Kinetic Origami Surfaces

From Simulation to Fabrication

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Abstract. On nowadays social, technological and economic context everything changes constantly so there is the persistent need to adapt at all levels. This research defends that Architecture should do the same through the use of kinetic and interactive buildings, or elements in a building. These elements should allow the building to adapt to changing needs and conditions. This article describes the current state of an ongoing research that proposes the use of kinetic Rigid Origami foldable surfaces to be used as roofs for spaces with big spans and the practical contribution that the Design Studio Surfaces INPLAY has brought to it.

Keywords: Origami Geometry, Parametric Design, Kinetic Architecture, Digital Fabrication, Design Studio

1 Introduction

"*Today's intensification of social and urban change, coupled with the responsibility of issues of sustainability, amplifies the demand for interactive architectural solutions. In the context of architectural need, the attribute of being able to adapt to changing needs is paramount in contemporary society.*" [1]

In the last decades the technological developments regarding computational design and fabrication generated advanced technologies and tools to be used in Architecture.

With these tools the architect has now at his reach the possibility to create buildings that can transform themselves in order to adapt to different needs, functions and ambient or environmental conditions instead of buildings that are static and immutable on their structure requiring to be heavily equipped with thermic, sound and/or lighting systems with all the financial and environmental costs that brings.

The kinetic deployable structures can be one way of responding to such matter.

"*It would seem that deployable structures offer great potential for creating truly transforming, dynamic experiences and environments. Their lightness and transportability allow them to adapt to a society that is constantly evolving and changing. Furthermore, these are reusable structures that make efficient use of* *energy, resources, materials and space, thus embracing the concept of sustainability*." [2]

This research proposes the use of Rigid Origami foldable surfaces to be used on buildings that can change themselves in order to meet the needs of a determined function or ambient/environmental demands. The choice of this kind of geometry is easy to justify, Rigid Origami geometry has very clear rules that fit perfectly a kinetic architectural objective and, in a more emotional way, they are incredibly hypnotic and dazzling structures. These surfaces have self-supporting qualities and, by the application of forces at strategic points, have the power to grow, shrink and adapt to several geometric configurations.

Furthermore the advanced technologies allow the architects to simulate digitally several solutions, or families of solutions, test them and optimize the chosen one before construction. So this research also proposes the use of Digital Simulation tools to test and evaluate the folding of the surfaces for what regards the geometrical and kinetic aims of those surfaces.

Throughout this article it will be classified the types of Kinetic Systems in Architecture (Michael Fox and Bryant Yeh), categories of Deployable Structures (Esther Rivas Adrover), it will be explained the fundamentals of Rigid Origami geometry (Robert Lang and Erik Demaine) and the way that this applied research combined these three areas in a workflow that was used in the Design Studio Surfaces INPLAY to create five prototypes, from conception to construction.

2 Kinetic Systems

In Architecture there has been always the use of kinetic elements embedded in the building, like doors, windows, shutters, etc. Even in a passive way buildings were thought about, from centuries ago, in a manner that allows them to be cooler in summer and hooter in winter or to have windows and solar shadings with a configuration that takes the best advantage of the solar trajectory depending on the time of year or day.

Despite the undebatable importance of these abilities, these are not always enough to make a building operational at all times with the needed comfort for a given situation. A kinetic building, or kinetic elements in a building, enriches the utilization of the building by allowing it to be used in more situations, shelter different events and to adapt to changing ambient or atmospheric conditions.

According to Fox and Yeh [3] the kinetic systems can be classified in three kinds of structures: Embedded, Dynamic and Deployable.

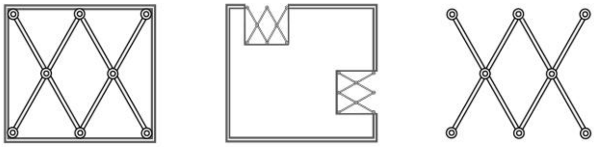


Fig. 1. Types of Kinetic Systems (Source: Fox and Yeh, 2000)

The **embedded** kinetic structures are systems that are integrated in an architectonic whole at a fixed location. Their function is to help control the whole in response to changing conditions. The **dynamic** systems act independently of the architectural whole, like doors, movable walls, etc.

The **deployable** kinetic systems are systems that are easily constructed and deconstructed systems. These structures can have one or multiple functions and their movement can be controlled in six different ways:

Internal Control: have the potential for mechanical movement but they do not have any direct control device or mechanism, they have a constructional internal control that allows it to move by rotating or sliding. It is the case of deployable and transportable architecture.

Direct Control: the movement is done directly by a source of energy such as electrical motors, human action or biomechanical changes in response to environmental conditions.

In-Direct Control: the movement is induced indirectly through a sensor feed-back system. The sensor sends a message to the control device that gives an on/off instruction to the energy source so it actuates the movement. It is a singular self-controlled response to a unique stimulus.

Responsive In-Direct Control: the operation system is quite similar to the last one but here the control device can make decisions based on the received input from various sensors. After analysing the inputs it makes an optimized decision and sends it to the energy source for the actuation of a single object.

Ubiquitous Responsive In-Direct Control: in this type of control the movement is the result of several autonomous sensor/motor pairs that act together as a networked whole. The control system uses a feedback algorithm that is predictive and auto-adaptive.

