# Interaction with a Kinetic Folded Surface

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*Kinetic systems offers new perspectives and design innovation in research and practice. These 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 as a way to respond to an increasingly technological society. The presented research attempts to answer to this question based on the results of a multidisciplinary on-going work developed at digital fabrication laboratory Vitruvius Fablab-IUL in Lisbon. The main goal is to explore the transformation of the shape of a construction by mechanisms which allow adaptation either to environmental conditions or to the needs of the user. This paper reports the initial development of a kinetic system based on an origami foldable surface actuated by a user. The user can manipulate a small scale model of the surface and evaluate at all times if it is achieving the desired geometry.*

**Keywords:** *Kinetic systems, interactive architecture, responsive surfaces, origami geometry, folded surfaces*

## INTRODUCTION

The technological advancements in fabrication and computational control are expanding the parameters of what is possible in robotics and, therefore influence the scale by which architects design and built the environments. As the objects around us become gradually more intelligent, they become more than just tools at our disposal, but somewhat, key collaborators in our everyday activities. In other words, the emergent digital processes and technologies are challenging the architecture to be adaptable and flexible at users needs. Although kinetic architectural structures have existed since antiquity, in the 1950s and 1960s, the development of computers and cybernetic control systems. Gordon Pask, Nobert Weiser and other cyberneticians made advancements toward a theoretical work concerned interactive systems related to adaptability. According to Pask (1969) "The designer is controlling the construction of control systems, and consequently design is control of control, i.e. the designer does much the same job as his system, but he operates at a higher level in the organizational hierarchy". The architects were encouraged to think architecture as interactive system rather than static. As John Frazer (1995:9) outlines "architectural concepts are expressed as generative rules so that their evolution may be accelerated and tested. The rules are described in a genetic language which produces a code-script of instructions for form-generation". In 1990s Fox founded Kinetic Design Group at MIT to explore adaptability in architecture based on full-scale interactive environments (2010).

Even though there are every time 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)

In this research we intended to pursuit a real and usable answer for kinetic systems in Architecture, where the building itself may be completely kinetic and adaptable to various intents through a direct interaction.

To respond to the flexibility asked by nowadays society we have developed a light surface obtained by the folding of a planar, rigid material with the geometric rules of Rigid Origami. The surface behaves at once as skin and structure, has self-supporting abilities, is collapsible, easily assembled and deployable, and able to assume a variety of geometric forms.

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 interact with the structure even if it is in an inaccessible location.

## KINETIC SYSTEMS

According to Fox and Yeh (2000) the kinetic systems can be classified in three kinds of structures: embedded, dynamic and deployable (Figure 1).

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)

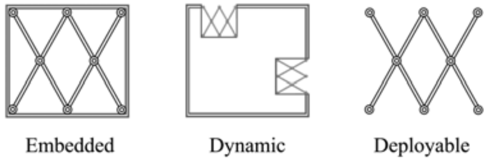



Figure 1
Kinetic Typologies in Architecture

These structures can have one or multiple functions and their movement can be controlled in six different ways (Osório et al 2014:

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 feed-back 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 in-struction 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 in-put 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 feed-back algorithm that is pre-dictive 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.

## INTERACTION

The forms of control described in the previous section are suitable for structures that function as a mechanical machine that is controlled by a non-mechanical machine, the computer. Guy Nordenson describes this phenomenon as the creation of a building as a body: a system of bones, muscles, tendons and a brain that knows how to respond. That is, the interactive space is achieved by joining the computation (intelligence) to a physical component (kinetic) which together provide environmental and human interaction. (Fox and Kemp 2009)

In kinetic, intelligent and responsive systems, the structure should be designed as an integral component of the whole, should not be considered singularly or independently. Structural solutions must simultaneously consider *ways* and *means* for kinetic operability. The means by which a structural kinetic solution operates may include, among others, folding, sliding, and expanding both in size and shape. The *ways* from which it operates can be, among others, mechanical, pneumatic, chemical, magnetic or natural. (Fox and Kemp 2009)

By implementing interactive systems in kinetic structures the built space can acquire sensory capabilities interpreting and responding to user actions or the surrounding conditions that will cause them to change their state or formal settings.

