KOS- Kinetic Origami Surface

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KOS- KINETIC ORIGAMI SURFACE

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Abstract. In an increasingly technological, informed and demanding society Architecture should be able to answer to its space requirements using materials and technological resources that today has at its service. Kinetic systems have been used by architects as an approach that embeds computation intelligence to create flexible and adaptable architectural spaces according to users' changing needs and desires. This paper describes one possible way of exploring kinetic systems to develop a foldable surface with geometric patterns based on the rules of rigid origami. This surface aims to take advantage of the elastic capacities given to a planar material by its folding. After folding the surface can assume different forms in order to create a range of spatial configurations ordered by a user through a remote control.

Keywords. Kinetic systems; interactive architecture; origami geometry; folded surfaces.

1. Introduction

The emergence of digital design processes and technologies are challenging the conventional assumption of architecture being immutable and static.

There has been interest for some time for 'intelligent' artefacts that can react to user needs in order to improve functional performance. As Fox and Kemp (2009, pp.18) put it:

"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. "

With these premises in mind we have tried to develop a surface that can assume different configurations in order to respond to the changing needs of a specific user. This user can manipulate the structure through a remote control that allows the user to evaluate at all times the forms it is assuming and their relevance for a specific need in a specific context. More than developing an object we intend to pursue a system that can be used in different contexts like roofs for sports buildings that sometimes are wanted open and other times closed. Like ceilings for theatres or concert halls where the structure can be used to enhance acoustics or even in a smaller scale where it can be used as a room inside another room that can adapt itself to fit inside the container and create the needed space for a given situation.

2. Transformable Architecture

In the 60´s and 70's, when computation and technology took a giant leap, groups like Archigram took this new kind of knowledge and used it in architecture so spaces could be changed in order to fit the user's wills and needs as they changed in time. Between the 80's and the end of the 20th century important projects were developed. At this time technological advancements allowed the economic and technological feasibility for kinetic and interactive Architecture ideas, such as the Herman Miller Factory and the IGUS Factory from Grimshaw Architects. It was also at this time that kinetic architecture started to be re-examined based on the premise that its performance could be optimized if computerized information could be used to process and control the buildings physical adaptation (Kolarevic and Malkawi, 2005; Fox and Kemp, 2009).

In more recent years we can find projects that use the new technologies in a remarkable way in sports buildings and theatres with huge kinetic roofs such as the Qizhong Forest Sports City Arena by Mitsuru Senda, the Wembley Stadium by Foster and Partners or the Bengt Sjostrom Starlight Theater by Studio Gang O'Donnell.

Even though there are more and more examples of kinetic architectural structures they are not yet completely disseminated and have a big potential for exploration and investigation. Specially in a world where the "increasing presence of sensors and actuators in domestic contexts calls for the need of architects and designers to develop the skills necessary to explore, think about, and design intelligent and adaptive architectural systems" (Fox and Hu, 2005, pp. 79).

In this research we intended to pursuit a real and usable answer for kinetic systems in Architecture, for the flexibility asked by nowadays society through a light surface able to create the demanded flexibility and adaptability.

The KOS structure we will present aims to allow a user to generate a range of spaces that can be used for different functions with different space needs. The surface should behave at once as skin and structure, should be light, collapsible, easily assembled and deployable, able to assume a variety of geometric forms and should be done in a recycled and recyclable material.

Our proposal to respond to these demands is a surface obtained by the folding of a planar, rigid material with the geometric rules of rigid origami. The user can control the movement of the structure through a tangible remote control, a miniature of the structure that can be easily manipulated allowing for testing and choosing the forms the structure will assume. This remote control allows the user to control the structure even if it is in an inaccessible location like a roof or a ceiling.

3. Kinetic systems and origami

3.1. KINETIC SYSTEMS

According to Fox and Yeh (2000) the kinetic systems can be classified in three kinds of structures: embedded, dynamic and deployable.

The embedded kinetic structures are systems within an architectonic whole at a fixed location. Their primary 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 usually easily constructed and deconstructed systems that exist in a temporary location (Fox and Yeh, 2000).

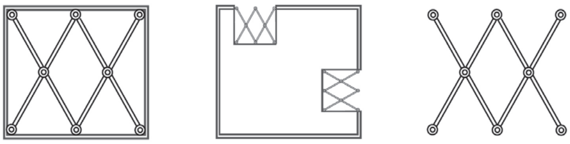

Figure 1.Kinetic Typologies in Architecture (Taken from Fox, 2003, pp. 177)

These structures can have one or multiple functions and their movement can be controlled in six different ways:

- Internal control: these systems 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 feedback system, i.e. there's an exterior input given to a sensor that then sends a message to the control device, this control device then 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.