Heuristic, Responsive In-Direct Control: in this case the control mechanism has a learning capacity. The system learns through successful experiential adaptation to optimize the system in an environment in response to change. The movement gets self-constructive and self-adjusted [3].

The structures that this research refers to would be the Deployable Kinetic Systems with an In-Direct Control, according to Fox and Yeh's categorization.

3 Deployable Structures

The deployable structures have been used for thousands of years, since the nomad man created shelters that could be transported from one place to another and easily assembled and disassembled [4].

These are the main reasons for these structures to continue to be used and even more in the actual architectural context. They are usually light, self-supported and can often be divided into its components parts or be collapsed into a compact volume to be transported from one place to another. When they are used as part of a building they offer the possibility to extend that building or to transform it in several ways.

Esther Rivas Adrover [2] defined the typologies of the deployable structures in Architecture through 30 existing examples of such structures. Esther Rivas Adrover classified two main groups; Structural Components and Generative Technique. The **Deployable Structures** classified as **Structural Components** are deployables that were developed with a structural approach, the structural components of the deployable mechanism are its essence and base of design. The **Generative Technique** concentrates on movement and form inspired by Origami and Biomimetics that can later be developed with several structural systems [2].

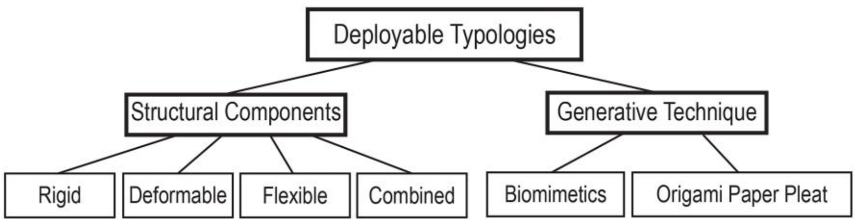


Fig. 2. Deployable Typologies (Source: Esther Rivas Adrover, 2015)

The group of Structural Components can be divided in four subgroups, Rigid, Deformable, Flexible and Combined, and the group of Generative Technique can be divided in two main subgroups, Biomimetics and Origami Paper Pleat. The last subgroup is the only that will be profoundly presented here since it is the subgroup in which this research is placed.

3.1 Rigid Origami

This research proposes a new subcategory within Esther Rivas Adrover's classification under the Origami Paper Pleat group, that is the **Rigid Origami**. In Rigid Origami the final model must be the result of the folding of a single planar sheet, where each face must be plan and have the same area at all times. This means that the material cannot bend, except at the creases, and it cannot stretch either. The creases work as hinges between the flat faces, they have to be straight and cannot change their length during the folding process. Also no face can ever penetrate another face [5] [6].

Rigid Origami can be subdivided into Flat Foldable and Non-Flat Foldable. The flat foldability of a given crease pattern can be determined before the folding by the verification of three fundamental rules stated in the Maekawa's Theorem, Kawasaki Theorem and Two-colourability Rule.

The **Maekawa's Theorem** states that a crease pattern is flat foldable if at every interior vertex the number of valley (V) and mountain (M) folds differs by two.

$$\sum V - \sum M = \pm 2 \quad (1)$$

The **Kawasaki's Theorem** states that a crease pattern is flat foldable if at every interior vertex the sum of the even and odd angles defined by the creases are equal to 180°.

$$\alpha_1 + \alpha_3 \cdots + \alpha_{2n-1} = \alpha_2 + \alpha_4 \cdots + \alpha_{2n} = 180° \quad (2)$$

Fig. 3. Graphic representation of Maekawa's and Kawasaki's Theorems (Source: Authors)

The **Two-colourability Rule** states that for a crease pattern to be flat foldable it must be possible to colour each face of the crease pattern in a way that two faces with the same colour never share a crease.

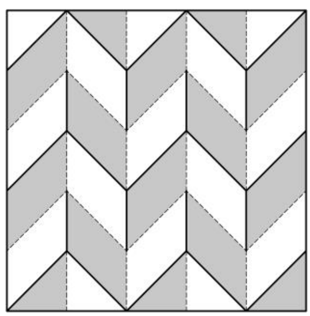


Fig. 4. Example of Two-Colourability Rule with Miura flat foldable pattern (Source: Authors)

3.2 Rigid Origami in Architecture

The present research categorizes the utilization of Rigid Origami in Architecture in three main groups, Static, Deployable Fixed and Deployable Kinetic.