These systems are relatively well studied in the area of home automation but are still in a very early stage in architecture, that is, to design a building as a system that works entirely as a biological organism, is something with great potential but has not yet responses adequately developed. When we find examples of interactive architecture they happen to be more as installations inside an architectural space. These systems change the space of course, they fill it with different colours, or lights that are responding to users actions but they are not the space itself. Commonly these systems can be implemented in several different spaces they are not united with one specific place. But they are obviously very important. All made experiences in terms of architectural interactivity are useful and belong to the path we have to make in order to achieve a truly interactive architecture.

*"It is hard to anticipate how quickly the types of interactive architectural systems will be widely adopted, but it is not difficult to see that they are an inevitable and completely integral part of how we will make buildings in the future."* (Fox and Kemp, 2009)

The ways of altering an object or a structure through an interaction can be divided in three categories:

- One way action
- Single-loop interaction
- Multiple-loop interaction

According to Usman Haque the first type cannot be really considered "interaction" it is more a "reaction" where one element reacts to the actions of another one without giving back any kind of response, *"like a brick wall that crumbles over years under the impact of rain".*

Haque also states that *"At its fundamental, interaction concerns transactions of information between two systems (...) these transactions should be in some sense circular otherwise it is merely "reaction"."* (Haque 2006)

It is considered a single-loop interaction when a user interacts with an object and it gives back just one response and the interaction ends. This is true for situations like withdrawing money from a cash machine or choosing the temperature in a thermostat. Even if at the initial action there are several possible choices it is chosen only one and after the response is given the interaction is over.

A multiple-loop interaction allows for a continuum of cycles of response in which each cycle brings some new information based on the "conversation" between user and machine. In this kind of interaction it is often possible to build knowledge about the user during repeated interactions that permit the computer to construct a data base specific to that user and consequently allows it to respond in a more personal way in future interactions.

## KINETIC ORIGAMI SURFACE (KOS)

When developing KOS we intended to create an interactive structure that could create spaces. It is not yet a building of course, but it may be the first step to define a building that can be interactive as a whole. We aimed to create a system that could assume different forms in order to configure different spaces, with a range of different areas and volumes and several different geometric configurations so it would be able to respond to several different needs of a user.

We designed a multiple-loop interactive structure, not in the sense of making the structure build knowledge about the user but in the sense of allowing for multiple responses. The user can interact with the structure through a remote control, a reproduction in a small scale of the structure itself. By manipulating it the user can choose the desired form, then watch the structure assume it, analyse the outcome and re-manipulate it or accept the form achieved.

The research design process used to develop the KOS encompassed four phases as shown in Figure 2:

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;
3. Explore possible forms of actuating remotely on a folded surface;
4. Building the prototype.

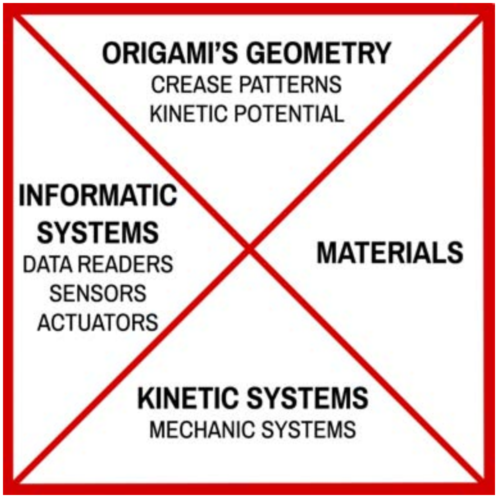



Figure 2
Areas of study

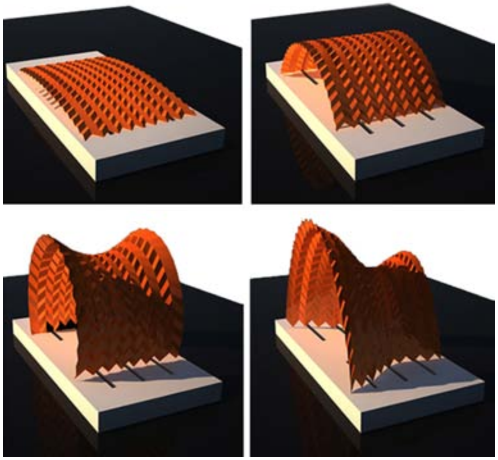
### *Step 1*

In the first phase we have studied origami regular and irregular crease patterns like Namako pattern and Miura Ori pattern in order to find their geometrical properties and capabilities of assuming different geometries when forces were applied. We decided to use the Miura Ori pattern with a regular tessellation because it proved to have the best compromise between all of our demands such as self-supporting abilities, geometry's predictableness and easiness to control.

