to a stimulus and what is a state machine. Several control programs were shown and discussed on the specific purpose of the Summer School.

**Digital Fabrication and Assembly**

For the fabrication and assembly of the prototypes the students had different materials and machines available on each year. The machines and materials, and how to work with them, were introduced to the students on the first days so they could think about their goals having in consideration the existing techniques.

For the first Summer School the offered materials for the surfaces were 3mm thick Poly Vinyl chloride (PVC) and 0.5mm thick Polypropylene (PP), the digital fabrication tools available were several 3D printers and a Mat Board cutting machine.

With the Mat Board it was possible to cut and engrave the creases on both sides of the PVC or PP which worked perfectly for the origami surfaces and was used by all groups.

For the second Summer School the available digital fabrication tools were a CNC milling machine, laser cutter and 3D printers. For the Origami surface first experiments the students could use paper, paperboard and cardboard. For the final prototype the available materials were 3mm thick plywood boards, 1mm PP or 160g/m² paper.

The students that used polypropylene or paper did the creases directly on the material with the laser cutter or plotter and bent it by hand. The participants that used plywood could not rely on engraving with the laser cutter because the plywood would break when attempting to fold it. Thus the faces where cut on individual pieces and stitched with a very strong nylon thread.

On both Summer Schools the Digital simulations made with Rhino, Grasshopper and Kangaroo were
used to adjust the geometries and create the drawings for the digital fabrication in a very close CAD-CAM relationship. The simulations were also very important to simulate the assembly and understand the relationship between contiguous faces.

RESULTS

Responsive Surfaces, Rome, September 2015

For the 2015 Summer School the groups developed four prototypes to be used together or individually as wall modules that reacted to user’s approximation or light conditions.

Each group had a 1x1m wood frame deep enough to accommodate all the mechanic elements, like cables and pulleys and the step motors that worked in response to distance and light sensors. (see Figure 2)

Each group created one crease pattern to be replicated in four modules. Every group used different movements, linear vertical, horizontal or diagonal and also rotational. The method to make the surfaces move was similar to all groups. Every surface had a fixed edge or point towards or around which the movement was created. Behind the surfaces was the mechanical system composed by one or two step motors that were connected to two or four lines of movement materialised by tense cables that were attached to specific points of the surfaces. (see Figures 3 and 4)

Surfaces InPlay, Lisbon, July 2016

At the 2016 Summer School the groups developed five prototypes to be suspended on the ceiling and that reacted to user’s approximation or manipulation. This Summer School had a similar workflow to the previous one, so the students also did all the geometric simulations on Rhinoceros with Grasshopper and Kangaroo. The movements tested were linear (on the plane XY and Z direction) and also rotational with different centres of rotation.

The squared plywood board with 1x1 meter was suspended on the ceiling and would hold and hide the linear actuator and all the mechanic system. It was only necessary to respect the limits of the board and the four points that would be used to attach the prototypes to the ceiling. The remaining configuration of the boards would be decided by the students so they could draw rails, holes and/or attachment points needed for their specific work. Each board was drawn by the groups and digitally fabricated at Vitruvius FabLab on the CNC milling machine.

Each group could use one motor actuator of 12” (around 30,5 cm) SuperJack. The available sensors were light and distance sensors but the students could also use potentiometers to mimic other kinds of interactions. (see Figure 5)
Although several kinds of gears, mechanisms and ironmongery were available these did not always suffice the needs. Every project was different from one another and was changing and evolving constantly so the students used the CNC, laser cutter and 3D printers to fabricate gears and pieces for the mechanical system customized to each prototype.

At the INPLAY Design Studio the organizing team decided that the students could have more liberty on the division of the 1x1m project base than on the previous year. Group A and B created four modules disposed radially on the board much like the Responsive Surfaces’ set and used PP as the material for the surface. Group C used two bigger surfaces made with plywood, one on the top of the base and the other underneath it. Group D made sixteen paper cylinders that would go up and down in pairs and moved at different speeds. Group E made 6 cloud like PP surfaces that compressed and decompressed on the same direction. (see Figures 6, 7 and 8)

CONCLUSIONS
The results from both Summer Schools were very satisfactory in several ways. The produced prototypes revealed that the students learned from the proposed workflow and were able to do everything from the beginning to the end very independently and in the available time. It is still amazing to notice how much work was done in only two weeks.

At the first year the organizing team gave less liberty to the creativity of the participants for fear that they would not be able to pass through all the stages of the workflow in a positive way. After the first experience it was possible to refine the workflow, by giving the masterclasses on a more focused manner and spending less time of the two weeks. This way was possible to give the students more time to work in group and with the tutors directly on their projects. The students were freer to create their own structure and crease pattern and learned how to solve unexpected problems at every stage the process.

All the students understood the potential of Rigid Origami surfaces to be used in a kinetic context and all of them were able to create their own crease pattern and make it move according to their aims. They were able to do so on the parametric simulation and physically.

It was also possible to conclude that by giving the students several raw materials to use in digital fabrication and by making available various kinds of
ironmongery the capacity to solve mechanical problems gets much easier. Probably because by being architects the ability to understand mechanical issues by using and manipulating gears is almost direct. Nevertheless the knowledge of teachers and tutors and the daily monitoring of the projects was paramount in the positive achievement of the initial objectives.

The only area were the results were not so positive was on the arduino and electronic steps. The groups obtained the basic knowledge necessary to use arduino and to make the motors respond to the input given by the sensors but they needed more help than on any other step of the workflow.

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