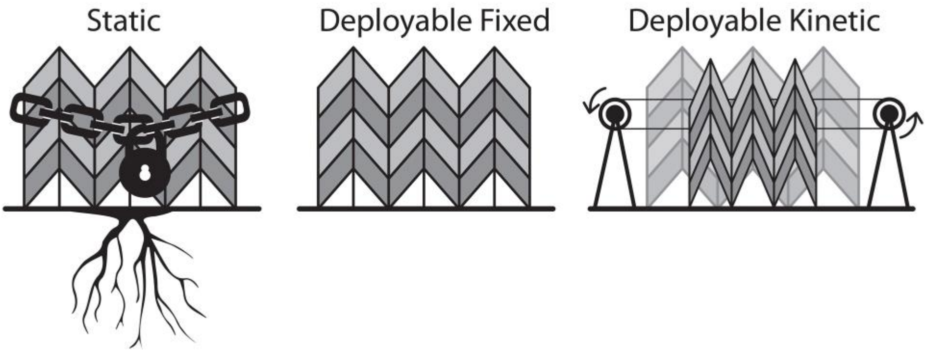


Fig. 5. Groups of Origami in Architecture (Source: Authors)

The **Static Origami** in Architecture happens when a building is constructed with an Origami form but this form remains with the same configuration through time. From the range of states an Origami surface can assume it is chosen only one state to reproduce in a permanent way. This state is chosen due to aesthetical and/or structural reasons since a pleated form has structural qualities that a plan form does not, like the division of the forces that the structure might be subjected to. This research finds this kind of Origami utilization in Architecture as the one that takes less advantage of the main qualities of Rigid Origami, so it will not be presented further here.

The **Deployable Fixed** Rigid Origami structures take advantage of the self-supporting capabilities of Rigid Origami surfaces and of their ability to be folded into a flat, compressed object. These surfaces can be easily assembled and disassembled without the need for additional supporting substructures and, when flattened, are easily transported and stored.

There are several examples of such utilization of Rigid Origami. In 2007 Miwa Takabayashi designed *Packaged*, a small pavilion to use in a Shopping Centre made of corrugated cardboard. *Xile*, 2008, by Mats Karlsson, was a 35 meter long translucent tunnel created to connect two buildings during the design fair *Interieur*. Matthew Malone developed the *Recover Shelter* in 2008, a temporary shelter to be used in emergency situations made with polypropylene. In 2009 the students from the third year of Architecture in the University of Cambridge designed, fabricated and assembled a temporary cardboard pavilion for a banquet at the University gardens. David Penner created the *Corogami Folding Hut* in 2010, a collapsible ice skating change hut, made with doubled wall polypropylene. More recently, in 2014, the students of the University of Southern California made a pavilion in polycarbonate that occupies an area of 15m x 3m and is 3m high. All these examples are able to support themselves without the addition of alternative structural systems due to the rigidity of the main material and the chosen Origami geometry.

The utilization of **Deployable Kinetic** Rigid Origami can be found in a wide variety of situations, from folded solar sails launched into space, medical devices, reconfigurable walls, shading systems, acoustic enhancement and artistic responsive installations.

The use of Kinetic Origami allow the designers to create not only transformable architecture in terms of the configuration of the lived space but make also possible the creation of responsive architecture or architectural elements such as kinetic roofs, or ceiling or wall panels.

The examples presented below are grouped in terms of their geometry, this is if they are **modules** (first) or **surfaces** (second).

Auxetic Origami of Christopher Connock and Amir Shahrokhi from Yale University, 2011, was a structure with sixteen flower like modules that responded to the ambient's levels of light by opening or closing themselves (Fig. 6). In 2011 David Lettellier exhibited *Versus*, two modules of Origami talking flowers placed on opposite walls that reacted to sound and communicated constantly with each other (Fig. 7).

Fig. 6. Auxetic Origami

Source: amirshahrokhi.christopherconnock.com

Fig. 7. Versus

Source: www.davidletellier.net

In 2012 AHR Architects finished the construction of the *Al Bahr Towers* where they used a façade protection system composed by several triangular modules with six faces. These modules protect the building from the sand storms and excessive sunlight (Fig. 8). In 2015 the mechanical engineering students of the Compliant Mechanisms Research Group designed the *Origami Kinetic Sculpture* based on the square twist pattern to be presented at the exhibition "Folding Paper: The Infinite Possibilities of Origami" at the BYU Museum of Art. (Fig. 9)

Regarding the utilization of Kinetic Origami as **surfaces** instead of modules there is a very interesting work by of Otto Ng that in 2010 at the John H. Daniels Faculty, University of Toronto, created *Wallbot*. These were mobile pieces of wall that worked together. It was used the Miura pattern stretching from 1m to 1,5m on each Wallbot that responsed to behavioural patterns and thermic conditions (Fig. 10).