3.2. ORIGAMI

Origami's mathematical and geometric capabilities have been studied and used by mathematicians, physicists, architects and in biology research. Despite of origami's usage for thousands of years it was only in the 80´s that were defined the 7 axioms that systematize and resume origami's geometric potential, the Huzita-Hatori axioms, quite similar to the Euclidian axioms. With these axioms one can build several mathematical models with origami such has platonic solids, fractals, tessellations, symmetries, Voronoi systems and developable surfaces among others (Lang, 2010; Demaine, 2011).

The magic of these models is that much of the folding happens by itself, due to the physical properties of paper the origamist only has to crease all the folds, this way the memory of the paper is changed and, quite naturally, it chooses the position that minimizes tensions. By applying specific forces we can collapse them into a bi-dimensional form and when we let go the models "choose" their state without the need to apply other forces or to support them in any way. The state they choose is the result of the strength done when creasing (or the time that the material was forced to remain in the fully folded position) and its geometry (Demaine et al, 2011).

In addition to this form of "comfort" we can also make the same surface adapt to various geometries, volumes and areas simply by opening more or less the angles between the faces and by applying forces at strategic points. There are several kinds of origami. The one that interests us most is rigid origami because of its imposition that all faces remain planar at all times. A rigid origami folded surface works as multiple faces connected by folds, which function as hinges, that gives the surface an elastic capacity. A surface like this can grow and shrink despite of the used material is rigid and has no elasticity.

These are the reasons that make these folded surfaces particularly suited to meet the demands of a structure that one wants to be light, with self-supporting properties, able to assume different forms and have a kinetic behaviour.

3.3 ORIGAMI USED IN KINETIC ARCHITECTURE

Despite all of the described above we find the use of origami in Architecture more commonly in a frozen state, i.e., from the range of forms that a surface may assume it is chosen one that is reproduced in a static way with heavy materials such as concrete, wood, metals, etc. It is the case of Yokohama Airport by Foreign Office Architects or the Pleats Building by Hironaka Ogawa.

We can also find another kind of buildings done with origami, like the temporary, mountable and demountable buildings. This form of using origami takes better advantage of its capacities than the one we have seen before. The structures can be collapsed for easy transportation and are self-supported with no need for additional structures, but when they are being used they remain static. It is the case of Packaged by Miwa Takabayashi, the Folded Hut by Ryuichi Ashizawa, the Recover Shelter by Mathew Malone and the Corogami Folding Hut by David Penner.

At last we can find examples of origami's utilization in kinetic and responsive structures. These structures are usually based in modules of origami instead of surfaces. These modules usually have a small number of faces arranged around a central point mainly because how simple it is to predict and control the open and closed geometries of the modules. These modules respond to the stimuli as a whole but geometrically they function as independent units. This is the case of Auxetic Origami developed by Christopher Connock and Amir Shahrokhi at Yale University in 2011 or the Lotus Dome by Roosegaard Studio in 2007.

4. Kinetic origami surface (KOS) research design process

The research design process used to develop the KOS encompassed three phases: (1) Study geometrical and mathematical properties of classical origami to generate rigid foldable structures; (2) Explore kinetic possibilities of folding transformable structures and material selection; and (3) Building the prototype (Figure 2).

In the first phase the research started with the study of regular and irregular origami crease patterns and the existing programs and algorithms that would help us simulate and test their kinetic potential.

The second phase consisted in building small scale prototypes with different materials and different mechanic systems.

Finally in phase 3 we built a real scale prototype.

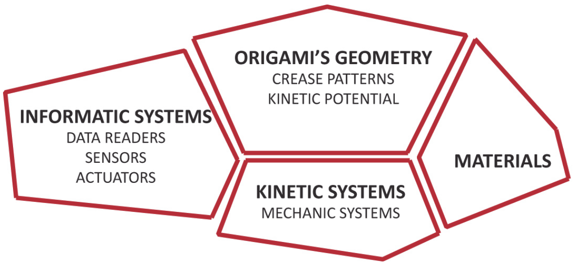

Figure 2.Areas of study

4.1. GEOMETRICAL AND MATHEMATICAL PROPERTIES OF RIGID ORIGAMI TO GENERATE FOLDING STRUCURES

The research started with the study of: (1) origami regular and irregular crease patterns like Nagamo pattern and Miura Ori pattern in order to find geometrical properties and their capabilities of assuming different geometries when forces were applied; (2) programs/algorithms already developed that would help us test various crease patterns and the geometries they could generate. We have studied the Digital Origami by Dave Lee and Brian Leounis at Clemson University (2011), The Rigid Origami by Tomohiro Tachi (2010) and several of Eric Demaine and Daniel Pikers's algorithms. Unfortunately none would let us test all the patterns we wanted and most of all it was impossible to test the application of forces in the surfaces. The main difficulty using these digital simulators was that for each crease pattern it would be necessary to make individual programming, so we finally decided to test the crease patterns with paper models.