### *Step 2*

The second phase, which consisted in building small scale prototypes with different crease patterns, different materials and different mechanic systems, led us to settle for 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 the 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 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.

### *Step 3*

In the third step we tested and developed several forms of indirect control, at last we decided to use a microcontroller board (Arduino compatible) 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 make each motor move until the remote control's shape was achieved. 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. The program is quite simple:

```
#include "Wire.h"
#include "SRF02.h"

boolean EXPAND = true;
boolean CONTRACT = false;

// Number of different configurations
// in the model and in the structure.
// That is the number of states
int NUM_STATES = 5;

// Number of control lines in the
// structure.
int NUM_LINES = 3;

// Pins and addresses for sensors and
// motors
int modelSensorPins[] = {A0, A1, A2};
int structSensorAddress[] =
                {0x70, 0x71, 0x72};
int motorPins[] = {7, 5, 12};
int motorDPins[] = {6, 4, 11};

// Ultrasonic sensors to measure the
// shape of the real structure
SRF02 s1(0x70, SRF02_CENTIMETERS);
SRF02 s2(0x71, SRF02_CENTIMETERS);
SRF02 s3(0x72, SRF02_CENTIMETERS);

SRF02 structSensor[] = {s1, s2, s3};

// Actual state for each control line
// for the structure and for the model
int structState [] ={0, 0, 0};
int modelState []= {0, 0, 0};
```

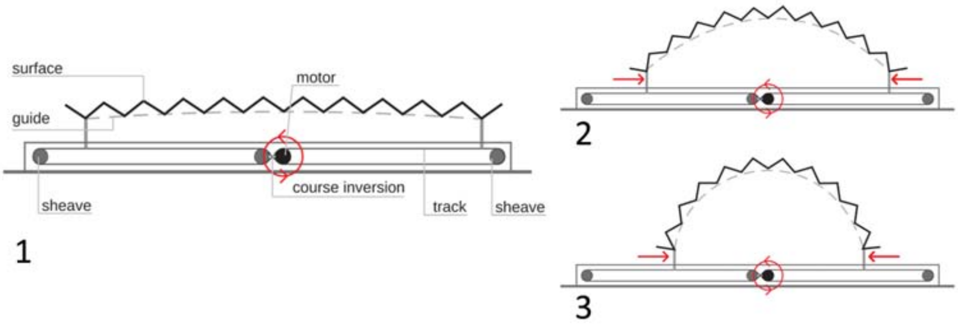



Figure 4
Mechanical system

```
// Setup and inicialization of the
//  arduino port configuration
void setup() {
   for(int i =0; i < NUM_LINES; i++){
       pinMode(motorPins[i],OUTPUT);
       pinMode(motorDPins[i],OUTPUT);
   }
   Wire.begin();
}

// Main control loop
void loop() {

  // read the shape of the model:
  for(int i =0; i < NUM_LINES; i++){

     // read the potentiometer
     // values that represents
     // the shape of the
     // model
     int sensorValue =
       analogRead(modelSensorPins[i]);

     // convert the model position
     // into a state
     modelState[i] = map(sensorValue,
                         0,
                         1024,
                         0,
                         NUM_STATES);
  }

  // read the shape of the
  // structure:
  SRF02::update();
  for(int i =0; i < NUM_LINES; i++){
       int sensorValue =
              structSensor [i].read();
       structState[i]=map(sensorValue,
                          30,
                          100,
                          0,
                          NUM_STATES);
  }

  //Activate all motor
  for(int i =0; i < NUM_LINES; i++){
      activateMotor(motorPins[i],
                    motorDPins[i],
                    modelState[i],
                    structState[i]);
  }

  delay(500);
}

// Activates the motor in the correct
// direction to change the structure's
// shape in order to replicate the
// model's state
void activateMotor(int motorPin,
                   int dirPin
                   int modelState,
                   int structState){
```

```
        if (modelState==structState){
            motorOff (motorPin);
        } else {
            if(modelState<structState){
               motorOn (motorPin,
                        dirPin,
                        CONTRACT);
            } else {
               motorOn (motorPin,
                        dirPin,
                        EXPAND);
            }
        }
}

// Switch on the motor attached
// to motorPin/dirPin in a
// specified direction
void motorOn(int motorPin,
             int dirPin,
             boolean direction){
     digitalWrite (dirPin, direction);
     digitalWrite (motorPin, true);
}

// Stop  motor connected to
// motorPin
void motorOff(int motorPin){
     digitalWrite (motorPin, false);
}
```