Fig. 8. Al Bahr Towers

Source: Christian Richters, www.ahr-global.com

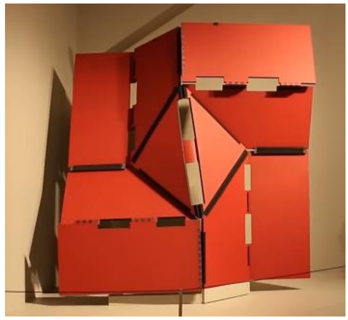


Fig. 9. Origami Kinetic Sculpture

Source: compliantmechanisms.byu.edu

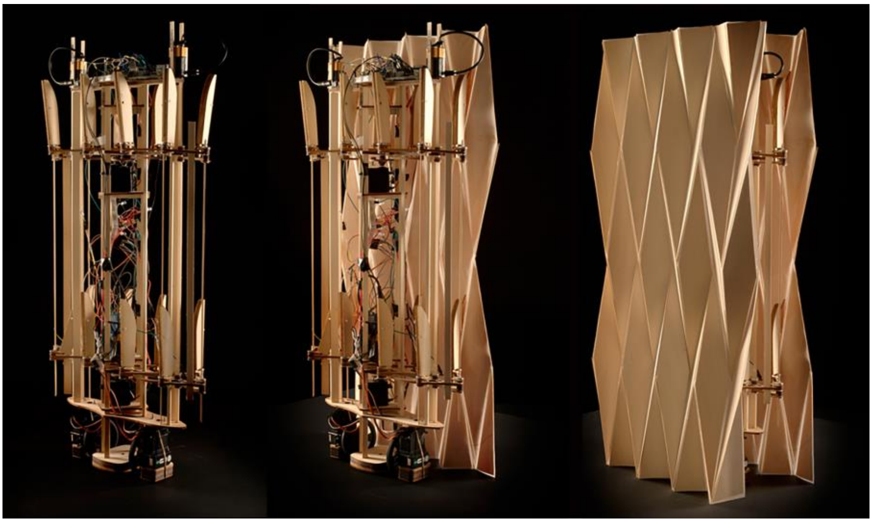


Fig. 10. Wallbot (Source: www.ottocad.net)

Fig. 11. Tunable Sound Cloud

Source: www.fishtnk.com

Fig. 12. Tessel

Source: www.davidletellier.net

Fishtnk created the first version of the *Tunable Sound Cloud* in 2010, a surface that modifies itself in order to enhance the acoustic performance of spaces (Fig. 11). With the same purpose David Lettellier created *Tessel* also in 2010 (Fig. 12). A similar surface, the *Ressonant Chamber*, was developed in 2012 by RVTR in a partnership with ARUP acoustics (Fig. 13).

Fig. 13. Ressonant Chamber (Source: www.rvtr.com)

Cerebral Hut was designed in 2012 by Guvenc Ozel and Alexandr Karaivanov and was an installation made with 11 hexagonal modules of surfaces folded with the Ron Resch Pattern that reacted to the user's brain frequencies with the objective of allowing the users to control it with their minds (Fig. 14).

In 2014 Foldhaus created *Blumen Lumen*, an interactive art installation that uses the Miura pattern to create 10 animatronic flowers that open and close in response to the people around them (Fig. 15).

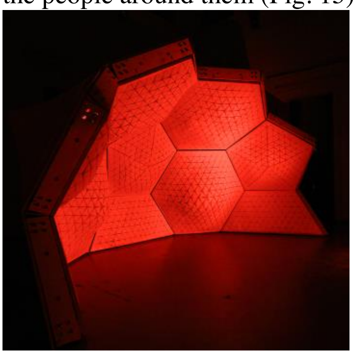


Fig.14. Cerebral Hut

Source: ozeloffice.com

Fig.15. Blumen Lumen

Source: blumenlumen.com

As a sum up of the groups and subgroups that were exposed on the last two sections, and to place the current research, Figure 16 shows Esther Rivas Adrover's classification extended with the branches proposed by this research.

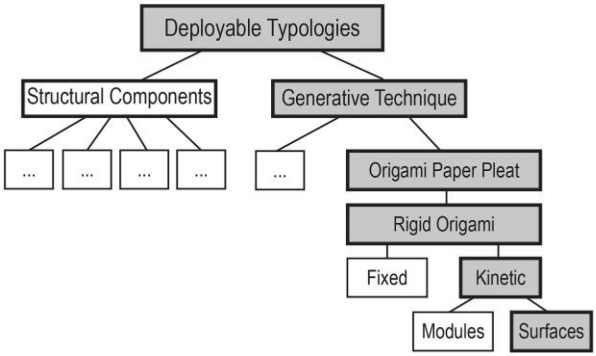


Fig. 16. Deployable Typologies Extended (Sources: Esther Rivas Adrover, 2015 and Authors)

This research places it self along the grey path, its focus are the Deployable structures made with Rigid Origami Kinetic Surfaces. The ultimate goal is to develop a kinetic roof for a space with a big span and build a part of it in a real scale prototype.

From the shown examples there are several conclusions made on this research. It is possible to conclude that when using Rigid Origami to develop kinetic objects the most common approach is to use modules with a small number of surfaces instead of using surfaces with a big number of faces. Probably because it is much more complicated to control an origami surface in a kinetic context. This is one of the contributions this research intends to accomplish, the use of surfaces rather than modules to cover spaces with big spans.

It is also possible to observe that, when using surfaces, the crease patterns more often chosen are the Miura-Ori and the Ron Resch pattern. Probably the two most studied and used patterns of Origami surfaces in Architecture.

4 Digital Simulation

The use of digital parametric tools by Architects enables the testing of several solutions in order to choose the most appropriate for a particular building site or function and to optimize the chosen solution before its construction.

In the particular matter of Rigid Origami folding simulations there is already an extensive work from authors like Robert Lang and Tomohiro Tachi that have the developed softwares available to the public on their websites. Daniel Piker has also several Origami folding definitions available at Grasshopper3d.com and is the creator of Kangaroo and the Origami component on Grasshopper. Then there is the work of Casale and Valenti that use Rhinoceros and Grasshopper to simulate the folding of different crease patterns each one with a different approach depending on the geometry of the pattern [7].