After all the testing it was decided to use the Miura Ori pattern, developed in 1995 by the Japanese astrophysicist Koryo Miura to fold the solar panels of Japanese spatial satellites. This pattern, with a regular tessellation, proved to have the best compromise between all of our demands such as self-supporting abilities, geometry's predictableness and easiness to control.

4.2. KINETIC POSSIBILITIES OF THE MIURA-ORI PATTERN AND MATERIAL SELECTION

In this phase we have developed a mechanical system where the forces would be applied on the horizontal plane in three parallel lines of action in order to make the surface rise in Z direction assuming different forms as shown in Figure 3.

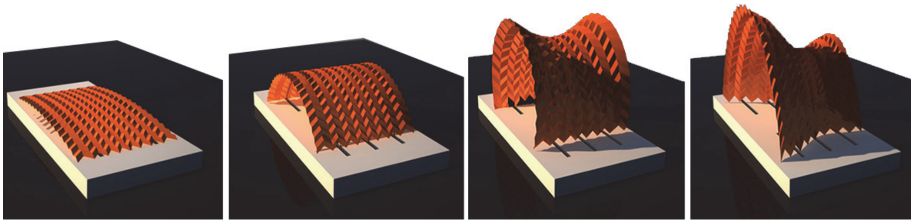

Figure 3.Some forms the KOS surface can assume

To implement such a structure we needed motors that would rotate in both ways and with enough strength to make the structure move, stop, and to maintain it steady so the tensions between faces and the force of its own weight would not make it move. We have chosen shutter engines able to pull 35kg and that have these exact competencies, rotate in both ways and stop.

Each one of the three lines of movement would work through cables and sheaves put to action by the shutter engines that would push and pull six points of the surface. To each line of action there are two control points that are pulled and pushed symmetrically. This symmetry of movement is achieved by having the shutter engines at the centre of the structure and a sheave that guaranties the inversion of course as shown in Figure 4.

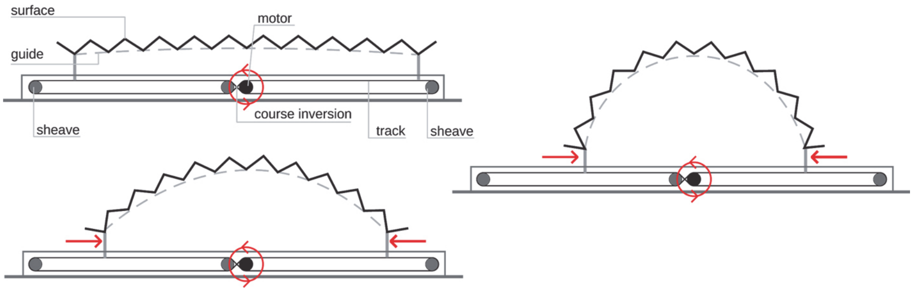

Figure 4. KOS - mechanical system

4.3. BUILDING THE FULL SCALE PROTOTYPE

After studying, exploring and testing some solutions through CAD studies, we began to build a full scale physical prototype. This phase involved digital fabrication, the development of the mechanical system and indirect control.

As material, we selected sheets of polypropylene (PP) because, such as paper, is isotropic, as a very low density, is rigid and at the same time flexible so it can bear multiple folds and unfolds and it is recyclable.

For the surface we have used 18 sheets of PP with 1,0m x 0,7m and 0,8 mm thick. As pre-creasing technology, we selected the CNC machine. The final creasing and folding was done by hand as shown in Figure 5.

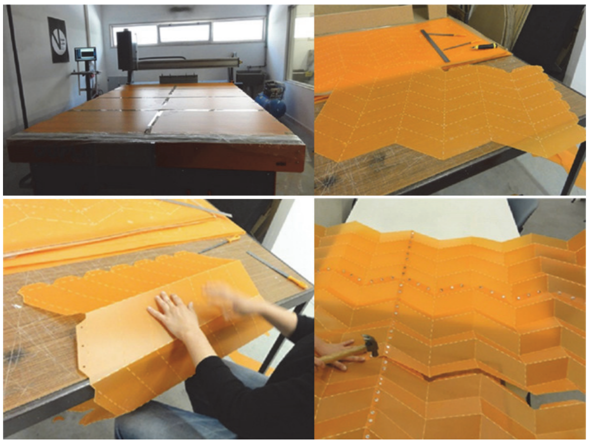

Figure 5.KOS - Digital pre-creasing, manual creasing and folding, assembling the sheets

When we had the surface we built the base where the mechanical system would work. Then we configured the controller of the structure.

A microcontroller board (Arduino compatible) was used to control the structure. The shape of the miniature was read by three potentiometers, one for each line of action. Using this information the microcontroller would adjust the speed of the structure's engines in order to replicate the miniature's shape. Distance sensors were used to measure accurately the positions of each control point.