Such a simple program allows a very reactive control as we will show in the next point.

### *Step 4*

Finally in phase four we built the prototype. For the surface we used 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. We did the precreasing with a CNC and then folded and assembled the 18 pieces manually.

Then we installed the folded surface on the base where the mechanical system would work. Then we configured the controller of the structure. Finally we could test if the cycles (Figure 5) between orders and reactions worked properly.

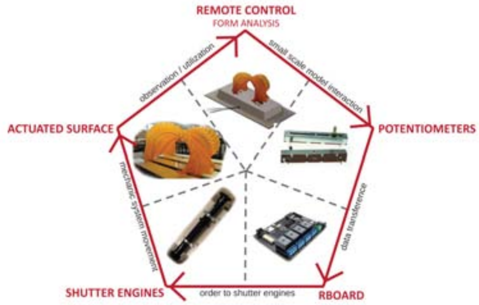



Figure 5
Interaction cycles

In Figure 6 it is possible to see the user manipulating the tangible remote control and how this manipulation affects the folded surface making it assume diverse geometries.

## CONCLUSIONS

Building the full scale prototype allowed us to test the movement of an origami surface in a real scale situation when controlled by a tangible remote control.

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 geometry of the surface has also shown some weak points. In particular the points where four sheets of PP meet, at these points the surface tended to lose its geometric continuity. 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 elastic properties and ability to self-adjust and find a "comfort geometry" when subjected to forces.

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

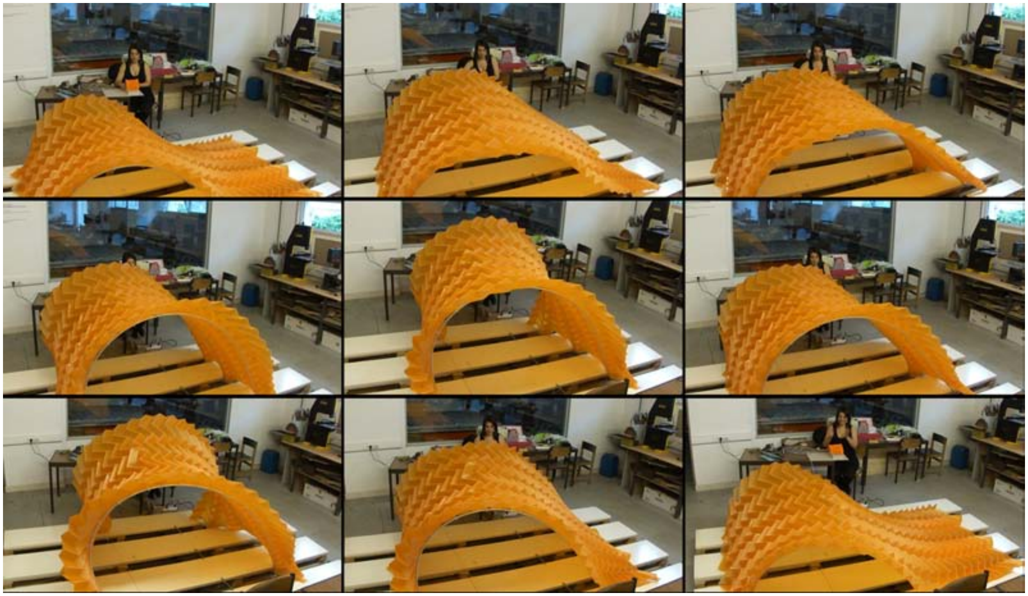


Figure 6
KOS movement storyboard

produced a direct response in real time and the result was reasonably close to the geometry in hands.

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 sub-structure. How should the crease pattern be defined and which crease patterns work better in which situations.

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