The simulation method used in this investigation is similar to the one used by Casale and Valenti, it uses Rhinoceros and Grasshopper. But these authors create definitions to fold the entire crease pattern at once and at this investigation the method is to define the minimum possible module of the regular tessellation, define the parameters to design the faces that constitute the module and the local rules for their folding.

This way is possible to alter the dimensions of the base module and simulate the folding from the plan state to the completely folded and then reproduce that module with vectorial copies allowing to extend the crease pattern as far as wanted and also change the configuration of the module faces at any point of the folding process.

This method comprises 3 steps:

1 – Analysis of the regular tessellation in order to define the base faces

2 – Simulate the folding of the base faces from the unfolded state to the completely folded state

3 – Generate the complete tessellation through vectorial copies of the base faces

On the developed definitions there is always one point or crease that does not change during the folding. This element behaves has the attachment to the XYZ referential, is the centre of all the transformations.

This method and the resulting definitions have proven to work perfectly and simulate in a rigorous way the folding that happens on physical rigid models with minimum thickness, but they are not suitable for irregular crease patterns.

5 Work Method

This research also intends to develop a method for the design and construction of Rigid Origami Surfaces to be used with kinetic purposes. The method encloses all the main areas previously described and also the materials and digital fabrication areas.

The proposed method starts with the study of the place to intervene. It is necessary to understand deeply the “problem” to solve, the objectives and constraints for the surface that is being designed, the configuration of the available space for the implementation, the desired covered area and the unobstructed height where the surface will move. Furthermore there is the need to know the purpose of the surface and also if it will be exposed to the natural elements, like sun, rain, snow and wind since the geometry of the surface can aide in solving such matters.

From the conclusions taken before it will be possible to decide which crease pattern will suit best the space and function of the intervention. At this point it is proposed the use of parametric tools that can help the designer simulate the movement that the surface will describe from the unfolded to the folded state. After the Digital simulation it is essential to observe the result and to confront it with the initial objectives, if it does not fit the purposes then modifications must be made to the crease pattern or even the choice of a different one.

Once the geometry of the surface is adjusted it is necessary to decide which material, or association of materials, will be used to fabricate it. These materials must replicate the rules of Rigid Origami, they must guarantee that all faces are planar at all times in order to keep the integrity of the simulation and the surface's behaviour in a real context.

The geometry of the surface and the movement that the hinges and vertices describe during the folding process are directly related to the kinetic system. This system must be in sync with the geometry of the surface so it will support it and flow with it as the folding process occurs.

The interaction with the surface must also be settled before the fabrication so any emergent issues may be solved before entering the final step of the workflow.

Finally, the last stage will be the fabrication of the surface. For the fabrication the Digital Simulation made before will be of great importance, with it will be possible to generate the drawing of the planar surfaces to be cut in a CNC milling machine, laser cutter or any other digital fabrication tool.

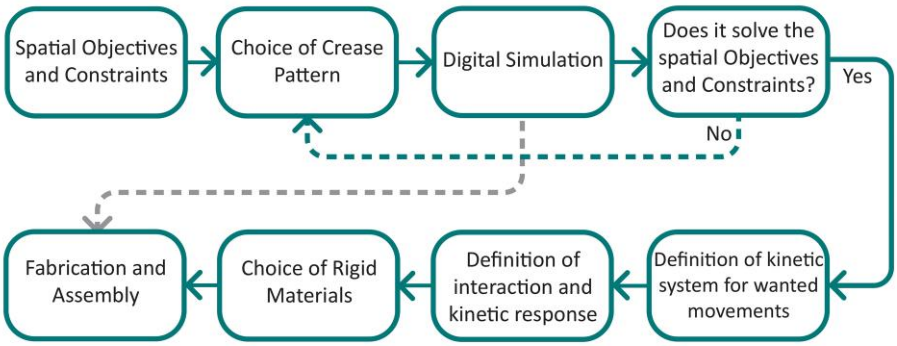


Fig. 17. Work method (Source: Authors)

6 Design Studio Surfaces INPLAY

On 2016 it was organised an event, Design Studio Surfaces INPLAY at ISCTE-IUL, Lisbon, Portugal, that was like a small replica of this research. Each group of students at the design studio had to create a suspended Rigid Origami surface that would move in response to an external stimulus, like light levels or the approach of a person or object. The main objectives of Surfaces INPLAY in relation to this research were to test several issues:

1) the work method

2) suspended surfaces with five different crease pattern's geometries, their capacity of compression and intrinsic possibilities of movement.

3) surfaces made with 0,8mm thick polypropylene, 3mm thick plywood and 160g/m² paper; how to fold these materials

4) linear motion systems, manual or with motors and their relation with the mechanical systems

5) arduíno controlling for the sensors reading and kinetic system operation

This issues were tested on five different prototypes that shall be called A, B, C, D and E from now on. The prototypes where conceived from concept to fabrication by

10 students from Portugal, Italy, Brasil, Canada, Greece and Belgium. The students were mostly PhD students, Architecture students and University teachers. Some of the students had already knowledge on Parametric Design and/or Origami Geometry, but most of them did not, so there were several masterclasses to level the general knowledge needed for the construction of the prototypes.