When the control points have reached the desired positions the microcontroller would stop the shutter engines until a new order was received. The controller's main cycle consists on reading the potentiometers values, reading the distance sensors values and, for each line of action, setting the motor speed so that the two values converge. Such a simple control program allows a very reactive control (Figure 6).

The storyboard of one movement test can be seen on Figure 7.

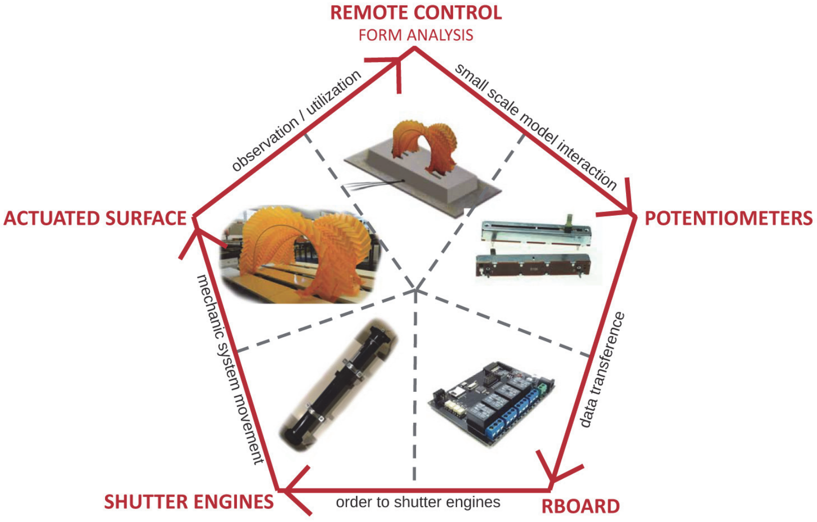

Figure 6. KOS - kinetic process

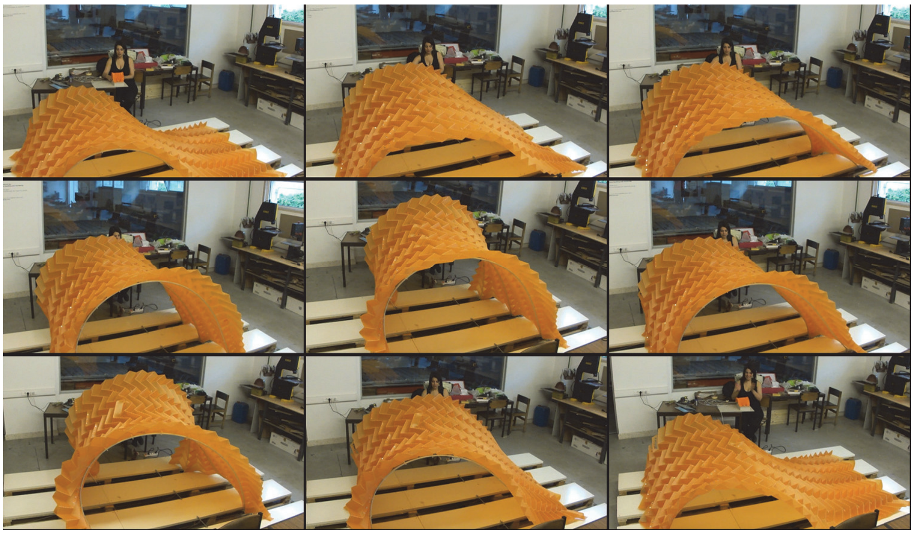

Figure 7. KOS movement storyboard

5. Discussion and Conclusions

The full scale prototype described in this paper allowed us to test the movement of an origami surface in a real scale situation.

The surface worked closely to what we expected but the forces between faces proved to be more difficult to control and have a greater role in the surface's performance than we initially thought which made us have to use a substructure to help it stand.

The surface has also shown some weak points. In particular the points where four sheets of PP meet. We believe that it would have worked better if it was all done in one single sheet, this way the isotropy of the entire surface would be guaranteed and its geometry would work as one. Despite those problems the origami geometry proved to be really appropriate to use in a kinetic situation due to its ability to self-adjust when subjected to forces and to its elastic properties.

Adding computation to control the movement and different geometries of a potential kinetic surface by a user proved to be a challenging endeavour that resulted quite well.

This project is part of an ongoing Phd research that from this experiment intends to test other materials and crease patterns with different kinetic and mechanic systems in order to develop surfaces that can be used for flexible, multifunctional spaces. Also it will try to respond to really important and practical questions for which we don't have yet the answers, like how to make it waterproof to use in an open air context. Which spans can it cover depending on the used material and/or substructure. How should the crease pattern be defined and which crease patterns work better in which situations.

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