6.1 Spatial Objectives and Constraints

The space for the implementation of the prototypes was a squared plywood board with 1x1 meter that would be the base for the suspended Origami surfaces and also hold and hide the actuator and all the mechanical system. The only mandatory constraints were 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 free and up to the students, so it was possible to make the rails, holes and attachment points needed for each specific prototype directly on the base. Each board was drawn by each group and digitally fabricated at Vitruvius FabLab..

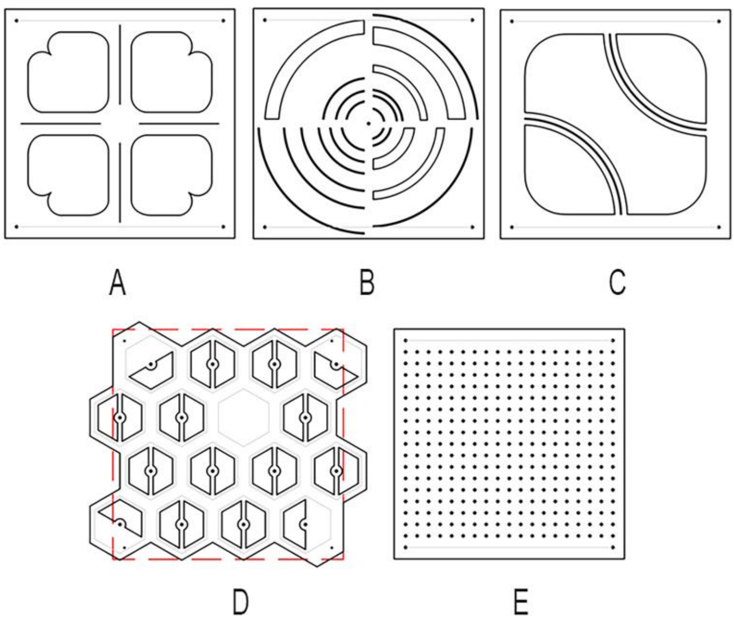


Fig. 18. Prototype bases (Source: Authors)

6.2 Digital Simulation

After the first geometric experiments with paper, paperboard and cardboard, based on the crease patterns presented by Paul Jackson on his 2011 book, Folding Techniques for Designers: From Sheet to Form [8], the students simulated the folding of their crease patterns with Rhinoceros, Grasshopper and Kangaroo and did the necessary adjustments to the geometry of the pattern in order to achieve the proposed effect, as preconized in the work method.

Prototype A was constituted by four symmetrical modules that intended to be four birds that opened and closed their wings in a diagonal movement set with vertical and horizontal moving points of the surfaces.

Prototype B used a parallel pattern with an inflexion in order to create four surfaces that were like a hybrid between a hand fan and a shell. These four surfaces open and close in a radial movement.

The geometry defined for the prototype C had some similarities with the previous one, it was also a shell like surface, but instead of having parallel creases the creases were radial and the faces used to achieve the inflexion on the surface were much less.

Prototype D used the Yoshimura pattern in sixteen helicoidal cylinders. This was the only prototype that used the movement in the vertical direction while all the others structures moved on the horizontal plane.

Prototype E was made with the Ron Resch pattern to create a surface that would act as a fluid when subjected to forces in different points. This was the only Non-Flat Foldable surface, since the Ron Resch pattern does not verify the Maekawa's theorem. The objective of this prototype was to make one unique surface that would have different things happening at the same time, pulling and pushing on different points. Unfortunately the students did not consider the material limitations and the final structure did not behave as initially intended.

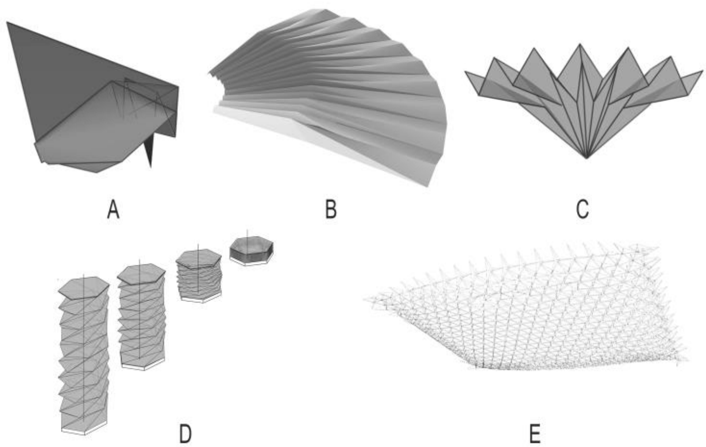


Fig. 19. Digital Simulations (Source: Authors)

6.3 Materials and Digital Fabrication

For the final prototype the available materials were 3mm thick plywood boards, 1mm polypropylene or 160g/m² paper.

The students that used polypropylene did the creases directly on the material with the laser cutter either with dashed lines where the dashes where cut all the way through (A and E) or by engraving the creases on both sides of the polypropylene (B). All these three prototypes had to have the vertices cut away where there would be more forces in action so they wouldn't inhibit the structure's movement.

The "engraving on both sides" method proved to be more efficient than the "dashed lines" method because it cuts away some material over the entire crease, while the dashed lines method obliges to a crushing on the non-dashed parts. The fact that the creases are engraved at their entire length and until half of the material's thickness makes the folding more natural and creates less "crushing" of the material under the crease lines and so inhibits less the folding.

Prototype C used the 3mm plywood and encountered a problem that did not exist on the other prototypes, how to make a surface with thickness fold. To resolve that each face was cut individually at the laser cutter and then stitched to the adjacent faces in a way that only allowed the faces to fold on one way, defining like this the mountain and valley folds.

Fig. 20. Plywood stitching (Source: Authors)

For prototype D it was initially tried to perforate the paper at the laser cutter to make a sort of pre-crease, but it did not work, after a few utilizations the paper would tear apart. So the pattern was simply printed on paper and the folds were made by hand.

These experiences proved that making the creases directly on the polypropylene with the laser cutting machine is a successful way of making Rigid Origami foldable surfaces if the vertices are cut away. It was also possible to observe that the patterns with bigger faces behaved better than the patterns with smaller faces, possibly because this material as the tendency to curve slightly the faces on the areas near the creases.

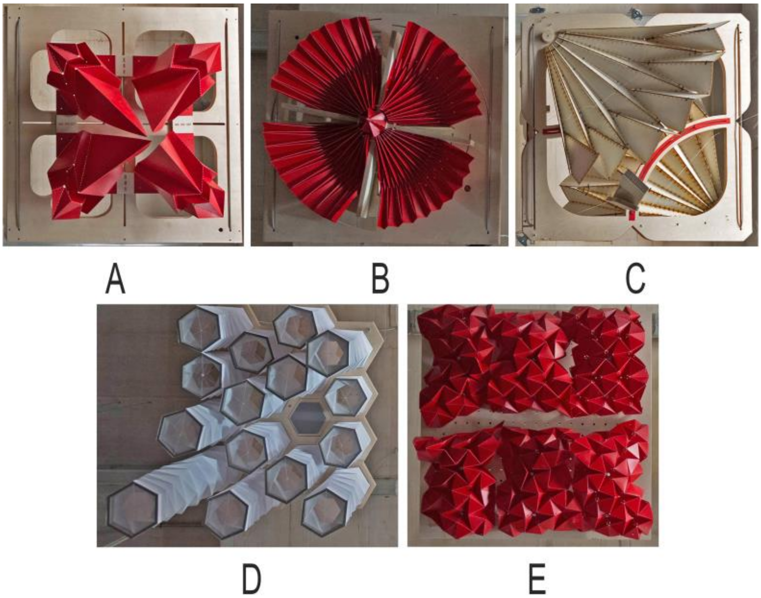


Fig. 21. Prototypes (Source: Authors)

The method to put together the plywood faces by stitching them with nylon thread also proved to be an efficient way of making these surfaces fold.

6.4 Kinetic System

For the kinetic system all groups, except C, used one motor actuator SuperJack of 12'' (around 30,5 cm). The objective was to use only linear movement.

Prototype A used rails on the plywood base for the moving pieces, like a cross, and had four voids behind the birds where the beak of each bird would always be in touch with the base. On this prototype it was used a mechanism with pulleys and cables that, with the force of one linear motor, made all the lines of movement work in a perfectly synchronised way, with this system all the birds moved at the same time in tri-directional symmetric ways. This prototype did not have fixed points on the geometry, only moving points.

Prototype B was divided in four spaces with circular rails cut on the plywood. Each origami surface was attached to the plywood base on one extreme as the other one was attached to the rotating cross, put in motion by the linear actuator. The movement was rotational and worked like four curtains that open or close at the same time when the motor made a rigid wood cross rotate 90 degrees.

Group C did not use the motor, the movement was achieved when a user pulled the cords to open or close the two module surface. This prototype used the upper and lower parts of the plywood base to place the surfaces, i. e. one was suspended while the other was supported by the base.

Prototype D had the plywood base completely redrawn, the limit shape was completely changed, although respecting the attaching points, in order to place and create an attaching base for each cylinder. To make the cylinders compress and expand it was used the linear motor in an horizontal position that would rotate 8 horizontal wheels with different diameters. These wheels made the cylinders move in a vertical direction at different speeds.

Prototype E had a grid of wholes on the plywood base so it would be possible to choose freely where to attach the cables to the structure's moving points. The linear actuator, placed on the XY plan, made the points of the surface move in Z creating an effect of compression of the surface at some points while at others the effect was of decompression.

It is possible to say that in what relates to the kinetic movement all structures worked perfectly, it is however important to refer that these results where only possible because all the structures started their folding in a slightly folded state. Otherwise, the motors or the manual pull, would have to make tremendous strength to make the surfaces leave the completely unfolded state to a folded one.

It was also possible to verify *in loquo* the capability of compression of each prototype. The real capability of compression differs very much from the folding simulations done on Grasshopper + Kangaroo because for the simulation the faces are considered as without having any thickness and the forces created by each material at the creases region are also inexistent on the simulations.

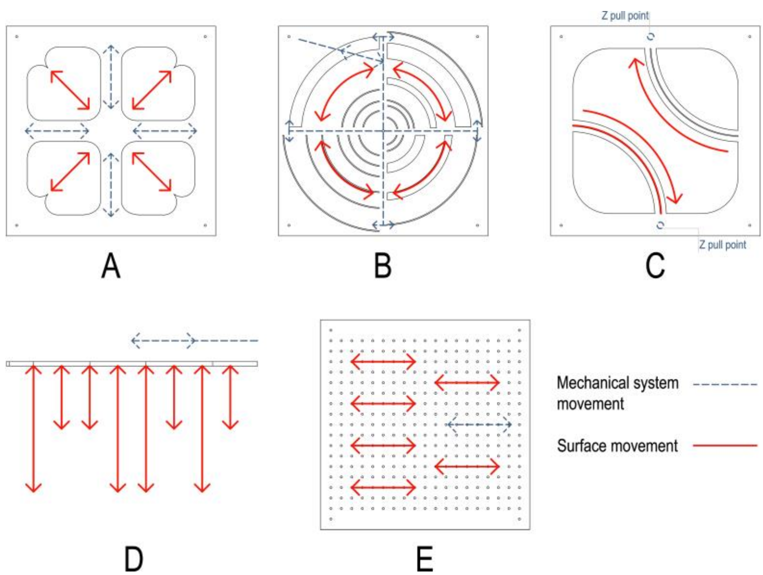


Fig. 22. Prototypes movements (Source: Authors)

The prototype with the best capacity of compression was D prototype because paper was the less thick of all the available materials and also because the Yoshimura pattern has that inherent ability, nevertheless the values of compression range from 10% to 95% because some cylinders never get completely folded, due to the kinetic system design, while others cylinders get maximum compression.

The worst capacity of compression was found on prototype E. The chosen geometry is not flat foldable thus it could never obtain good values of compression, but even so the fact that it does not have fixed points and that the used material was polypropylene did not help to the compression ability.

The other prototypes had values of 60% (A), 75% (B) and 85%(C).

6.5 Interaction System

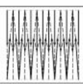
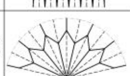
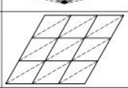
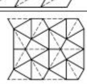
For the interaction system the available sensors were light and distance sensors but it was also possible to use potentiometers to mimic other kinds of interactions. Prototypes A, B, D and E used the distance sensors so their structures moved every time a person, or an object, gets in the range of the sensor. The values of the sensors would be read by the arduíno that would then make the motor work inside a preprogramed range that fitted the surfaces purpose.

Group C explored more the interaction between the object and the user and worked the most the arduíno possibilities. Every time a user opened the C prototype surfaces there was a little “being” inside that would react badly to the intromission making an awful sound and flashing a light so the user would feel obligated to close it again so the “creature” could be comfortable on his cocoon.

6.6 Synthesis

The next table intends to make a compared synthesis on the remarks and results described on the last five sections regarding the prototypes developed at the Design Studio Surfaces INPLAY.

Table 1. Synthesis of results

	Crease Pattern	Is it Flat Foldable?	Fixed Points	Direction of Movement Actuator	Surface's Movement	Material	Creases	Capacity of compression	Behaved as Grasshopper + Kangaroo simulation?	Followed work method?
A		Yes	No	linear at XY plan	Symmetrical to the diagonals at XY plan	Polypropy-lene	On material dashed lines	60%	Yes	Yes
B		Yes	Yes	linear at Z direction	Radial at XY plan	Polypropy-lene	On material engraved	75%	Yes	Yes
C		Yes	Yes	linear at XY plan	Radial at XY plan	Plywood	Stitched	85%	Yes	Yes
D		Yes	Yes	linear at XY plan	Helicoidal at Z direction	Paper	On material by hand	between 10% and 95%	Yes	Yes
E		No (Does not follow Maekawa's Theorem)	No	linear at XY plan	Z direction	Polypropy-lene	On material dashed lines	15%	No	No

7 Conclusions

As stated at the Introduction chapter this research intends to make a contribution to nowadays Transformable Architecture solutions with Deployable Rigid Origami Surfaces by structuring the knowledge on Kinetic Systems, Deployable Structures and Rigid Origami Geometry. It is believed that that goal has been positively achieved.

In addition it is proposed a comprehensive work method that follows every step of the architectural process for this kind of structures, from design to construction. In this process the architect is placed as a constant presence in every stage and has the tools for the decision making with awareness and consideration to those same stages and the ways they influence each other and the final design and construction.

In order to prove the applicability of the suggested geometries and work method it was used the Design Studio Surfaces INPLAY. This Design Studio was of great importance to test in a practical way the work method, the proposed digital simulation tools, Rigid Origami geometry, materials, kinetic and mechanic systems and digital fabrication.

From the developed prototypes it was possible to verify that the fixed points on a kinetic structure can be very important for the surfaces behaviour and capacity of compression but it is also possible to construct them without any fixed points, at least in suspended situations. The geometry of the pattern, the used material and the force of the motors used are also key factors for the range of compression this surfaces can undertake.

It was verified physically the importance of starting the movement with the pattern already slightly folded, in the case of prototype C, for instance, was impossible to make it move and fold if it was not initially folded.

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